

Virtual Environment Training: A New Tool for Neurorehabilitation

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ABSTRACT

This paper is designed to introduce the reader to the use of virtual environments (VE) in rehabilitation by describing the theoretical and practical basis for the technique. Clinically relevant aspects of visual display devices which are available for use in VE are discussed. Next, key features of a VE system developed by the authors and colleagues are presented. The system is designed to enhance motor learning through the use of augmented feedback provided by a virtual teacher. Finally, preliminary clinical findings from a study in which the system was utilized to retrain UE motor control in subjects with chronic stroke are reported. Following treatment, subjects were found to have significant ($p < 0.05$) improvements in the Fugl-Meyer Test of Motor Recovery, the Wolf Motor Test, and selected strength tests.

INTRODUCTION

The past 10 years have brought rapid change and significant advances in the field of computer-related technologies. One such technology that has tremendous potential for application to the field of neurorehabilitation is that of virtual environments (VE). In this paper our goals are to: (1) provide the clinician with a basic explanation of VE and the theoretical basis for their use in rehabilitation; (2) discuss clinically relevant aspects of selected visual display and motion capture devices; (3) describe key features of a VE system developed by the authors and their colleagues to enhance motor learning; and (4) present preliminary findings from a study on motor learning in subjects with stroke in which our VE system was utilized.

What is a virtual environment? A VE is a simulation of a real world environment that is generated through computer software and is experienced by the user through a human-machine interface. A wide variety of hardware devices and software can be used to create virtual environment simulations of varying degrees of complexity. To understand the concept more intuitively, think of how one gathers information about the environment in the real world—through the use of one's senses. In a virtual environment, one utilizes these same senses and receptors, but they will now obtain information about the virtual world through a human-machine interface (eg, a computer monitor or head-mounted visual display). The information gathered about the virtual environment, through the interface, is then used to guide interactions of the subject within the virtual world environment.

Why use a virtual environment? One might ask, why bother using a virtual environment for neurorehabilitation

treatments when one can just as easily use a real environment? There are many answers to this question, from both a theoretical and practical perspective.

While it may seem intuitive that it is better to practice the real task in order to learn it, there is some experimental evidence that learning may be easier in a virtual environment.^{1,2} For example, Todorov et al¹ found that healthy subjects who practiced a table-tennis stroke in a virtual environment, with augmented feedback from a virtual teacher, performed better following training on a real world performance test, than did subjects who had practiced the table tennis stroke with feedback from an expert coach or had just practiced on their own. In addition, Brooks² found that a patient with amnesia was able to learn 2 routes around a (real world) hospital rehabilitation unit following training (for 15 min a day/3 weeks) in a VE simulation of these routes. Later, this same patient was trained on 2 additional routes in the same rehabilitation unit—one in VE and one in the real world. After 2 weeks of training, she had learned the route trained in VE, but not the route trained in the real world.

What might account for these findings? Learning may be enhanced because VE allows one to utilize principles derived from neuroscience and motor learning research to facilitate learning in some unique ways. For example, in VE training one can use the hypothesis that the brain plans movements in terms of the kinematics of the endpoint of the moving limb by displaying only the endpoint of the limb to the subject during training. This idea of planning in terms of endpoint kinematics is supported by 2 types of experimental findings: (1) If a subject's endpoint movement trajectory is repeatedly distorted by external perturbation forces, or perceptually via distorted visual feedback, the motor system often adapts so that the movement trajectory returns to the original trajectory (ie, approximate straight line path), in terms of the endpoint kinematics^{3,5}; and (2) Certain geometric features of movement trajectories (the individual writing style, the shape of the speed profiles) are preserved when the movement is executed with different actuators (left or right arm, foot), requiring very different muscle activation patterns and dynamic interactions with the environment.^{6,8}

A VE also allows one to program into the display a virtual teacher, who performs the task repeatedly. This visual input of the teacher repeatedly performing the movement may provide enhancement of 'learning by imitation' by facilitating direct input to M1 (primary motor cortex) via 'mirror' neuron inputs. Mirror neurons are cells in the monkey

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premotor cortex that fire both when a monkey observes a movement and when he performs that movement.⁹ These neurons may represent the output stream of a 'resonance' mechanism that directly maps a pictorial or kinematic description of the observed action onto an internal motor representation of the same action. In humans, a similar mechanism has been identified using functional magnetic resonance imaging (fMRI).¹⁰ This resonance mechanism may provide a neurophysiological underpinning to 'learning by imitation' in VE.

Most important for motor learning, practice in VE allows the use of augmented feedback about performance. Feedback can be presented concurrently with performance, directly following a trial (knowledge of results) or as a summary after multiple trials (summary feedback). The principle of enhancing learning through augmented feedback is well established for healthy subjects,¹¹ though less well understood for subjects with neurological impairments. However VE systems offer an excellent research tool with which to investigate issues, such as, which types of feedback and practice schedules are most effective for learning and for generalization to nonpracticed tasks.

