# Mixed reality environments in stroke rehabilitation: development as rehabilitation tools

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## ABSTRACT

A virtual or mixed reality environment for neurological rehabilitation should simulate the rehabilitation of the task, and not simply simulate the task. This involves identifying the errors in task performance that neurologically damaged patients make during task performance and replicating the guidance given during skilled rehabilitation. Involvement of a skilled therapist in the design and development team is essential. Neurological rehabilitation is complex and replicating it requires compromises between the desire to replicate this complex process and the amount of development time. Virtual or mixed reality systems that can simulate the rehabilitation process are suitable for clinical effectiveness studies.

## 1. INTRODUCTION

Loss of the ability to make a hot drink after a stroke is common. It is important because this loss makes returning home independently from hospital more difficult. Accordingly, this ability is commonly assessed during stroke rehabilitation in hospital and treatment aimed at restoring function is commonly given. We have developed virtual and mixed reality environments to aid the rehabilitation of this task.

### *1.1 Prior development of mixed reality environment for making a hot drink*

A user-centred design process was used. Initial work, in which patients and Occupational Therapists were consulted, confirmed that virtual environment based systems could potentially be useful for this purpose (Hilton et al, 2000). Early experience with patient groups showed that acceptable means of interfacing with a virtual environment were needed before the virtual environment itself could be developed. A keyboard, mouse, or joystick was not appropriate for this group of patients. One approach, taken from earlier experience in the use of virtual environments with people with learning disabilities, was to develop a Tangible User Interface in which objects were manipulated to control the virtual environment instead of a mouse / joystick or keyboard (Hilton et al, 2002). Initially a keyboard-mounted device was developed in which movement of the objects simply generated pressed keys on the keyboard. The Tangible User Interface was found to be too inflexible. Consequently, a second approach used objects containing movement sensitive switches, thereby replacing the keyboard entirely. Objects in the first movement sensitive objects interface version connected to the virtual environment using cables, but in a later version the wires were replaced with radio transmitter devices. This provided a very flexible system, free of cables, keyboards, joysticks or mice.

Another approach to interface with the virtual environment has been to use an off-the-shelf touch screen interface, requiring no new technical development. Yet another approach has been to use machine vision of normal kitchen objects to drive the making of a hot drink in the virtual environment: this has required considerable technical development (Ghali et al, 2003). The development of three interface approaches (touch screen, movement sensitive objects interface, machine vision) has enabled us to develop a mixed reality system, which offers the opportunity to train both the cognitive and physical aspects of task performance. Details and justification of this approach are given in another paper (Hilton et al 2004).

Once workable interfaces had been developed, it was then possible and necessary to develop our VIRTOOLS virtual kitchen environment controlled by these interfaces. At this stage the elements of an acceptable and usable system for people with stroke had been developed.

The development team until this stage included experienced technical staff, and had consulted with health care staff including Occupational Therapists, but did not include an Occupational Therapist within the team, and no field tests with stroke patients undergoing rehabilitation had been undertaken.

In this paper we report our experience during the necessary work to develop our system for making a virtual hot drink into one that was not only usable by people with stroke, but was also fit for purpose as a rehabilitation tool.

### *1.2 Virtual environments as rehabilitation tools*

The development work so far had focussed extensively and necessarily on means to interface with the virtual environment. In this next phase we had to concentrate more upon the virtual environment itself and how the system would be used as a rehabilitation tool in clinical practice. This required attention to the reasons why these types of technologies have potential value in rehabilitation, and why they may fail. The potential rehabilitation benefits of practice in a virtual environment include:

- Treatment of the cognitive processes of task performance can take place sooner in a virtual environment than in a real environment. For example, patients with physical problems might be able to rehearse the cognitive aspects of task performance needing only sufficient motor capacity to control a virtual environment rather than real objects.
- Virtual environments can avoid retraining in potentially hazardous settings. For example, patients would not be at risk from boiling water or electricity as they would be if they were in a real environment.
- Working with virtual environments can be enjoyable and compulsive, so providing motivational benefits. Many rehabilitation experts believe that motivation during rehabilitation is a factor in its success. One reason for this is simply that patients who are more motivated spend more time and effort into promoting their recovery and that this drives neural plasticity, the presumed underlying mechanism of neurological recovery after brain injury (Taub et al, 2002). Virtual environments can be designed so that patients can use them with little or no clinical supervision. This could increase the amount of time spent in rehabilitation.
- Virtual environments can allow the learning process to be more strictly controlled and defined than might be possible in the real environment. “Scaffolded” learning could be used (Wood et al, 1976), in which the task is initially simplified and then progressively made more complex as the patient’s ability increases. This process is called “shaping” in the neurorehabilitation literature (Taub et al, 2002). The distractions of real world learning, and de-motivation caused by repeated failure if too complex a task is attempted, can be avoided.

