From Mirror Therapy to Augmentation[1]

Holger T. Regenbrecht*, Elizabeth A. Franz, Graham McGregor, Brian G. Dixon, and Simon Hoermann

University of Otago

P.O. Box 56, Dunedin, New Zealand

{holger.regenbrecht*|elizabeth.franz|graham.mcgregor|brian.dixon|simon.hoermann}@otago.ac.nz

*corresponding author

Abstract

Video mediated and augmented reality technologies can challenge our sense of what we perceive and believe to be "real". Applied appropriately, the technology presents new opportunities for understanding and treating a range of human functional impairments as well as studying the underling psychological bases of the phenomenon. This paper describes our "augmented mirror box" (AMB) technology which builds on the potential of optical mirror boxes by adding augmentations that can be applied in therapeutic and scientific settings. Here we test hypotheses about limb presence and perception, belief, and pain using laboratory studies to demonstrate proof of concept. The results of these studies provide evidence that the AMB can be used to manipulate beliefs and perceptions and alter the reported experience of pain. We conclude that the system has considerable potential for use in experimental and in clinical settings.

Introduction

The line between what is real and what can be computer generated is increasingly blurred (cf. IJsselsteijn et al., 2005). Augmented reality might change the way we view the world and what we perceive and believe to be "real". Creating a mirror image of what is real (let us say human hands), and presenting this image in an augmented environment, adds to the blurring effect, since it can raise doubt about whether we think we are looking at our hands or at some enhanced or manipulated version of them projected on a screen. This effect is related to the phenomenon of neuroplasticity; the brain's ability to adapt its functions and activities in response to environmental and psychological factors (Doidge, 2010). In our view, neuroplasticity is mediated by beliefs, perceptions, sensations and emotions. It is the brain's ability to act and react in ever-changing ways, through thought and activity based on environmental input, which has led to the novel system that we describe in this paper.

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The system is an augmented development of the standard optical mirror box (Ramachandran et al., 1995) and has enabled us to explore the mirroring process and its potential application in experimental and clinical settings. A brief background of the issues that led us to develop an augmented mirror box is presented by way of introduction. We then provide a detailed description of our new system approach and the capabilities that we are currently exploring. Finally, for proof of concept purposes, data is presented from two experiments involving control participants along with a case study on a patient with severe (complex regional) pain.

Background

Our augmented mirror box system emanates from research from the sensory and motor domains that has led to developments of therapeutic devices to ameliorate unilateral (one side) sensory and motor impairments. For example, research on the effects of amputation has revealed that some amputees experience phantom pain in the stump of a missing limb. Other amputees experience a phenomenon referred to as phantom limb movement, often not involving pain but rather a vivid experience that the missing limb still moves, even by the participant's own volition (Carlen et al., 1978). In the perceptual-motor domain, 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 (Franz, 1997). Combining these findings, Franz and Ramachandran (1998) 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.

An initial reflection technique, known as the "mirror box", was developed during the course of that study to project an image of the healthy limb's movement, giving the visual appearance of two limbs moving, i.e., bimanual coupling. The hope was that this form of virtual movement could be used to engage the brain's processes associated with the other (impaired) limb, thereby reducing its spatial and motor impairments. Positive results followed, with case studies showing a reduction of pain in amputees (Ramachandran & Rogers-Ramachandran, 1996); people with chronic pain (Tichelaar, 2007; Rudd et al., 2008); enhanced motor output in patients with unilateral stroke (Gaggioli et al., 2005; Jang et al., 2005; Dohle et al., 2008); wrist fracture (Altschuler & Jeong, 2008).

Franz's lab demonstrated an initial proof of their concept in a larger group of control participants who experienced enhanced bimanual coupling with use of an optical mirror box (Franz & Packman, 2004). However, prototypes of *virtual reality* mirror approaches that are in the direction of our AMB system, but with still some use of optical mirrors, have only recently been developed (Giraux & Sirigu, 2003; Sveistrup, 2004).

We integrate these approaches into an augmented reality therapy treatment apparatus and methodology that can represent the realism of the visualisation of one's own limb in the optical mirror box with the flexibility of control of the virtual reality approach. We have developed and implemented a system comprising a combination of customizable off-the-shelf (COTS) and specialized hardware and software. The system is designed to provide (a) a well controlled environment to test our hypotheses on perceptions and beliefs and (b) a reliable and robust system for use in therapeutic settings.