Virtual environments offer the unique capability for providing real time feedback to the subject during practice in a very intuitive and interpretable form. Patients can see their own movement attempts in the same spatial frame of reference as that of the 'virtual teacher' (unlike practice with a real coach or therapist). That is, patients can place their arm 'inside' the arm of the teacher and practice the movement simultaneously along with the teacher. This eliminates time lags between patient and teacher, divided visual attention between one's own arm and the teacher arm, and the need to perform mental translations or rotations of observed movements, as would occur when observing and modeling a 'real' teacher perform the movement. (Because the patient's and the teacher's limb movements are in the same coordinate frame of reference in VE, no mental rotations are required when a patient attempts to imitate the teacher's movements). Recent experimental findings have revealed that cells of the motor areas of primates are involved in mental rotations of the direction of voluntary movements.¹² Conceivably, for some patients with cortical motor stroke, recovery may be hindered by an impairment of their ability to perform mental rotation of movements displayed to them by the therapist during training.

In VE the task can be simplified in the early stages of learning, allowing the learner to focus on key elements of the task. (For example, making the virtual scene very simple with only 1 or 2 objects; showing only the endpoint trajectory vs. the whole limb.) In contrast, in the real world situation many potential distracters exist, and may slow down learning as the subject attempts to distinguish, through trial and error, the key aspects of the task on which to focus. (This factor may have enhanced learning for the amnesia patient in the study by Brooks²). Training environ-

ments can also be customized for different therapeutic purposes and the system can be designed to help the learner detect and correct errors more rapidly. Finally practice, which is an essential element in motor learning, can be facilitated by making the task fun. This can be accomplished through various game interfaces.

From a practical perspective, VE offers advantages over real environments in several areas. These include: (1) safety - fewer negative consequences to failure; (2) reduced space and equipment needs; (3) automated documentation (see Whitney et al page 72 and Deutsch et al page 79); (4) less time—to change or set up new equipment for each practice task; (5) lower cost—if patients are able to practice some of the time on their own, with ancillary personnel, or from their home via telemedicine applications.

EQUIPMENT CONSIDERATIONS

A variety of equipment can be utilized to create virtual environment set-ups with different capabilities and purposes. The basic components of a VE system are a computer, usually with a special graphics card that will allow fast computation and drawing of 3-D images, display devices through which the user views the virtual environment, hardware devices that can be used to monitor movements, or provide simulations of haptic (touch) and force feedback to subjects, and provide an interface between the user and the virtual environment, and of course specially written software that coordinates all these elements. In this paper, we will focus on discussing visual display in interfaced devices most relevant to our VE system.

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In working therapeutically with VE, one of the first decisions a therapist makes is whether to employ an immersive or nonimmersive environment. In an immersive environment, the user has a greater sense of *presence*, or the feeling that the environment is real and 3-dimensional. Nonimmersive environments provide less of a sense of presence and are more akin to looking through a window at a scene. While it seems intuitive that immersive virtual environments would be the best to use for training, especially motor training, that may not actually be the case. This is because one major difficulty with immersive environments is that they can generate *cybersickness* (a constellation of motion-sickness like symptoms) in many subjects.¹³⁻¹⁶ Common symptoms of cybersickness include nausea, vomiting, headache, somnolence, loss of balance, and altered eye-hand coordination. These are obviously undesirable events, particularly in subjects with impaired function in the CNS.

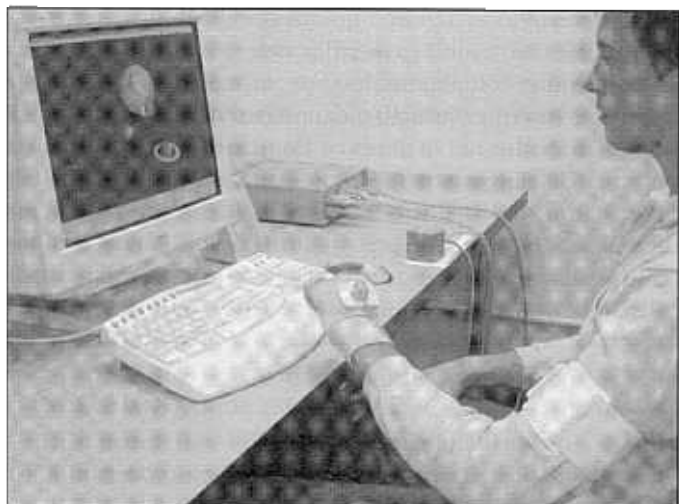


Figure 1. Equipment setup for virtual environment therapy. Magnetic tracking device, to the right of the computer, includes the transmitter unit that induces an electromagnetic field. This field is received by sensors attached to the back of the hand and upper arm. The transmitter and sensors are connected to the control unit, which interprets the data from the sensors as positions and orientations, and in turn relays this information to the desktop computer. Virtual environment software displays a scene and animates the hand and arm trajectory of the subject using the motion information collected from the tracking device.

Visual Display Devices

For a low-immersive VE, the user can employ a simple desktop computer display (Figure 1). Because the user can see the world around them as well as the virtual world, their sense of presence in the virtual world may be less, but also there is also less likelihood of cybersickness. Depth perception will not be as realistic as in a true-stereo 3-D display, but the 2-D graphics can be displayed on the screen using enhanced 3-D perceptual cues, to provide a sense of depth. Examples of monocular depth cues that provide the appearance of depth include perspective, relative motion, occlusion, and aerial perspective (changes in color and luminance with distance).¹⁷ An alternative to the desktop display, which may enhance the sense of presence, is to use an LCD projector and large wall screen as the monitor instead of a desktop computer monitor. These set-ups are convenient, easy to use, require no glasses or headset with wires, and allow both the therapist and patient to view the same scene with ease.