The potential rehabilitation drawbacks of virtual environments are:

- Interfacing with the virtual environment could be too difficult for patients to use. Patients cannot benefit from rehabilitation if they do not participate in it.
- The system could be too difficult, unrealistic or intuitive to be enjoyable and motivational. Patients may not benefit if not motivated.
- The system could fail to train the cognitive skills that are lost. Brain injuries such as stroke cause a huge variety of neurological impairments, singly or in combination, and these differ between individuals. It is important to design environments and training routines that deal with the common faults and errors neurological patients make during making a hot drink, which may differ from those made by non-neurologically impaired people.
- Training in the virtual environment could fail to generalise to real world settings. It has been found that people with cognitive problems due to acquired brain damage such as stroke often show poor generalisation from a training task to performance in naturalistic settings (Manly, 2002). Little is known about the benefits of mixed reality rehabilitation environments.

## 2. DEVELOPMENT OF THE SYSTEM AS A REHABILITATION TOOL

Further to the development of a system that was usable by stroke patients, where a virtual hot drink could be made, we now needed to develop the system so that it simulated rehabilitation of this task. In particular we needed to ensure that the learning processes invoked during use of our system were likely to promote recovery. For example, an early version of our system used in usability trials simply instructed the user through the steps of making a hot drink. Clearly, that version did not provide scaffolded learning, or opportunities for problem solving. In this stage therefore, we required the typical errors in performance made by patients to be identified, and the presumed effective parts of the guidance and feedback used during rehabilitation to be replicated. For this, we needed the contribution of an Occupational Therapist experienced in stroke rehabilitation. The following observations were made.

### *2.1 Task model*

The Occupational Therapist observed that many stroke patients do not drink or want to make coffee (the task within the virtual environment at this stage) and therefore they would not see this as a meaningful part of their rehabilitation. Both tea and coffee making therefore needed to be included in the task model and the virtual environment.

The Occupational Therapist also observed that there is no set procedure for making a hot drink and people do this task in many different ways, e.g. some people put milk in the mug before the tea and some do it after the tea, some people even put everything into the kettle and boil them up together. In clinical practice the therapist would therefore find it inappropriate to try to train a pre-determined, "correct" method for making a hot drink. Instead, the therapist would teach the patient to do the task the way they want to do it, providing it is functional and safe. The task model therefore had to be examined and adjusted so that several means of completing it were permissible, not one alone.

### *2.2 Virtual environment*

In clinical practice, the Occupational Therapist often attempts to simulate the patient's home setting including the range of objects, colour of objects, shape of objects, position of objects, other clutter, etc. The ability to do this in a hospital or clinic setting is limited, but is potentially possible in a virtual environment. However to do so, would need the system to be reconfigured each time, and would require a considerable further development. The need to reconfigure the system would put increased demands upon the Occupational Therapist. By contrast, a simple model that does not need configuration is likely to be more widely applicable.

In clinical practice, milk jugs, mugs and kettles can be almost any colour and it would not have been difficult to allow different shaped and coloured objects to be selected in the virtual environment. However a constraint of our mixed reality system is that the machine vision approach we used involves recognition of colour, rather than shape, to recognize objects. This meant that a different colour had to be used for each object (i.e. green kettle, blue mug, etc) and these could not be modified easily. Thus the use of machine vision makes configuration more complicated.

It is possible that a lack of configurability may mean that patients find the virtual environment too unreal or perceive it to be a game or toy, with the implication that it is a frivolous activity. If so, they may not be motivated to engage in it. However, our experience has been that patients do not need perfect simulation. For example, in our system, a "ping" sound with a white arrow flashing above the object was used to denote that a virtual object had been selected, and when the virtual environment gives a prompt to move an object, the object "flashes" indicating which object needs to be moved. These unreal effects did not seem to trouble either the patients or the Occupational Therapist.

We elected to keep the model simple, on the basis that we did not feel that additional complexity was necessary at this stage, but also because of limitations upon development time.

### *2.3 Identification of errors*

People with stroke have many different and complex impairments of varying severity, many of which reduce their capacity to make a hot drink. These may include weakness of the arm, impaired vision, a variety of cognitive and executive problems or a combination of these impairments. In clinical practice, errors during attempted task performance are noted by therapists and used to infer the likely underlying impairments. The Occupational Therapist then helps the patient to find means to overcome these problems. Helping the patient to overcome these errors during task performance is the rationale for occupational therapy: promoting recovery through purposeful activity.

