Mixed reality environments in stroke rehabilitation: interfaces across the real/virtual divide

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ABSTRACT

Previous studies have examined the use of virtual environments (VEs) for stroke and similar rehabilitation. To be of real benefit it is essential that skills (re-)learned within a VE transfer to corresponding real-world situations. Many tasks have been developed in VEs, but few have shown effective transfer of training. We believe that, by softening the real/virtual divide, mixed reality technology has the potential to ease the transfer of rehabilitation activities into everyday life. We present two mixed reality systems, designed to support rehabilitation of activities of daily living and providing different mixtures of digital and physical information. Functional testing of these systems is described. System development and user evaluation continues, some of which is described in a sister paper (Edmans et al 2004) in this volume.

1. INTRODUCTION

Stroke is a term used to describe a sudden neurological deficit within the brain. The extent and precise location of the damage is unique to the individual, making intact function and observed behaviour also individual to each stroke survivor. A thorough assessment of the patient's cognitive and motor function is the first stage of rehabilitation. For most patients the priority is to facilitate a return home as soon as it is safe and timely for them to do so.

Rehabilitation necessarily aims to restore function and so may be aimed at reducing impairments or promoting activities. Following a series of workshops and seminars with stroke survivors, occupational therapists and consultants, the activity of making a hot drink was selected as a suitable activity of daily living upon which to base the research reported here (Hilton et. al. 2000, 2002).

A number of previous studies have examined the use of virtual environments for stroke rehabilitation focussed on activities of daily living. Davies et al (2002) used virtual reality in three different scenarios: a kitchen activity, operating an ATM (cashpoint) and way finding. A meal preparation task in a virtual kitchen was the focus of research by Christiansen et al (1998), while Brown et al (1999) considered a variety of activities taking place within a virtual city. A virtual environment to train stroke survivors to cross a street safely was the focus of work by Weiss et al (2003). Gourlay et al (2000) have developed a hot drink task as a virtual environment for rehabilitating stroke survivors accessed via a mouse or data glove.

Virtual environments (VEs) have as their core the simulation by computer of three-dimensional space; they can be explored in real time with similar freedom to real world exploration, and the user may interact with objects and events in the simulation. Interactions with VEs reproduce similar visual-spatial characteristics to interactions with the real world, and they can preserve the link between motor actions and their perceived effects (Regian, Shebilske and Monk, 1992). This has lead to a focus on virtual rehabilitation environments, in which survivors of stroke and those with other, similar conditions rehearse tasks that would be problematic in the real world. It is often pointed out that rehabilitation tasks presented within a VE enable patients to repeat tasks in safety, to feel free to manipulate the world autonomously and, if the experience is an enjoyable one, gain much needed confidence. To be of any real benefit, however, it is essential that skills (re-)learned within a virtual environment transfer to corresponding real-world situations. While many tasks

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have been developed in VEs, only a limited number have demonstrated effective transfer of training (Linden et al. 2000; Mendozzi, Pugnetti, Barbieri et al 2000; Rose, Brooks & Attree, 2000; Stanton et al., 2000).

A potential alternative to the self-contained virtual rehabilitation/learning environment is provided by the recent development of mixed reality environments and systems. Mixed realities are spatial environments in which participants can interact with both physical (real) and digital (virtual) information in an integrated way (Milgram and Kishino 1994). Mixed reality technologies have been employed in a variety of entertainment, art and educational scenarios, but have yet to be explicitly and systematically applied to rehabilitation. By softening the real/virtual divide we believe that mixed reality technology has the potential to ease the transfer of rehabilitation activities into everyday life. This might be achieved either by making critical physical information available during a single and otherwise virtual rehabilitation activity, or by performing that activity in a series of increasingly physical mixed reality systems over an extended rehabilitation programme.

The adoption of a mixed reality approach naturally focuses attention on the technology used to interface the real and virtual environments. The provision of effective and usable interfaces to virtual rehabilitation environments is non-trivial; standard interface technologies are frequently inappropriate per se, and a wide variety of user abilities must be provided for. Previous work on interfaces to VEs, including our own (Cobb et. al. 2001), has, however, focussed on providing the user with access to or a sufficiently high level of immersion in a virtual rehabilitation environment. Residual perception of the surrounding real environment is seen as a shortcoming. Mixed reality work differs from traditional virtual reality in two key respects. First, emphasis is placed on the complete system, not just the virtual environment. Second, information regarding the real environment is viewed as a resource, not a problem. We adopt these views here.