To move toward a more immersive virtual environment, one needs a display, which can provide true 3-D stereo. This can be done inexpensively with flicker glasses (VR Standard Corporation, Cerritos, Calif) (Figure 2), or more expensively with a head mounted visual display (HMD) (Intersense Corporation, Burlington, Mass) (Figure 3).

Electronic shutter (flicker) glasses display alternating views of the picture synchronized to the frame rate of the desktop screen, such that one interleaved frame in each pair is presented to each eye. The pictures presented to right and left eyes contain a disparity; binocular fusion then provides the stereopsis. Because the pictures are actually displayed on the computer screen (the glasses simply block

the image to right or left eye, alternately), the image can become blurred or distorted with head movements, obviously an undesirable event. Flicker glasses also have a restricted field of view and typically require high monitor refresh rates (>120 Hz) to produce flicker-free vision.¹⁸ Therapists assisting the patient also would need to wear the flicker glasses to avoid seeing a double image on the screen, which in turn could limit her ability to observe the patient in the real world. For full immersion, a HMD will allow stereo viewing. The stereo mechanism is similar to flicker glasses, but the alternating views of the picture are displayed on tiny computer screens located within the headset; higher quality optics also are added to enhance viewing clarity (with higher cost yielding better optics). The HMD also provides the ability to link the head movements of the subject with the viewpoint of the virtual environment display. This linkage in effect simulates the function of the vestibulo-ocular reflex (VOR), updating the visual display to accommodate for altered head position during viewing. This linkage is a key factor in making virtual reality seem 'real' (see Whitney et al, page 72, for more details).

While these attributes will enhance the sense of presence or 'reality,' there are some disadvantages to the use of HMDs. The field of view is restricted (<80° horizontal) compared with a real-world field of view (~160° horizontal).¹⁸ The HMDs are limited by the size of small monitors relative to the interocular distance and the optics necessary to allow clear vision at near distances. Thus, many optical compensatory arrangements result in eye-strain and visual aftereffects.¹⁹ There is also an inherent delay in sensing the position of the head with the motion-tracking device, then updating the viewpoint of the visual scene observed by the user through the HMD. This 'phase-lag' delay can be as long as 250 msec,²⁰ and lead to illusory motion or cybersickness.¹⁷ The weight and inertial properties of the HMD also may interfere with the natural ease of movement of the user, inducing fatigue and possibly motion sickness due to increased head inertia.²¹ Large screen stereo displays, obtained by special computer projectors, avoid many of the problems engendered by the HMDs, but are fairly expensive (see Whitney, page 72, for further detail).

Interface Devices

While any type of motion tracking device could be used to monitor movement or simulate movements in a virtual world, in practice, electromagnetic tracking devices are frequently utilized (Ascension Technology, Incorporated, Burlington, Vt or Polhemus Inc., Colchester, Vt). They offer the advantage of relatively low cost, and are impervious to optical occlusion problems. However, they are susceptible to signal distortion from large metal objects or from electromagnetic fields generated by electronic devices. An electromagnetic tracking device (Polhemus Inc., Colchester, Vt) used to monitor subjects' arm and hand movements and display them in the virtual world is shown attached to different body segments in Figures 1 through 3.



Figure 2. Subject is wearing 'flicker glasses' that induce a depth illusion in the viewed scene. The liquid crystal panels in front of each eye rapidly darken in synchronization with the display of left and right side images generated by the VE software, ensuring that each eye sees the appropriate images. Cyberglove on hand transmits hand and finger joint positions and orientations using fiber optic cables and a magnetic tracking sensor as described in Figure 1. Subject is also holding a 'real' object, which corresponds to a held object in the virtual environment to increase the sense of immersion and to elicit natural movements.

For capture of hand kinematics, a Cyberglove (Immersion Corporation, San Jose, Calif) may be used. This allows the motion of each finger joint to be captured using fiber optic cables embedded in the glove, and displayed on the screen as a virtual hand moving in space (Figure 2).

DESCRIPTION OF OUR VIRTUAL ENVIRONMENTS TRAINING SYSTEM

Hardware

A laboratory designed VE system based on the principle of learning by imitation has been developed and used by the authors and colleagues.^{22,24} The system consists of a computer, specially developed software, and an electromagnetic motion-tracking device (see Figures 1-3). The graphics for the VE can be visualized using a variety of different devices (see *Visual Display Devices* above). A desktop display was chosen for the first experiments, mainly for simplicity, ease of use, and to reduce the likelihood of subjects experiencing cybersickness. However, future plans include experimenting with fully immersive environments because of the advantage they offer in terms of depth perception. The VE system can be interfaced with any motion tracking system. An electromagnetic motion tracking system was chosen because the lightweight equipment, ease of use, and lower cost of these tracking devices make the system easier to use in a clinical setting.