The questions and issues we seek to address here include: (1) How does an optical mirror box work and how is it used in therapeutic and scientific settings? (2) How can the concept of an optical mirror box be amended to (a) mitigate its shortcomings and (b) explore new effects achievable by way of augmentation? We also present a number of proof of concept studies that: (a) compare our augmented mirror box with the standard optical version, (b) test our assumptions about possible changes in perceptions and beliefs when using our technology and (c) explore potential application areas beyond optical mirroring. Finally, we consider how the AMB can be developed and its potential uses in experimental and clinical settings.

The optical mirror box

The optical mirror box is well known as a therapeutic device that assists in the treatment of unilateral sensory and motor impairment, such as phantom limb pain and the early and intermediate stages of Complex Regional Pain Syndrome (Giummarraa et al., 2007). The optical mirror box uses an ordinary mirror to confuse our senses about the ownership of our hands, or limbs in general. For instance, in phantom-limb pain management the stump limb of an amputee is placed behind a mirror while the healthy limb is reflected in the mirror. If the client moves both limbs (real and illusory movement) in a simultaneous way, the reflected healthy limb is often taken for the other one. This bimanual coupling effect could also be investigated and reported in studies with normal controls where the participants reach a higher coupling of simultaneous movements with the help of a mirror (box) than without (Franz & Packman, 2004).

Figure 1. Bimanual movement in an optical mirror box setup

However, in these studies participants are aware that it is their own limb being reflected, given that they can always see the reflection. While this fact does not seem to pose problems for mirror therapies that have been developed to date (within the limits of successful applications), it leaves open the question of whether the effects of the mirror box are a result of sensory influences, or possibly higher order beliefs. As has been suggested in previous work on neurologically normal controls without unilateral impairment, perhaps the mirror box fools the brain into thinking it sees two hands moving, resulting in a fusion of the visual onto the proprioceptive inputs (Franz & Packman, 2004). With the optical mirror box it is clear at all times that this so-called illusion of bimanual movements exists only in the mirror (see Figure 1).

Desmond et al (2006, p.74) report that there are methodological limitations inherent in the use of conventional mirrors:

> *They necessarily reflect the image of the remaining intact limb; thus, visual feedback is dependent on movement of the intact limb. This limits the potential for experimental manipulation and the realism of the phantom representation. In many cases, the phenomenologically experienced phantom limb differs substantially from the limb before amputation, and from the remaining "intact" limb. The lack of resemblance between the phantom limb and reflected image may diminish or inhibit the therapeutic value of the intervention. Furthermore, the standard mirror box protocol is inaccessible to those with bilateral amputations or those who experience phantom-like sensation or pain after spinal cord injury.*

Our research seeks to extend the therapeutic possibilities of the optical mirror box by allowing the illusion to be mediated in different ways. The technology involved for this purpose is described in the following section.

The augmented mirror box system

This section reports on the development of a computer assisted augmented mirror box set-up (AMB) to test hypotheses about limb presence and perception, belief and pain under laboratory conditions (Regenbrecht et al, 2008). The prototype developed for this purpose projects a moving, real-time image of a person's healthy limb via a computer and camera system. This projection provides a bimanual (mirror box) illusion, which can be used to help to treat symptoms of unilateral impairment associated with paralysis and pain. The augmented aspect of the technology, which we call Augmented Reflection Technology (ART), enables us to alter perceptions and beliefs using mixed reality environments; hence enabling both users and practitioners to 'reflect outside the box'.

Hardware

The technology involves a standard personal computer which is connected to our Augmented Mirror Boxes and two screens: one for the experimenter or therapist, the other for the user or client (see Figures 2 and 3). The video signals of the cameras built into our AMBs are connected via USB (v2.0) to the computer system. This setup allows for a decoupled capturing and visualization of the user's limbs. The AMB consists of a black wooden cubic box (dimensions 370 x 370 x 370 mm[3]). The front opening of the box is covered with a black curtain; the back opening is 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; hence the setup is suitable for experimentation and clinical use. The arrangement of the LEDs on the ceiling of the box was determined by experimentation – optimizing brightness, diffuse illumination and provision of sufficient shadowing effects for background subtraction and depth cuing purposes, including perceived texture depth of the hands. We have developed different lighting versions for different application setups including arrangements of about 100 low energy LEDs, 9 high energy LEDs, and a translucent or open back (using no LEDs at all).