2. A MIXED REALITY FRAMEWORK

Mixed reality technologies can be characterised by their relative positions along an axis spanning the real/virtual divide (Figure 1). Immersive virtual reality, experienced via head-mounted displays or CAVEs (Cruz-Neira et. al. 1992) provide the most completely virtual experience; participants can become involved in the virtual environment to the complete exclusion of the surrounding physical world. In augmented virtuality (Milgram and Kishino 1994) representations (e.g. images or video streams) of real objects are included in the virtual environment, allowing the inhabitant of a VE to access physical information. Mixed reality boundaries (Benford et al 1996) mark the midpoint of the continuum between real and virtual environments. Mixed reality boundaries connect virtual and physical spaces by creating a transparent boundary between them. Projective displays allow inhabitants of the real world to view events in the virtual, while co-located cameras or other sensor technology allow those in the virtual environment to view the physical. Mixed reality boundaries with a variety of properties are in existence (Koleva et. al. 1999). Moving further towards the physical, augmented reality overlays digital data on views of the real world, usually via a transparent display (e.g. Billinghurst et al 1996), allowing the user to view but not usually to manipulate digital information. The physical manipulation of digital information is, however, key to the notion of "tangible bits" proposed by Ishii and Ulmer (1997). Tangible bits uses graspable physical objects to manipulate digital data, so the movement of an object in the physical world has a corresponding and predictable effect on the virtual.

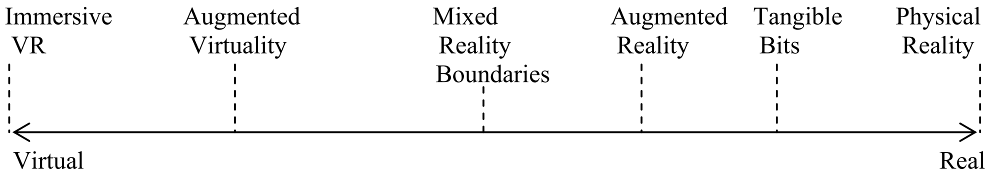

Figure 1. *Technologies across the real/virtual divide.*

The technologies overviewed above each provide the user with a unique mixture of the real and the virtual. This mixture should be exploited and explored to determine which provide(s) the most appropriate experience(s) at each stage in the rehabilitation process. With this goal in mind we have developed a variety of interfaces to a virtual environment designed to support the making of a hot drink. The resulting mixed reality systems can be characterised by their position on the continuum of Figure 1. Following a brief account of the common virtual environment they are described below.

3. THE VIRTUAL ENVIRONMENT

The role of the VE is to encapsulate and support the presentation of the digital information made available to the user (patient). Here this comprises a model of the task at hand, expressed via direct visual feedback and pre-recorded audio-visual guidance and demonstrations. A hierarchical task analysis (HTA) was developed to divide the top-level activity of making a hot drink into progressively smaller discrete subtasks, the process continuing until the subtasks represent individual actions.

Close integration of the VE and any sensors providing information from the physical world is critical, and for this reason we have shifted VE development from SuperScape™ to Virtools™, in recognition of the latter's enhanced ability to communicate with external software and devices. Objects were modelled in Lightwave ™ and are based on real kitchen objects used in patient assessments. The functional status of each object is maintained and used to determine which actions are permissible/desirable. Suitable words and phrases were compiled (Edmans et. al. 2004) and a health care of the elderly nurse with experience of multimedia recording provided the voice-over. Figure 2 shows a sample view of the environment.

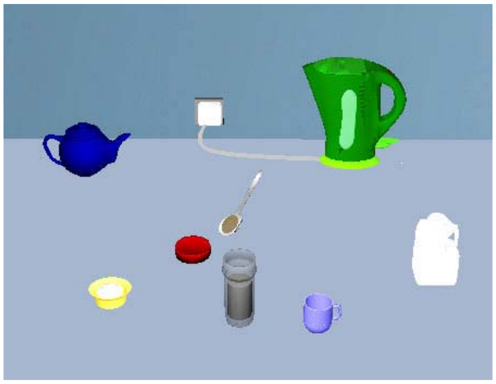

Figure 2. *The kitchen activity layout in Virtools™*.

In operation, each interaction is logged and scored according to a scheme devised in collaboration with an Occupational Therapist (Edmans et. al. 2004). A correct action scores 2 points. If after 20 seconds no input has occurred a verbal prompt is given and subsequent actions score one point. Following a further time period a verbal instruction is given, informing the user what to do. If there is still no response a demonstration of the correct action is provided and the user scores 0 for that subtask. To test the functionality of the scoring system 20 representative scenarios were designed and scored manually before being executed within the VE by one healthy user. In each case the automatically generated scores were as expected.