The first challenge this poses in the development of the virtual environment as a rehabilitation tool is that, like a therapist, it must be able to detect when a pathological error (i.e. an error due to the stroke, as opposed to a simple error caused by carelessness or unfamiliarity with the system) has occurred.

To deal with this problem, the Occupational Therapist repeated a task analysis for making a hot drink, with the intention of creating a list of all the possible stages required to make a hot drink. Twenty-five stages were identified. Some of the stages were essential, such as getting the kettle, and other stages were optional, such as spooning sugar into the mug. Using the touch screen interface to the virtual environment involves 21 of the stages. Use of the movement sensitive objects interface alone only involves 10 of the stages, although all are involved when the movement sensitive objects and vision systems are used as a single interface (Hilton et al, 2004).

Next, the Occupational Therapist also compiled a list of the different types of pathological error types frequently made by patients when making a hot drink. These error types were categorised empirically into four groups: attention; sequencing; object use; dexterity and accuracy. Occupational Therapists identify these pathological error types from an almost infinite number of incorrect actions that stroke patients may make whilst making a hot drink. These include leaving the kettle lid up whilst boiling (it will not switch off with the lid up), holding a mug to the kettle spout instead of tipping the kettle to the mug, or putting insufficient water to cover the element in the kettle. These incorrect actions could be due to a variety of error types. For instance, if a patient left the kettle lid up whilst boiling, the therapist would try to ascertain whether this was due to an attention error or an object use error. Each patient's rehabilitation is then based on their impairments, the types of incorrect actions made and the possible types of errors.

Having established the types of errors commonly seen during stroke rehabilitation, we then reviewed which interface approach (touch screen, movement sensitive objects interface/machine vision) might be suitable for detecting incorrect actions and for treating patients with the different types of error. Our findings are presented in the table below.

Our interpretation of this analysis is that our mixed reality system would be able to detect most of the errors made by stroke patients undergoing rehabilitation. As expected, the movement sensitive objects / machine vision interface would be able to detect errors in the physical aspects of task performance. Although we have not had the time to do so, it would be possible to develop our system so that the degree and duration of tilt of the kettle would affect the speed the mug is filled with boiling water, and allow it to overflow. Similar changes could be made to the filling of a water jug, the kettle and so on.

We did not feel that our system could be easily used without an Occupational Therapist to interpret incorrect actions. This limits the extent to which our system can be used unsupervised and, hence, potentially limits the opportunity for increasing the amount of time a patient spends in rehabilitation activity.

### *2.4 Prompts and guidance*

The second challenge to the development of the virtual environment as a rehabilitation tool, after identification of pathological errors, was to replicate the effective aspects of prompts and guidance used during rehabilitation.

To do this, the Occupational Therapist videoed several clinical sessions during which she assessed hot drink making ability in patients in a real kitchen and when attempting to do so using our mixed reality system. Together with a colleague, she identified that she used a three-stage process. First, a prompting question would be used such as "What would you do now?" If this did not produce the correct behaviour a more direct instruction would follow, such as "Put the teabag into the teapot". Third, if this did not produce the desired action, a visual demonstration would be given. These prompts were individualised to suit individual patients' impairments.

The initial questions were felt to be the most important part of the educative process because they tended to prompt problem solving rather than provide ready-made solutions. Examples include: "What do you need now?" or "What do you need to do next?" These questions were used to concentrate on problems of sequencing, attention and initiation, when the patent was stuck, when the error was failure to proceed to the next step. Another question type was to ask patients to reflect on what stage they have just completed and ask a question. For example "You have cold water in the kettle, will it boil like that?" This can be used to question object use, sequencing, problem solving or safety issues. These questions were easily incorporated into the mixed reality system in response to errors in performance of the virtual task.

However, not infrequently the therapist had to ask the patient "What are you trying to do?" in order to understand the patient's behaviour or to identify the type of error (for example, if the patient had difficulty locating an object). In practice, this enquiry was not simple, and often involves a conversation between the therapist and patient, including the interpretation of non-verbal information. We did not think this part of the process was likely to be easily achieved through interaction with the system alone. For that reason we felt that our mixed reality system alone is unlikely to be useful without the Occupational Therapist to supervise.