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 approximately 80 degrees of diagonal field-of view are used to capture a maximum of the space within the box. Philips SPC1000NC and Logitech Quickcam Pro9000 cameras are currently used in the setup. While each box contains one camera, some include pairs of cameras for stereo depth capture purposes.

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.

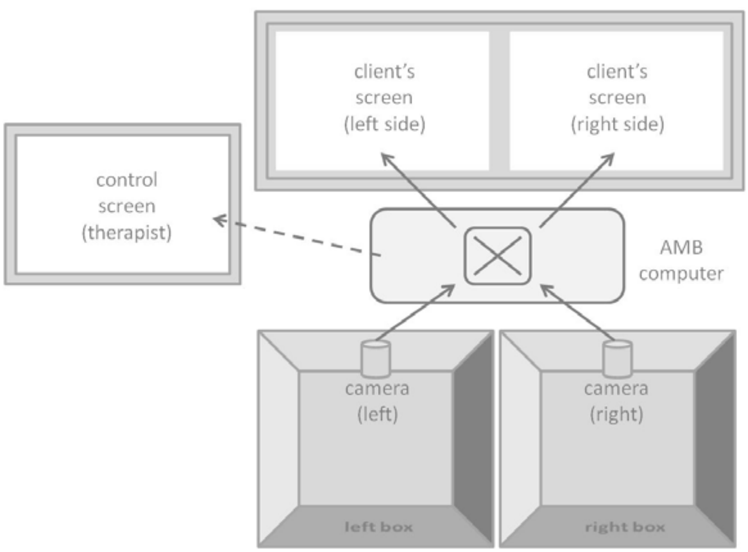

Figure 2: Schematic Overview of AMB setup

Figure 3: The AMB system in use

Software

The main functions of the software are: (1) controlling the incoming stream of video signals (left and right box cameras); (2) background subtraction (and future depth map estimation); (3) provision and rendering of a 2D or 3D environment in which (4) the box content (e.g. hands) is merged; (5) manipulation of the box content and environment (in particular mirroring); and (6) providing a control mechanism and GUI for the experimenter, including specific recording functionality explained later. Figure 4 shows a combined view of the experimenter's screen (left) and the user's screen (right).

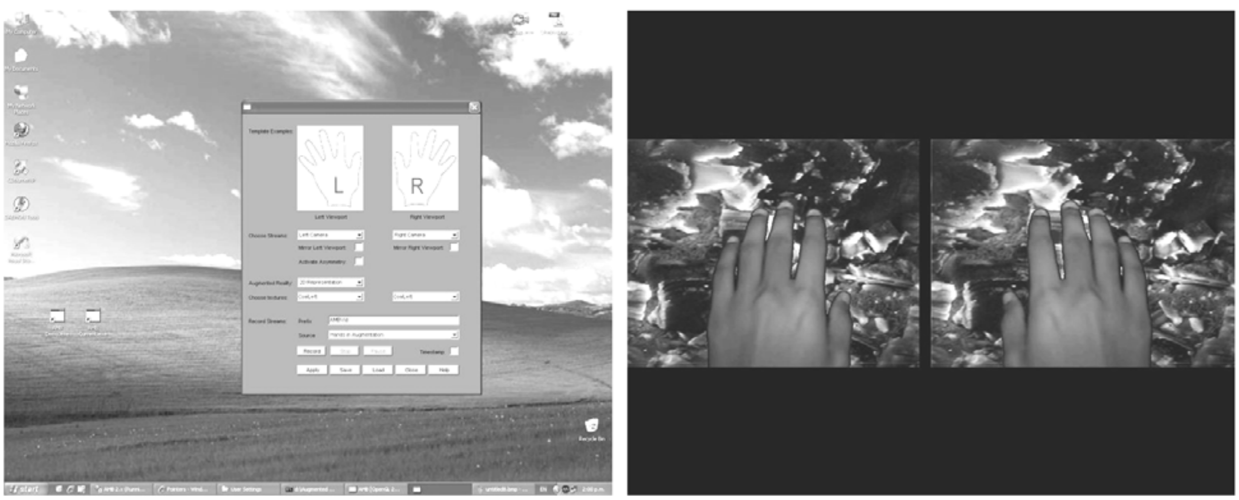

Figure 4: Control dialog (left) and user's view (right)