A central feature of our VE rehabilitative system is the simultaneous display on the computer screen of the prerecorded arm movements of a virtual 'teacher' and the arm movements made by a patient using the motion-tracking device. The movements of the teacher (recorded by a ther-

apist) and those of the patient are monitored with electromagnetic sensors and displayed on the screen as movements of the limb's endpoint. (For movements where marked abnormal compensatory movements are anticipated, the entire arm may be displayed.) During training, a prerecorded movement of the teacher is displayed for the patient, and the patient is asked to imitate the trajectory, as it is displayed. The same teacher movement can be displayed over and over, or different teacher movements may be displayed in turn. The difference between the teacher's trajectory and that of the patient's provides the augmented feedback in a visual context. This feature of learning by imitation is not only an important way to provide enhanced visual feedback, but also a way to develop, through repetition, the formation of the correct pattern of cellular activity in the central nervous system (CNS).^{9,25}

Software

Virtual scenes

The major features of the system provided by software are *Virtual Scenes*, *Virtual Teacher*, *Augmented Feedback*, and *Scoring System*. *Virtual Scenes* are used to prompt patients into making arm movements, by creating a 3-D picture that suggests a functional task or goal. Each scene can be designed to elicit a different movement. The scenes allow one to create an environmental context for the movement-by providing a goal for that movement - in effect mimicking the way movements are planned in the natural world. The scenes allow one to control and monitor which movements are being trained, for how long, and for how many repetitions.

Scenes also provide a vehicle for flexible adjustment of the task difficulty and practice sequence. A Scene Editor



Figure 3. Head-mounted display consists of 2 mini displays mounted directly in front of the eyes, which provides a stronger sense of stereo separation. Head position and orientation collected by a magnetic sensor (arrow) change the viewpoint of the scene displayed by the VE software to compensate for head movement. Since the subject can only see what the HMD displays, the computer monitor can be used by the therapist to view what the patient is seeing without having to wear the equipment, if a dual monitor video card is used.

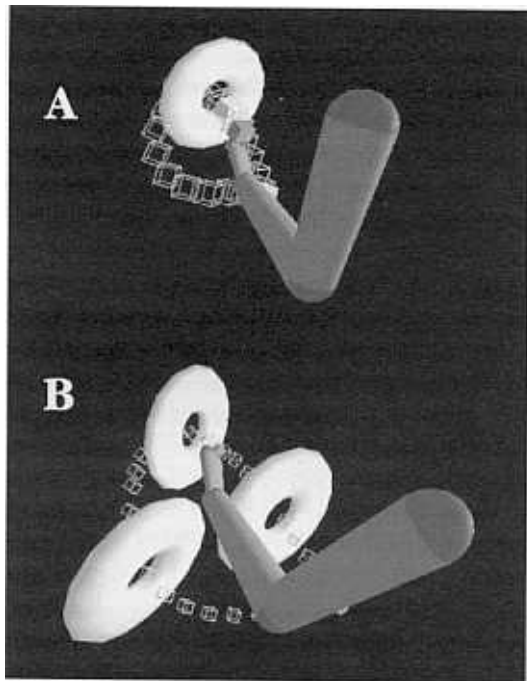


Figure 4. Example to illustrate how scenes can be used to progress a reaching movement from easy to more difficult. The subject's goal is to move a hand-held cube through the 'donut' hole. The movement starts and ends with the hand resting in the lap. The teacher trajectory is shown with the wire-frame cubes. Panel A: An easy level movement of shoulder flexion to 30° , moving toward shoulder abduction of $\sim 30^\circ$, with the elbow remaining in 90° of flexion, and forearm in pronation with wrist neutral or slightly extended. If the subject is unable to grasp the cube, it can be attached to the hand in software (as shown), so that it moves in concert with the hand automatically. Panel B: A more difficult variation of the same movement. The shoulder flexes to $\sim 60^\circ$, with $\sim 45^\circ$ of horizontal abduction and elbow extension to \sim minus 30° (highest donut). To reach the far left donut, the subject must move to $\sim 40^\circ$ of straight abduction with full elbow extension. Note also that speed of teacher is faster in panel B (wire frame cubes further apart) and the teacher object is smaller, to provide less visual cueing.

allows for the creation of different scenes to meet the needs of various patients. An example of how scenes can be used to progress a reaching movement from easy (Panel A) to more difficult (Panel B) are shown in Figure 4.

Virtual Teacher

The *Virtual Teacher* shows the patient the trajectory of the end-point (hand) path for the movement (ie, the same form used by the brain to plan the movement). In theory, this should facilitate motor learning by assisting the patient's motor planning process in a natural way. The teacher speed and appearance can be altered in a variety of ways to enhance learning; the teacher also may be removed from the display so that the subject does not become overly 'dependent' upon guidance to perform the movement. In studies on healthy subjects, highly augmented and frequent feedback has been found to be effective in improving performance (task 'acquisition') but to lessen task retention and generalization.²⁶⁻²⁸ The system allows one to vary feedback frequency so that one can provide subjects with the optimal feedback frequency for their learning needs. In VE,

the patient's limb movements and the teacher's limb movements are displayed on the computer screen in real time and in the same coordinate frame of reference. This may offer an advantage over practice with a real or videotaped teacher, where there will always be a time lag and/or a different coordinate frame of reference for the observed movement.