**Table 1.** *Categories of errors and suitability of interfaces for their rehabilitation*

| TYPE OF ERROR | | SUITABILITY OF INTERFACES |
|---|---|---|
| **ATTENTION** | | |
| **Initiation** | Does not automatically begin the task or a stage | Detectable using all interfaces |
| **Attention** | Does not attend to an individual event (e.g. pays no attention to the fact the kettle has boiled) | Detectable using all interfaces |
| **Neglect** | Cannot find an object or does not respond to a visual or auditory cue to the affected side (e.g. unable to locate teapot positioned on his/her affected side) | Detectable using all interfaces but will need an OT to interpret behaviour |
| **SEQUENCING** | | |
| **Sequence** | Performs an action at the wrong time within the task (e.g. puts the sugar in the cup before the teabag) | Detectable using all three |
| **Addition** | Adds an abnormal action (e.g. rips a teabag open and pours loose tea into the teapot) | Will need an OT |
| **Omission** | Omits a stage (e.g. fails to put any water in the kettle) | Detectable using all interfaces |
| **Perseveration** | Repeats a stage (e.g. pours the milk into the cup twice) | Detectable using all interfaces |
| **OBJECT USE** | | |
| **Selection** | Does not select the correct object to accomplish a stage (e.g. stirs the tea with a finger or pours milk into the teapot) | Detectable using all interfaces but will need an OT to interpret behaviour |
| **Object Use** | Does not use object appropriately (e.g. uses the kettle as a teapot) | Detectable using all interfaces but will need an OT to interpret behaviour |
| **Problem Solving** | Gives unmistakable signs of not knowing what to do (e.g. continues to place the cup near the spout of kettle without picking up the kettle or looks hesitatingly at the objects, picking them up, turning them over, putting them down and trying with another object.) | Detectable using all interfaces |
| **DEXTERITY & ACCURACY** | | |
| **Dexterity** | Fumbles when attempting to use objects (e.g. spills coffee when spooning) | Best detectable using movement sensitive objects and machine vision interfaces |
| **Quantity** | Misjudges the amount of something (e.g. fills the cup with more milk than tea) | Not currently detectable |
| **Spatial** | Misjudges the location of objects (e.g. misses the cup and pours the tea onto the table) | Not detectable using movement sensitive objects interface alone. |

### 2.5 *Feasibility*

The original aims were for the virtual environment to be suitable for use at the patient's bedside in a hospital ward situation and to be safe for use by both patients and staff. Consideration therefore needed to be given to the security and portability of the virtual environment in this setting, any disturbance it may cause, plus the confidentiality of patient information stored in the virtual environment.

The virtual environment currently includes:

- Laptop with touch screen interface
- Second laptop connected to a tangible interface and visual monitoring interface
- Computer table with a video camera mounted on a bracket above the table
- Tangible interface i.e. a set of kitchen objects with sensors attached

The amount of space and equipment involved presented a problem for making the virtual environment portable. In its present state, it takes a long time to set up and requires two members of staff to do so. The long-term plan is to build a suitable workstation on wheels, so the virtual environment can be left set up ready to use. This will resolve the portability problem but then requires a hospital ward to have sufficient space to store the virtual environment.

The equipment presents a security risk: theft is common in hospitals, and computers are particularly vulnerable. There is also a need to protect confidential patient information that might be stored in it. Therefore, the virtual environment cannot be left unattended, for instance, whilst not in use or even whilst taking a patient to the lavatory during treatment.

The majority of patients in our hospital are in bays of 4-6 beds and only a minority are in individual side rooms. This presented problems for using the equipment by the patient's bedside, due to the disturbance to other patients and staff in the bay, caused by the verbal prompts and sound effects from the virtual environment. To resolve this, the Occupational Therapist had to take the patient and the equipment to a more suitable room, such as the rehabilitation room, dayroom or single room. This is another factor that makes our system more suitable as an occupational therapy aid, rather than a system for independent use by the patient.

## 3. FIELD TESTS WITH STROKE PATIENTS

To assess the clinical relevance of the mixed reality environment as a rehabilitation tool, field tests were conducted with stroke patients. These field tests so far have been conducted primarily using the touch screen interface with 10 patients. The tangible / machine vision interface field tests are in progress.

Despite the large amount of preparatory work on making the virtual environment system accessible to stroke patients, the Occupational Therapist found that she needed to train patients in the use of the touch screen, so that they knew when they had selected or moved a virtual object. For this reason, a brief training programme, involving putting a letter in an envelope and sticking on a stamp was developed.