In both application cases, experiment and therapy, three different configuration controls for the visualization of the hands (or other box content) are needed. First, the video streams are directed, thus enabling all possible connections between the cameras in the left and right boxes with the left and right display for the user. The left camera image can be displayed on the left or right or on both simultaneously;

the same applies for the right camera image. Second, in order to implement the mirroring effect, the hands can be displayed either as captured or mirrored. For example, if the left hand is to be displayed on both user screens, we would mirror the display of the hand on the right screen to achieve the illusion of having both hands displayed correctly, even if only the left hand movement controls the visualization. Our technique allows us to reflect images of either hand or both, which increases the flexibility of the system. Third, the ways in which the hands move on the screens can be manipulated. We call this feature symmetric / asymmetric movement. A mirrored hand would normally, without intervention, act in a mirrored way. If the actual hand moves to the right, the mirrored left hand on the right screen would consequently move to the left. In some cases, it is desirable to have the hand moving in an asymmetric way. If the left hand moves to the right, the hand displayed on the right screen also moves to the right. While this feature is implemented and has been technically evaluated, it has yet to be empirically or clinically tested.

Figure 5 shows the controls as they appear for the experimenter, including the two hand illustrations built into the GUI to help with the (rather complex) understanding of the direction and mirroring options. Visual representations were used to help address this complexity and to ensure that our research group discussions about the options were unambiguous.

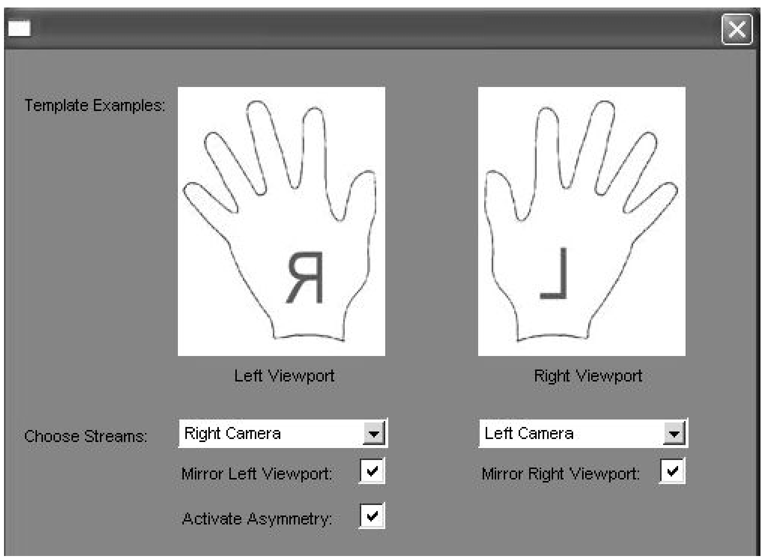

Figure 5: Experimenter/Therapist's GUI control for direction, mirroring, and symmetry

The display of the virtual environment the hands are acting in can be controlled by the experimenter in three ways:

(1) the hands are displayed in a dark box. No augmentation at all is used, but instead the background subtracted video stream is displayed in the desired fashion (direction, mirroring, and symmetry);

(2) a so-called 2D augmentation is applied where the (usually black) background is substituted with textures (e.g. photographs or other pictures). Here the hands are operating in front of the textured background;

(3) a 3D augmentation is achieved by placing a 3D virtual model of a cube, representing the physical AMB into the rendered view. Here the hands are operating inside the rendered environment. Normally the sides of the cube are textured to provide the impression of 3D impression. For a convincing 3D representation, correct depth information about the hands (pixel-wise) is desired to correctly determine occlusions between real hands and virtual objects. Currently, the 2D augmentation technique is used for experiments and clinical studies only. Figure 6 shows different environments loaded into the system.