Augmented Feedback

The computer-generated virtual environment provides enhanced feedback available to the patient relative to feedback available during practice in the real world. This enhanced (or augmented) feedback of the system is derived from the temporal and spatial match (or mismatch) of the patient and teacher trajectories on the screen. Selected aspects of the subject's error can be isolated and displayed visually, concomitant with the movement, to help subjects learn to correct that aspect of a movement. Two schematic examples of these error feedback displays are shown in Figure 5. Panel A shows linear distance (translational) error between the teacher and learner endpoint objects, displayed as a line connecting the two objects. The visual effect is that of a stretched rubber band connecting the learner to the desired teacher position. As the learner's movement more

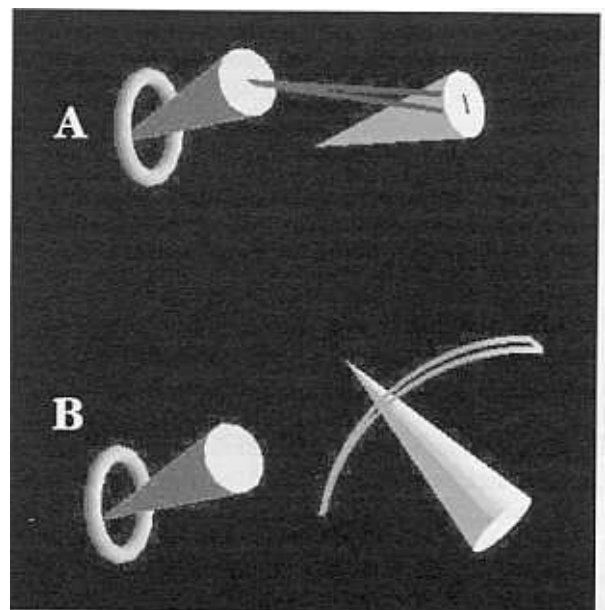


Figure 5. Schematic to illustrate augmented feedback of distance and angular orientation errors. Virtual Teacher object is left cone, and Virtual Learner object is cone to the right. At this point in time (single frame) the Learner trails the Teacher as both move left towards the ring. Panel A: Distance (translational) error is denoted by straight lines between the learner and teacher objects. No matter where the learner is at any moment, the lines will lead to the correct position on the teacher trajectory. When the learner's position fully matches that of the virtual teacher, the 2 objects will appear superimposed and the error lines disappear. Panel B: Angular position (orientation) error is displayed as a curved arrow centered at learner object. The arrow points in the direction that the learner needs to rotate the endpoint for the Teacher and Learner orientations to become aligned (here, \sim counterclockwise). As the learner's orientation approaches that of the teacher, the arrow reduces in size, disappearing at complete alignment.

closely matches that of the teacher's movement, the length of the line decreases. Thus, the learner can be instructed simply to move so that the error line 'disappears.'

Panel B shows the visual display for angular position (orientation) errors of the learner endpoint position relative to that of the teacher. The error is displayed as an arrow, centered near the learner object, which points in the direction of rotation needed to align the learner and virtual teacher's orientation. The arrow is also scaled to the difference in orientation. Thus, a larger arrow is displayed when there is a large amount of discrepancy, and the arrow disappears when the orientations are equal. The arrow display represents the error for all three axes (x,y,z) combined.

This visual feedback about error can be enhanced with auditory cues to assist timing, or to provide feedback about performance when combined with other errors to yield a score. Over a hundred optional settings allow the user to tailor feedback specifically to each patient's need.

The scoring system

The VE system includes a flexible algorithm for scoring the degree of matching between patient and teacher's trajectories. The scoring system allows the experimenter to emphasize a variety of different aspects of the patient's movement such as velocity, spatial errors, and timing, selectively or in combination in the score calculation. The score can be displayed on the screen following each trial, providing knowledge of results feedback. Knowledge of results has been extensively investigated and there is general agreement that it improves learning rate.²⁹ Raw data from many sequential sessions can be rescored with the same set of criteria and used to measure the patient's performance over time.

The score is calculated in 2 stages. First, overall movement characteristics for the entire trajectory, such as average velocity and number of velocity peaks, are calculated. Next a frame-by-frame comparison of the patient and teacher trajectories is made. The score algorithm allows the user to select which types of errors (eg, angular velocity, linear distance error, arm movement, or hand movement error) to use in the final score calculation, and how much to weigh each type of error. The values for errors derived from overall movement characteristics and the frame-by-frame comparison with the teacher trajectory are then combined and transformed into a single standard score that is easy for the patient to understand (eg, 0-100% match with teacher). The score computation algorithm is thus very flexible, allowing the therapist to emphasize not only different aspects of the movement such as velocity or spatial characteristics, but also different temporal parts of the movement, such as the beginning, middle, or end. It can serve as a powerful tool in shaping the learning of movement during training.

A goal for the score value can also be set and displayed on the screen to further motivate the patient to improve. The goal can be set to a standard value (such as 75% match) or be made to automatically adjust upward or downward following each trial, based on patient performance (shaping).

Replay

The replay feature allows the last movement performed by the patient to be played back repeatedly in a loop, along with the 'teacher' movement, similar to a video 'instant replay.' During training, this can be a powerful tool to direct the patient's attention to particular aspects of their performance. The patient can rest and concentrate on the replay and listen to a therapist explain which aspects of the movement need to be corrected. The 3-D playback can be paused at any point in the movement, and the therapist also can activate different types of augmented feedback (eg, distance and orientation error) or change the viewpoint of the displayed scene, so that the movement can be seen from the side or from above. Multiple trajectories can also be plotted together to quickly and conveniently monitor progress and movement variability.