Commonly we found that patients spoke to the system as if it were a person. We found this encouraging as it indicated that patients were activity engaging in it. They found the system challenging, and generally indicated this with good natured comments indicating mild frustration when they made errors. Examples include "*She doesn't trust me does she? Don't blame her*" (error prompts are given by a female voice): to the prompt "*What would you do next*?" the reply was "*Throw it out the window*". Only one patient became quite angry due to frustration. However, despite these frustrations, most patients after using the system were complimentary about the system and its purpose, including the person who became angry. The system was described as *"Clever", "Good for people who find this difficult" and "Easier, cleaner and quicker that the real task".*

However, the field tests have indicated that the touch screen interface is probably not suitable for all patients. Those with limited vision had difficulty seeing the objects clearly on the screen. Patients with poor upper limb co-ordination had difficulty with accuracy when using the touch screen pen to operate the virtual environment. Patients with poor short term memory had difficulty remembering how to use the touch screen pen. Patients with poor hearing had difficulty hearing the instructions given the virtual environment.

Some patients were not comfortable with feedback coming from the virtual environment rather than the Occupational Therapist. Feedback from the virtual environment is at a set speed and some patients might want it quicker, or slower. For example, to the question "*What do you need to do next*?" one patient said, irritably, "*I'm about to tell you".*

Many users (both staff and patients) had difficulty relating the virtual task to the real world task. For example some tried to put the coffee jar into the mug without taking the lid off the jar and putting the spoon into the coffee jar. They said that it was in some respects harder to do the task in the virtual environment than in the real world.

## 4. FURTHER EVALUATION

The experiences reported here, including an Occupational Therapist in the design and development team, have improved the degree to which our rehabilitation system simulates the rehabilitation of the task of making a hot drink in stroke patients. We have developed the task model to make it reflect the variety of ways patients make hot drinks. We have checked that our system is able to identify the typical errors made by stroke patients during task performance, and we have developed a system of prompts that mimic the problem-solving process used in clinical rehabilitation practice. It seems to be well received by the sorts of patients for whom it is intended. In these respects, we have developed a system that is fit for purpose as a rehabilitation tool.

On the other hand, we recognise the limitations of our system. It needs to be used by an Occupational Therapist rather than to replace her. Some errors in real world performance may not be detected when performing the task using the mixed reality system. Inflexibility of the system, for example in terms of configurability, may hamper active involvement. The cognitive demands necessary to use the system may prove a barrier to it is use in some patients, as may the effect of poor vision or poor hearing.

Some of the limitations of our system could be overcome with yet more development of the virtual environment. However, ultimately the test of effectiveness of a rehabilitation tool is not simply that it can be used, or the degree of similarity between the virtual and real environments. We feel that the most important question now is whether there is any value in using our mixed reality environment in clinical practice. We are now conducting a randomised controlled trial, using the system in patients undergoing in-patient rehabilitation after stroke.

## 5. CONCLUSIONS

This stage of development of a mixed reality environment system took a system to make a virtual hot drink, with interfaces that made it usable by stroke patients, and developed its ability to simulate the rehabilitation of that task. The process required an Occupational Therapist who was experienced in stroke rehabilitation. This work required us to review the underlying task model for making a hot drink, to undertake an analysis of the errors made during neurological rehabilitation, and an analysis of the sorts of prompts and guidance given during skilled stroke rehabilitation. A system has been developed that is fit for purpose and, although further development could continue, it now requires further evaluation using clinical effectiveness studies.

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## 6. REFERENCES

A Ghali, A Cunningham and T Pridmore (2003), Object and event recognition for stroke rehabilitation, *Proceedings of Visual Communication and Image Processing Conference, 2003.* Details available on *http://www.cs.nott.ac.uk/IPI/publication29.html*

D Hilton, S V G Cobb and T Pridmore (2000), Virtual reality and stroke assessment: Therapists' perspectives, *Proceedings of the 3rd International Conference on Disability, Virtual Reality and Associated Technologies 2000,* Alghero, Italy.

D Hilton, S Cobb, T Pridmore and J Gladman (2002), Virtual reality and stroke rehabilitation: A tangible interface to an every day task, *Proceedings of the 4th International Conference on Disability, Virtual Reality and Associated Technologies 2002,* Veszprem, Hungary.

D Hilton, J Green, T Pridmore, R Eastgate and S Cobb (2004), Mixed reality environments in stroke rehabilitation: interfaces across the real / virtual divide, *Proceedings of the 5th International Conference on Disability, Virtual Reality and Associated Technologies 2004,* Oxford, UK.

T Manly (2002), Cognitive rehabilitation for unilateral neglect: Review, *Neuropsychological Rehabilitation*, **12**, 4, pp. 289-310.

E Taub, G Uswatte and T Elbert (2002), New treatments in neurorehabilitation founded on basic research, *Nature Reviews Neuroscience*, **3**, 3, pp. 228–236.

D Wood, J S Bruner & G Ross (1976), The role of tutoring in problem solving, *Journal of Child Psychology and Psychiatry*, **17**, 2, pp. 89-100.