4. THE TOUCH SCREEN: A MIXED REALITY BOUNDARY

Touch-sensitive screens offer a direct mode of controlling objects in a virtual world. A touch screen is a simple example of an (asymmetric, Koleva et al 1999) mixed reality boundary, and so lies at the midpoint of the continuum of Figure 1. Recent developments have made the touch screen an affordable option that might offer an opportunity for patients immediately post-stroke to commence rehabilitation using a notebook computer from their hospital beds. Providing a single, localised view of the virtual environment, this technology may be of particular use to individuals with diminished ability to divert attention between multiple locations. Hofmann et. al. (2003) used touch screens to train Alzheimer's patients on a shopping task and attribute the positive effects of their training regime in part at least to the ease of use of the interface.

A lightweight and robust Toshiba Satellite Pro A10 notebook computer with a 14" touch sensitive monitor was selected and alternative touch screen controls developed. A two touch operation was devised to provide the simplest form of input: an action is be initiated by selecting appropriate objects or pairs of objects. Identification of successful selection is an important design feature and feedback has been incorporated in the form of a pointer accompanied by a brief audible tone. The base functionality of the system was tested by taking a typical scene from the hot drink environment, selecting all possible pairs of objects and ensuring that the required/expected model subtask was generated. A drag and drop mode was offered as an alternative, relying upon proximity detection between objects. While they may slow interaction, Potter et al (1988) show that more realistic but more complex interactions of this type are acceptable to touch screen users and can produce fewer selection errors.

To compare the touch screen controls, a simple task was implemented in Virtools™. This required the user to apply a clearly visible stamp to a clearly visible envelope. In two touch mode the user must first select any point on the stamp, followed by any point in the upper right quadrant of the envelope. The stamp then moves to a predefined position in the corner of the envelope. If the second point is not in the acceptable area an audible error message is generated. In drag and drop mode, selecting and dragging the stamp onto the upper right quadrant causes the stamp to fly to the predefined stamp position when the finger is released (the "take-off" strategy of Potter et al 1988). If the stamp is released outside that quadrant it remains at the point at which it was released and an audible error message is generated.

The stamp task was attempted by nine patients, at various stages post-stroke, under the supervision of an experienced OT. Each made ten attempts using each of the touch screen controls. Every patient managed to successfully complete the task within ten trials using the two touch interface, but none could reliably use the drag and drop system. Several were forced to use non-dominant hands, but even those using dominant hands had difficulty. When asked which they would prefer to use for the hot drink task all selected the two touch version. Lack of accuracy at anything above a very slow speed was cited as the primary cause of difficulty, though the need to steer round other objects generated noticeable, if secondary, problems. In a study of brain-injured patients by Linden et al (2000), all subjects expressed a desire for a drag and drop mode. Our studies found that the precision required to complete a drag and drop action using a touch screen significantly increases the difficulty of the task for stroke patients.

Following a period of frequent design iteration to determine system function, 10 patients admitted to a stroke unit have been involved in a continuing programme of participatory design informing the development of the VE/touch screen system. Patients completed the hot drink activity both independently and with OT supervision. Video recordings, field notes, verbal feedback and automatic data recorded in the VE have been used to assess the developing system. Details are given in a sister paper (Edmans et al 2004). The only issue raised regarding touch screen control was the standard difficulty in selecting small objects. Observed sequences of object selection are consistent with the task model, indicating that identification of objects in the VE does not appear to have been an issue with these particular patients. Although common, requests for increased realism centred on realism of behaviour, not of appearance. Evaluation of the system continues.

5. INCREASING REALISM: A TANGIBLE INTERFACE

Ishii and Ulmer (2001) define tangible user interfaces (TUIs) as giving "physical form to digital information, employing physical artefacts as representations and controls of computational data". As such they provide more physical information than do mixed reality boundaries. The use of TUIs is rare in rehabilitation, though Sharlin et al's (2002) "Cognitive Cubes" have shown some potential as a cognitive assessment tool.

Cobb et al. (2001) describe TUIs to an everyday task designed for use by young adults with a learning disability. Studies with stroke survivors in the community criticised these early systems, in which the graspable objects were mounted on a base board, as lacking flexibility (Hilton 2002). The ability to reposition objects is considered to be essential, as is the freedom to complete the task in a preferred sequence. To improve mobility the base board was removed. Real kitchen artefacts were retro-fitted with compact sensors and machine vision techniques employed to recognise and recover the position of individual objects.