Parser

Because some patients will have difficulty synchronizing their movements with those of the virtual teacher, a feature that allows initiation of the teacher animation in response to the patient's movement has been developed. This is achieved by the *parser*, which is a movement recognition system that detects when a patient starts and stops moving. The patient's motion parameters (such as distance from a predefined start position and velocity) are monitored online and if one or more of these measurements exceeds a configurable threshold, the system determines movement has begun. This event then triggers the start of the teacher animation. Likewise, the end of the movement can be detected when the patient slows down and returns to the starting position. The system then waits in a 'resting' state until movement begins again and the process is repeated. The transitions between moving and resting as computed by the parser then trigger the score computation for that trial.

Scripts

The script is a software feature that allows the therapist to create a semi-automated training session ahead of time that will more closely simulate a typical rehabilitative therapy session. Using a script editor, the therapist can specify a sequence of scenes (which define desired movements or task goals), the number of repetitions that should be attempted for each scene, and training options such as the types of feedback that should be employed for each scene. The scenes will then play automatically one after the other. Additionally, text messages can be included during each step that indicates special instructions or reminders for the therapist/and or patient. The script can also be configured to skip repetitions if the scores computed online exceed a threshold, so the patient doesn't have to spend time performing movements that are too easy. Once composed, a script can be replayed many times, or modified to emphasize selected scenes or training options, depending on the needs of an individual patient.

PRELIMINARY CLINICAL RESULTS IN PATIENTS WITH STROKE

The first prototype of the system was used to achieve improvements in the reaching ability of 2 individuals with stroke who were several years post stroke and had shown no improvement in the prior 6 months.³⁰ Based on the results of that pilot study, several new features were developed and added to the VE training system (eg, scoring function, scripts).

Using the revised system, a study on motor learning and generalization in individuals with stroke was recently conducted.^{31,32} In this article, the results of clinical outcome measures performed on the subjects before and after VE training are reported. Quantitative analysis of the kinematics of the subjects' trajectories following VE training, and a detailed analysis of specific types of generalization achieved, will be presented in a later publication.

Methods

In this study, 2 selected movements were trained in VE. The movements were chosen, because they contain elements that are difficult for patients with stroke to combine and perform normally. The *first movement* was a reaching movement, to the forward horizontal position, in a shoulder-centered frame of reference (neutral abduction/adduction). The subject began with the hand in the lap on the involved thigh, with forearm in neutral, and holding a Styrofoam 'envelope' using a lateral grasp. An electromagnetic motion sensor was attached to the envelope. In the scene designed to evoke this reaching movement, the patient was asked to put the (virtual) envelope into a 'mailbox' slot. The subject held the (real) 'envelope' (using a lateral grasp) then extended the arm to place the (virtual) envelope in the mailbox slot.

This movement highlights some of the typical motor control problems seen in patients with stroke. It requires a combination of elements from the flexion and extension synergies, ie, shoulder flexion to 90° with full elbow extension and forearm supination, which is typically difficult for patients with stroke. It requires elevation of the arm while simultaneously maintaining a grasp, another difficult combination for a patient with stroke. It also requires a complex intralimb joint coordination, with sequential timing of distal to proximal joint movement components, again, difficult for stroke patients. A series of 6 variations of the mailbox scene provided a way to progress training from easy (Level 1) to more difficult (Level 6) in a sequential fashion. Near (easy) and far (more difficult) reach settings were used with 3 different hand orientations; forearm pronation (easiest), neutral (more difficult), and supination (hardest), to progress the level of task difficulty. Level 1 was a near reach with forearm pronation; Level 6 was far reach with full supination.

The *second movement* trained was a reaching movement, to the impaired side. It involved full elbow extension combined with shoulder abduction to 45° and an open

hand with extended fingers and pronated forearm. Such a movement is essential not only to using the arm for reach and retrieval, but also for the functional use of the arm in posture-related activities such as catching oneself during loss of balance, assist for trunk balance while using the opposite hand for reaching or manipulation, use of the involved arm for object stabilization during manipulation of the object with the other hand. Several versions of this scene were developed, so that learning could be progressed from an easy level to the more difficult final version. For example, the whole arm or just endpoint could be shown; the target could be located closer to the midpoint of the teacher movement so that the subject could first practice the movement with less elbow extension and shoulder abduction.

Subjects were trained in 1-hour sessions, 3 times a week. The number of repetitions was not set to be equal across subjects; rather each subject worked at their own comfortable pace, as would occur in real therapy sessions. Initially, upon first practicing with a new scene, subject's received feedback from the virtual teacher at a high frequency (~90-100% of trials); later, as their performance on that scene improved, feedback from the teacher was gradually withdrawn. The goal was to lower feedback frequency to 50% to 75% of trials. Training was administered in blocks of 10 sessions, for a total of 30 sessions. For the first 20 sessions, subjects trained in the 2 movements using the same set of standard scenes. During the last 10 sessions, 2 scenes were added for subjects who had difficulty with the wrist extension and/or supination elements in the mailbox scene. The new scenes provided better visualization of these elements, through a 'close up view'; but subjects were essentially practicing a component of the original movement, in approximately the same spatial location along the trajectory as the original movement. Subjects also continued to practice with the standard scenes during the last 10 sessions. Progress was assessed following 10 treatments; if no progress was noted, the subject did not continue. Subjects who completed 20 sessions, and showed some improvement were offered an additional 10 sessions.