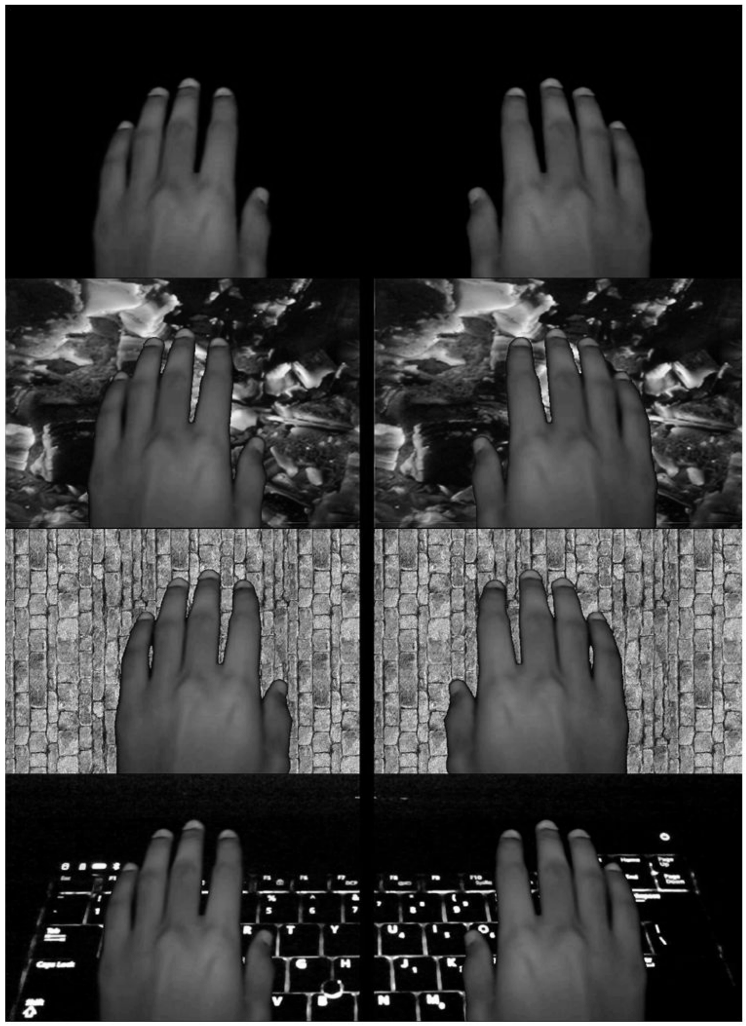

Figure 6: User's hands operating in different environments

The software can record raw video streams directly from the cameras in the boxes, the hands only, background subtracted and shown on black background and/or the hands within the augmented environment as seen on screen. The recordings can be optionally visibly time-stamped. Researchers are also able to measure and record different types of information for experimental purposes, including: (a) quantifying the effect of users' reactions, (b) measuring the extent of therapeutic progress and (c) video files for home therapy use. Sessions can be captured in two separate video file for the left and right sides respectively. Laboratory research used to test the reliability and usability of the system is presented in the following section.

Proof of Concept Studies

Our prototype system went through many stages of hardware and software refinement during technical and empirical testing. These refinements also led us to constantly review and revise our research agenda and questions, which currently include:

- Can the brain be fooled with our system?
- How does prior knowledge of the systems underlying principles influence the perceived outcome? How is the sense of presence (of body parts) affected by the system?
- Does visual or tactile augmentation affect perceptions and beliefs?
- Can therapeutic effects be achieved?
- Is the technical quality of the system sufficient for scientific and therapeutic research purposes?
- Can similar or improved effects be achieved in comparison to the optical mirror box?

This list is not exhaustive, but challenging enough to require initial proof of concept studies. Three such studies are presented in this section. The first two studies involve non-clinical participants. They illustrate the potential of augmentation and particularly its capacity for 'fooling the brain' by challenging human perceptions and beliefs. The third study is based on a clinical case and explores possible therapeutic applications that could be developed using our system. All three studies were conducted in our Multimedia Systems Research Laborato**ry,** following ethical approval granted by the University of Otago.

Play with virtual ice and fire

Both non-clinical studies test the novelty aspects of mirroring, believability and augmentation. The first study uses virtual augmentations, while the second uses real (tactile) augmentations.