Non-mercury tilt switches were mounted inside vessels intended for pouring. Sub-miniature micro-switches were mounted inside ABS boxes with 49x29.5mm plastic lids mounted on rubber shims to provide pressure operated switching. A test bed was developed in which twin cables connected each sensor and an input pair of a keyboard encoder. A connection made across an input pair emulates a key press, allowing individual sensors to provide unique codes. In a single case study, part of the iterative design process, a 60 year old stroke survivor unable to use the left side of his body completed the hot drink making activity using the sensor driven TUI, demonstrating that the sensors operated as expected. A wireless system was then constructed using RF Solutions Ltd AM-RT4-433 Transmitters and AM-HRR3-433 Receiver operating at the general purpose telecommand / telemetry band of 433MHz frequency. The wireless system has been tested up to a distance of 2m from the receiver and found to be effective.

Object position is recovered from colour images provided by a vertically mounted digital camera whose field of view covers the workspace. As real time response and robustness are of primary importance we follow Swain and Ballard (1991) in basing object recognition on colour histograms. An 8*8*8 bin histogram of the colours present in each camera frame is compared with a set of pre-calculated model histograms, one per object. As objects can be chosen to be fairly colourful in this environment, each model histogram will contain peaks at certain chromaticities; the image histogram should contain similar peaks if the object is present. A given bin of the image histogram may, however, contain more pixels than the corresponding model bin. These extra pixels should be discounted. The difference between the value $N_I(i)$ in the i^{th} bin of the image I and the value $N_M(i)$ in the i^{th} bin of the model M is calculated. The minimum of zero and this calculated difference forms the basis of the histogram comparison operation. Summing this over the image I gives a value between 0 and $-N_M$ where N_M is the total number of pixels in the model histogram. If all bins in the image contain at least as many pixels as the corresponding model histogram bin, the result is 0, if the image histogram has no pixels in the bins in which the model histogram pixels are found – if the occupied

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sets of bins from the histograms do not intersect – then the result is $-N_M$. To produce a fractional estimate we use:

$$C(M,I) = \left[1 + \frac{\sum_{i=1}^{511} \min(N_I(i) - N_M(i), 0)}{N_M}\right]$$

If this value exceeds a threshold the object is considered to be present in the image.

The location of the recognised object must now be determined. If $p_{ij}(x,y)$ is the location of pixel j, in bin i of the image histogram, the average location of pixels in bin i will be $L_i(x,y)$. Weighting this by the proportion of pixels of the model histogram M in bin i, and taking the sum of the weighted averages across all the bins of I gives an estimate of the location M(x,y) of the model M in the image I:

$$L_i(x,y) = \frac{\sum_{j=1}^{N_I(i)} p_{ij}(x,y)}{N_I(i)} \qquad M(x,y) = \sum_{i=1}^{511}\left(L_i(x,y) \times \frac{N_M(i)}{N_M}\right)$$

To increase robustness, a background image, showing the workspace with no objects present, is constructed using median filtering. Subtracting the background from each input image means that the histogram containment operator can be restricted to areas of the image most likely to contain an object. While Ballard and Swain (1991) used the familiar red-green-blue colour coding, we build histograms of hue-saturation-intensity values, this representation being more stable under changes in illumination.

To assess the ability of the method to recognise kitchen objects, models were built of six everyday items: a jug, yellow and blue mugs, a sugar pot, coffee jar and a redbush tea packet. Figure 3 shows samples of the image data used to create the model histogram. Each object was placed in the field of view, the background image subtracted and those pixels considered significantly different to the background (i.e. sufficiently likely to depict objects) used to build the histogram. Six recognition trials were then run. In each, one model was loaded into the system and the corresponding object moved across the field of view. Table 1 shows the mean, maximum and standard deviation and maximum values of C(M,I) reported. Values are close to 1 in all cases.

To estimate the level of potential confusion between objects, all six models were then loaded into the system and each object once again presented in turn. Table 2 shows the mean confidence level obtained when each object (vertical axis) is compared with each model (horizontal axis). In most cases maximal values lie along the diagonal. The red tea box is, however, confused with the coffee jar and the jug with the blue mug. Care must be taken when choosing object; the image data reveals similarities not obvious to the naked eye.

Figure 4 shows the system recognising and tracking the positions of two objects simultaneously, the input image is shown in Figure 4a and the system output in figure 4b.

The system has been applied to sequences of images of the stroke patient described above testing the sensor–equipped kitchen objects. Although these early hospital trials were broadly successful, shadows cast by the patient and OT disrupted processing. Large variations in (natural) light also made recognition increasingly difficult as the trial progressed. Future trials will use more controlled illumination. Alternative, illumination independent recognition methods may be considered. Again, development continues.