Measures

Subjects' clinical progress was measured using two standard clinical tests, the Fugl-Meyer Test (FM),³³ and the Wolf Motor Test.³⁴ We used the upper extremity portion of the FM, Total Score, and the Motor score. The Wolf Motor test consists of 15 functional task items scored on time (sec) to complete, and 2 tasks scored on force (grip, using a dynamometer; shoulder strength, using cuff weights applied to the forearm). The clinical tests were administered twice prior to treatment (1 week apart), twice (1 week apart) after 20 sessions, and once after 30 sessions.

Subjects

Nine subjects participated in the study. Prior to commencing participation in this study, all had been discharged

from active rehabilitation for the arm, and were considered to have plateaued in their upper extremity motor recovery. The clinical characteristics of the subjects are listed in Table 1.

Eight of the 9 subjects completed the standard protocol of 20 treatment sessions. Of these 8, 6 continued for 10 additional sessions, completing a total of 30 sessions. One subject's (S2) participation in the study was terminated after 10 treatments due to a lack of progress, as perceived by both the investigator and the patient. This patient's data was eliminated from the analysis presented below. The reasons for this patient's lack of progress as compared to the progress other subjects' is not immediately apparent (see Table 1). For example, she was our youngest subject, so age was likely not the factor; she had a long duration post stroke (40 mo.), but 3 other subjects who had longer durations post stroke did make progress; she had a low initial FM motor score, but one subject with a lower initial FM and another with a similar initial FM both made progress. Other factors are currently being investigated (eg, lesion size and location).

RESULTS

Fugl-Meyer

Percent change in the FM UE Total and Motor Scores averaged across subjects were calculated. Calculations were made using, for the pretest values, the mean of pretest 1 and pretest 2; for post-test values, the last post-test for that subject (post 20 sessions for S5 and S9; post 30 sessions for the rest). The mean values post training were significantly higher on both the FM Motor and Total scores, indicating improvement ($p=0.008$ and $p=0.048$, 2-tailed paired t-test, for FM Motor and Total scores, respectively.) The improvement in Total FM score was not completely accounted for by FM Motor score improvement (ie, some subjects had decreased pain, increased range of motion, and improved sensory scores post training, though these effects were small). No significant difference was found between pretest 1 and pretest 2 values for either the FM Motor or Total

scores ($p=0.090$ and $p=0.104$, respectively, 2-tailed paired t-test). Individually, all subjects showed some level of improvement on the Motor subtest, 7 of 8 improved on the Total FM score. The average improvement across all subjects on the FM Motor test was $15\% \pm 14.8$; range was 2.5% to 42%. Individually, 3 of the 8 subjects improved by greater than 20% on the FM Motor test.

Wolf Motor Test of UE Function

The percent change in the UE Functional test (total time and median time) averaged across subjects, from pre- to post-training was calculated, using for pretest values, the mean of pretest 1 and pretest 2; and for post-test values, the final post-test for that subject (post 20 sessions for S5 and S9; post 30 sessions for the rest). The mean values post-training were significantly lower, indicating improvement, for the total time score ($p=0.021$, 2-tailed, paired t-test), but not the median time score ($p=0.10$, 2-tailed, paired t-test). No significant difference was found between pretest 1 and pretest 2 values for either the total time or median time scores ($p=0.936$ and $p=0.177$, respectively, 2-tailed paired t-test). Average improvement was $31\% \pm 25.7$ and $24\% \pm 23.15$ for total and median time scores, respectively; range of improvement was 1% to 83% for the total time score, and -3% to 54% for the median time score. Individually, 6 of the 8 subjects improved by greater than 20% on either the total or median time measure, or both.

Strength Tests

The changes in shoulder flexion and grip strength, respectively, following VE training (mean of pretests 1 and 2 compared to the last post test for each subject) are shown in Figure 6. These 2 strength test items are part of the Wolf Motor Test. The differences for shoulder flexion strength were statistically significant ($p=0.020$), and the differences for grip strength were close to significance ($p=0.058$). If we set a 'clinically significant' criterion of greater than 20% increase in strength, we find that the average percent

Table 1. Subject Characteristics

Subject Number	1	2	3	4	5	6	7	8	9
Age	57	26	62	72	67	40	44	68	64
Involved Side	R	L	L	L	R	L	R	R	L
Gender	M	F	M	M	M	F	M	M	M
Duration Post Stroke	6 mo.	40 mo.	6 mo.	11 mo.	46 mo.	24 mo.	10 mo.	63 mo.	64 mo.
Lesion Type	Lacunar Infarct	Dissect. Carotid	Embolic	Ischem.	Embolic	Infarct	Dissect. Carotid	Embolus	Dissect. Vertebral
Lesion Location	L Int. capsule, Post. Limb	R MCA territory	R MCA territory	R Int. Carotid	L MCA territory	R Cortical + Subcortical	L MCA territory	L MCA territory	Pontine Infarct
Initial FM*									
Total	72	74	87	83	74	77	112	97	114
Motor	32	23	40	31	18	26	54	44	55

* Fugl-Meyer, Upper Extremity Total (Max=126); Motor Score (Max=66)