The AMB 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 Augmented Mirror Box, and a similar environment showing hot coal burning (see Figure 7). We conducted a within-subject experiment with a randomized order of the two conditions.

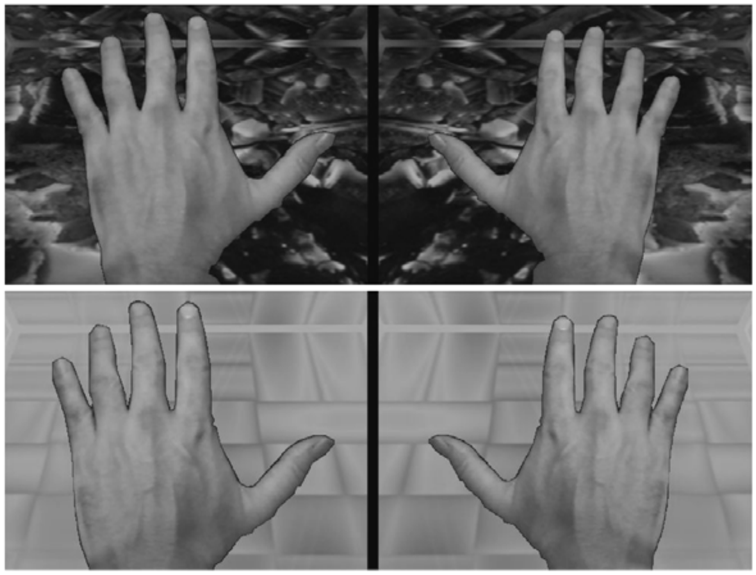

Figure 7: Hot (upper panel) and cold (lower panel) environments

We hypothesized that (1) the participants would notice the mirrored conditions, but (2) they would be unable to determine what exactly is happening. We also hypothesized 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.

Participants: Thirty-two non-clinical staff and students from Otago University were recruited as participants. The age ranged from 19 to 54 years, m=28.7, s.d.=8.7; 28 of them were male. All participants had normal vision or wore spectacles providing normal vision and were free of health problems with their hands. Five participants were left-handed.

Procedure and Apparatus: We used a standard PC (Dell Optiplex 755, Quadcore Intel Q6600 @ 2.4 GHz running WinXP SP3, ATI Radeon HD 2400XT, 256 MB) in combination with a 22" monitor for the participants (1680x1050@60Hz). The participants sat approximately in 50cm distance from the monitor showing both screens. Each experimental session lasted for about ten minutes. The participants were asked to remove any jewellery or accessories before they were seated. The task was to guess the temperatures felt before, between and after the two conditions. During the exposure they were asked to make slow grasping movements with both hands for about 20 seconds, a task used in standard optical mirror therapy. The hot and cold environments were shown in randomized order. After completion of the tasks the participants were asked to fill in a questionnaire with 8 items which were modified versions of the Igroup Presence Questionnaire (Schubert et al., 2001) and two additional questions: “I did realise that my hand was mirrored” and “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 such comments were recorded in writing.

Results and Discussion: Thirty (94%) of the participants reported that the hands displayed on the monitor were their own hands (m=1.97, s.d.=1.1). Nine participants (28%) reported that they noticed that the hands were mirrored (ratings of 1,2 or 3 on a -3 - +3 Likert-like scale), but only 4 (12.5%) participants recognized that the left hand was mirrored. Twenty-four participants (75%) chose "don't know" when asked which hand was mirrored. This finding is supported by our observation that even if individuals are highly motivated to identify and explain the manipulation, they were mostly unable to do so.

To our surprise, there was no significant effect involved in the reporting of perceived temperature. This could be because our augmentations were not of really convincing quality. It may also relate to the fact that the colour and lighting of the hands did not change with the augmentation. Most importantly, however, the participants did not realize what was going on when placing their hands in the AMB setup. Fooling the brain seemed to work.

Play with water

In the second non-clinical study, real tactile feedback was combined with visual (mirrored) feedback as a form of non-virtual augmentation. Our interest was again in how the mirroring was perceived (if at all) and the effects of augmentations.