An early version of the vision system (Ghali et al 2003) was used in isolation, employing a task model expressed in XML to recognise events (sub-tasks) in the hot drink making activity. Although that configuration had some success in determining the relative positions of objects it could not recognise other events, such as an object being tipped. The various embedded sensors can identify (some) binary events but do not record their location. The combination of these complementary technologies is natural. The object recognition/location software is written in C++ over Microsoft DirectShow, and produces a text file listing the name of each object present and its position in image coordinates. These are then converted into the Virtools™ coordinate frame and associated with the corresponding virtual object. Evaluation of the complete tangible user interface is underway.

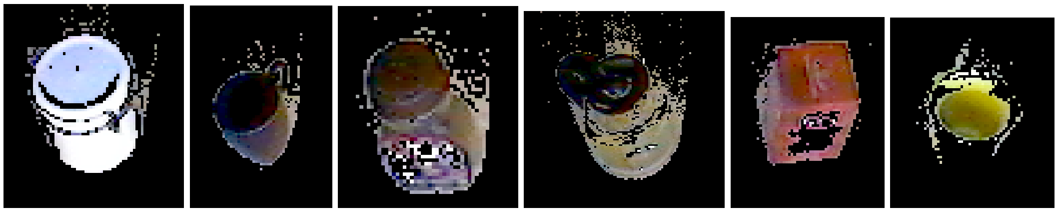

Figure 3. *Background-subtracted image fragments used to build model histograms.*

Table 1. *Confidence scores in a single model/single object trial.*

	JUG	YELLOW MUG	BLUE MUG	SUGAR POT	RED TEA	COFFEE
MAX	0.936198	0.995757	0.994943	0.983957	0.856031	0.979574
MEAN	0.811353	0.925159163	0.888821092	0.830353814	0.6651334	0.81934
STD DEV	0.071397	0.050094091	0.071219554	0.10395138	0.0673606	0.157848

Table 2. *Six object confusion matrix.*

	JUG	YELLOW MUG	BLUE MUG	SUGAR POT	RED TEA	COFFEE
JUG	0.600527955	0.698621582	0.725871254	0.24182894	0.315906881	0.583295731
Y. MUG	0.251440304	0.732824768	0.335289893	0.171731804	0.115175089	0.431838357
B. MUG	0.319896646	0.315210958	0.718631458	0.206522979	0.337775625	0.572546604
SUGAR POT	0.190307208	0.151663981	0.348305208	0.608503226	0.100183472	0.450333453
RED TEA	0.230223298	0.157844021	0.474890362	0.292937234	0.449076957	0.560163957
COFFEE	0.346011333	0.414849035	0.636746737	0.336417579	0.299952175	0.776323632

a. *b.*

Figure 4. *Visual recognition and location of two kitchen objects.*

6. CONCLUSION

The mixed reality systems presented above lie at widely separated points on the continuum of technologies shown in Figure 1, and raise differing technological challenges. In the touch screen system the user/patient interacts directly with virtual objects, focusing attention on the ecological validity of the virtual environment and the extent to which s/he feels immersed in that environment. The tangible interface centres the user's attention on real, physical objects, with the VE providing a task model and a medium for audio-visual feedback rather than a focus for the rehabilitation activity. Manipulation of those objects must, therefore, be smoothly mapped into corresponding changes in the virtual environment. Iterative improvement of these systems, and the design of new systems, will continue over the next period. It should also be recognised that, whilst this combination of technologies may seem cumbersome now, advances in the specialist technologies we are using will improve over the next few years.

We have produced a first version of an integrated mixed reality system that works. Users can access the virtual environment using a variety of interface methods to control activity and complete the task of making a hot drink, with prompts and feedback provided as required. At present, however, this procedure is slow and requires users to learn how to work with it. This is not acceptable for a system intended to support rehabilitation of users who will have very different needs and abilities. Whilst we are aware of the general requirements for stroke rehabilitation, we need to understand more about individual differences amongst the patient population and how this will affect their attitudes towards, and the effectiveness of, the mixed reality system for supporting them through the rehabilitation process. A participatory design approach used for the current phase of development will take information from users (occupational therapists and patients) to directly inform iterative development of new versions of this system.

The longer-term objective is to identify how the various mixtures of the physical and the digital, made available via mixed reality technologies, can and should be exploited during the rehabilitation process:

- Which provide(s) the most appropriate experience(s) at each stage in the rehabilitation process?
- What activities are best supported via these systems?
- Are individual mixed reality systems effective, or is a suite of systems required?

These questions are the focus of clinical evaluation studies conducted by our research team (see Edmans et al 2004) under research currently funded by the Stroke Association.

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