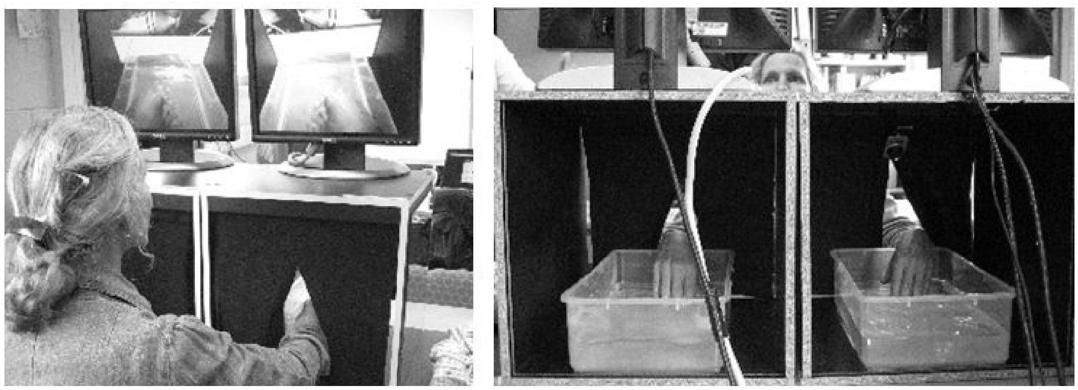

Figure 8: AMB Setup for water experiment

The visualisation of participants' right hands was mirrored on the left screen while the actual hands were exposed to (real) water (Figure 8) set to certain temperatures. In a within-subject experiment with 3x2 conditions: (mirrored, vision, no vision) x (same or different temperature) we tested three main assumptions:

1. Participants believe that the hand(s) shown are their own (mirrored and non-mirrored conditions);
2. The mirror effect works;
3. There will be a perceived temperature transfer from one hand to the other during mirroring.

Twenty-two participants took part in this study, all of whom were right handed. We tested three visual conditions in fixed order (1) no visual feedback, (2) correct visual feedback (left screen shows left hand, right screen shows right hand), and (3) mirrored feedback (right hand shown mirrored on left screen). The temperatures were counterbalanced as same versus different for the two hands.

We measured (self-report) the perceived temperature, non-specific psychological distress (*K10* questionnaire), each individual's current level of general well-being (*Affectometer*), and also asked people to report on their perception/belief of what was happening.

Results. Only one participant correctly reported the nature of the manipulation. Half the sample did not report on any awareness of the manipulation at all. The other half of the participants thought they knew what was going on, but were wrong or only partially correct when queried further. Three participants (14%) realised some sort of mirroring was occurring, but were unable to say what they thought it was; another three participants reported on definitely noticing mirroring.

All participants perceived the system as realistic / believable. However, a perceived temperature difference was not reported. While the augmentation effect (the perceived temperature transfer) could not be demonstrated, the mirroring effect clearly worked.

The results from both non-clinical studies proved the concept that the brain can be 'fooled' using our system. Given that this was the case, we were keen to explore whether this finding could be used for therapeutic purposes.

A therapeutic case study

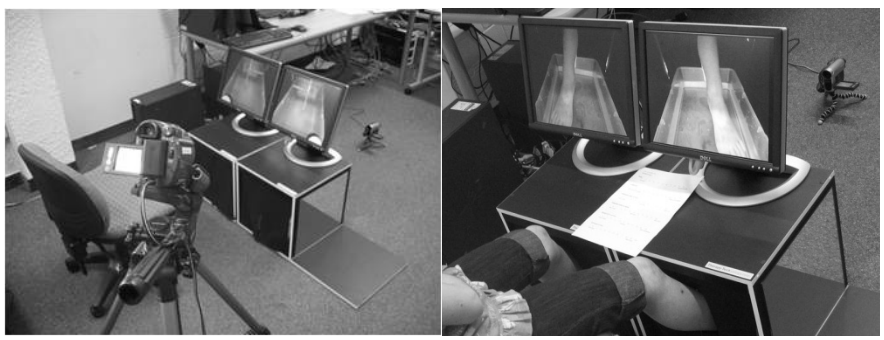

Figure 9: AMB Setup for CRPS case study

Our first task was to test whether our augmented system could replicate the kind of effects identified in the original Optical Mirror Box research. We were fortunate in being able to recruit a volunteer (referred to as F1) who had undergone regular OMB treatment for Complex Regional Pain Syndrome (CRPS). Moreover, this individual was keen to explore a new technologically based approach to treatment.

F1's pain had been present in one foot for a number of years and most recently has been treated using conventional mirror box therapy, with reported positive outcomes. We consequently modified our system (designed for hands) for use with feet (see Figure 9).

Detailed physical and psychological background information was obtained from F1 with particular attention to the injury and related medical history. For our experiment, we used a setup similar to that described for the "play with water" study (above). The AMB boxes contained bins filled with water set to a comfortable temperature. Mirroring was used with both the pain free (healthy) foot and the CRPS-affected foot. The principle of the AMB, the apparatus and goals of the study were explained to F1, including the use of mirroring.

Likert scales were devised to reflect the key features of F1's CRPS (pain, comfort, temperature, sensitivity and itch). The scales were adapted to incorporate two distinct features of F1's pain; a "general" pain sensation across the area of the foot and ankle affected by CRPS and a localised sense of sharp or "stabbing" pain in a defined smaller area on the foot. F1's ratings on the Likert scales across the conditions were recorded.

As is common with those with CRPS, F1 reported a diminished sense of "ownership" of the injured limb. This effect extended to perception of the mirror image of the "healthy" limb despite F1's awareness of the mirroring effect. Throughout the experiment, F1 consistently rated the temperature of her limbs as different; the affected limb was sensed as colder than the "healthy" limb. F1 also rated the foot affected by CRPS as more "sensitive". Ratings of "Comfort", "pain" and "stabbing pain" in the affected limb revealed marked changes when the pain-free limb was "reflected" and being moved. These changes were positive and significant. Pain ratings fell from a subjective 6 to 2 (and returned to the higher levels in subsequent conditions) and the "stabbing pain" reduced from 8 to 2. Ratings of "comfort" shifted from 4 to 7.5 (where 10 represents "very comfortable"). The ratings for the "healthy" limb maintained minimum pain and maximum comfort levels on the scales. These findings demonstrate that the pain that F1 was experiencing was able to be reduced dramatically when F1 perceived the affected limb as if "moving" due to the effect of mirroring the movement of the healthy limb. The fact that this effect was observed for the three variables (general pain, "stabbing" pain and "comfort") lends credibility to the finding that mirroring had "fooled" the brain. These results, albeit from a single subject study, suggest that the AMB was capable of producing effects that have been reported in therapeutic applications of the optical mirror. The finding is encouraging and lends support to the belief that the AMB has the potential for useful therapeutic applications. Further single-subject studies are currently being conducted with other volunteers suffering with unilateral limb pain.

Conclusions and Future Work

The system presented in this paper consists of an augmented mirror box hardware and software system that we have developed and used in experimental studies to 'fool' the human brain. Questions that we confronted in developing the system, along with the summary answers we have been able to provide at this stage of our research are presented here by way of conclusion.

Is our system able to do what an optical mirror box does?

Participants report that they believe the AMB shows their own hands and feet. One participant, who had previously used an OMB, attested to the face validity of the AMB and reported a significant reduction in subjective pain ratings using it.

What can our system provide over and above what a mirror box alone provides?

The AMB provides a system for recording and measuring impaired and improved limb movement, as well as its perceived physical and psychological effects.

What can our system do that the more standard optical mirror box cannot?

The AMB enables both limbs to be hidden, while projecting real time images immediately in front of users on a computer screen. It allows the display of different simulated environments for therapeutic and rehabilitation purposes (e.g. changes in size, colour, and dimensionality). It allows for the mirroring of symmetrical and asymmetrical movements.

What are the limitations of the AMB?

While the system design has been successfully used for experimental purposes, there is plenty of scope for improvement. The system has limited portability compared to some optical mirror box products. The interface is not user friendly enough for non-specialists and work is underway to address this issue. A short to medium term goal is to develop a reliable and robust “shipping” version of the AMB for use in clinical trials and therapy outside of a laboratory setting. Further proof of concept studies are underway (e.g. Hoermann et al., submitted), including clinical case and control studies.

Our goal now is to investigate unilateral limb impairments in a series of clinical studies using the AMB system as a diagnostic and therapeutic tool. We look forward to reporting the outcomes of this research in due course.

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