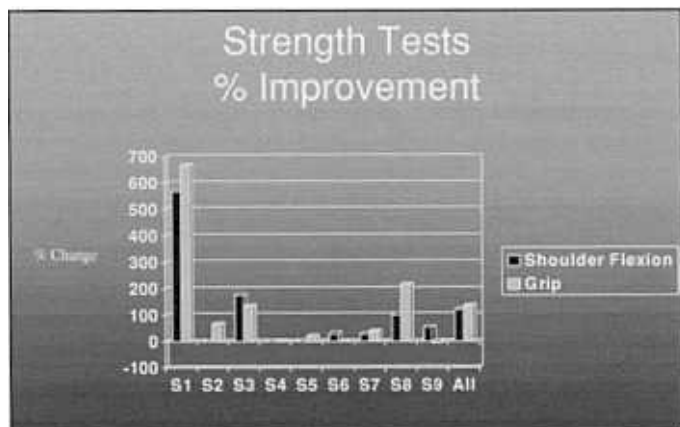


Figure 6. Percent change for shoulder flexion and grip strength, respectively, from pre to post VE training. Values are displayed for all subjects individually as well as the combined average for the 8 subjects who completed the training. The differences for shoulder flexion were statistically significant ($p=0.020$); the differences for grip strength were close to significance ($p=0.058$) (2-tailed paired t-test was used.).

improvement across all subjects exceeded this for both shoulder flexion (118%) and grip strength (133%). Considered individually, 4 subjects increased both shoulder flexion and grip by greater than 20%; 2 increased only shoulder flexion.

Discussion

Using the response as measured by all 3 tests, and >20% as a standard for clinically significant improvement, 1 subject improved on all 3 tests (S1), and 5 subjects improved on 2 of the 3 tests (S3, S6, S7, S8, S9), and 2 subjects improved on 1 of the 3 tests (S4 and S5). Comparing the group response across all 3 tests, the strength tests showed the greatest change (>100%), the WMT the next highest (24-31%), and the FM the least (7-15%). Subjects who improved the most (more than 20%) on the FM test (S1, S5, S6) also tended to have lower initial FM motor scores than the other subjects (see Table 1). Conversely, subjects who improved on the Wolf Motor Test all had initial FM scores higher than 30. Perhaps subjects needed a minimum level of intralimb joint coordination (a key component of the FM score) before they could demonstrate much improvement on the WMT, where the score is based on speed rather than quality of movement.

The improvements in the WMT as well as the FM are impressive in light of the fact that the training involved only 2 movements, which would be considered an atypical therapy regime for treatment of patients with stroke by most approaches. (Only 2 movements were used in this study because the goal of the experiment was to study motor learning and generalization in greater detail, rather than to design a treatment aimed at achieving maximal functional change.) However, these findings of significant functional improvement raise interesting questions about what sorts of movements and tasks should be practiced to achieve functional gains. In fact, they run counter to accepted

thinking that many movements and tasks must be practiced, and that practice must be very similar to the target task one wishes to improve. We speculate that the augmented feedback derived from the use of a VE system contributed to the improvements found. However, the results should be interpreted with caution. The sample was small, and there was no control group. Such findings should be replicated in larger studies before they are used in as a guide to change treatment methods in clinical practice.

The increase in the strength scores were surprising and encouraging, especially considering no progressive resistance training was employed. Subjects trained only an active movement. This suggests that the improvement in strength measures may have been due to improved neuromotor recruitment rather than muscle fiber hypertrophy. The repetitive grasp of the envelope (though lightweight) during training likely contributed to this change. Subjects may have also used their arms more in everyday functional activities, contributing further to the improvements we found. Overall, these preliminary findings indicate that VE treatment may be a valuable adjunct to rehabilitative care.

SUMMARY

The scientific basis for use of the new technology of virtual environment, as applied to motor training has been presented, and some equipment considerations pertinent to the use of VE in rehabilitation have been discussed. A description of a VE system for motor retraining developed by the authors and colleagues, and preliminary results of a clinical experiment on patients post-stroke using the system have been reported. Results obtained to date indicate that VE shows promise as a new rehabilitation tool for use in research and clinical applications.

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REFERENCES

- 1 Todorov E, Shadmehr R, Bizzi E. Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *J Motor Behav.* 1977;29:147-158.
- 2 Brooks BM. Route learning in a case of amnesia: A preliminary investigation into the efficacy of training in a virtual environment. *Neuropsychol Rehabil.* 1999;9:63-76.
- 3 Lackner JR, DiZio P. Rapid adaptation to Coriolis force perturbations of arm trajectory. *J Neurophysiol.* 1994;72:299-313.
- 4 Shadmehr R, Mussa-Ivaldi S. Adaptive representation of dynamics during learning of a motor task. *J Neurosci.* 1994;14:3208-3224.
- 5 Wolpert D, Ghahramani Z, Jordan M. Are arm trajectories planned in kinematic or dynamic coordinates? An adaptation study. *Exp Brain Res.* 1995;103:460-470.

- Atkeson C, Hollerbach J. Kinematic features of unrestrained vertical arm movements. *J Neurosci.* 1985; 5:2318-2330.
- Lacquaniti F, Terzuolo C, Viviani P. The law relating the kinematic and figural aspects of drawing movement. *Acta Psychol.* 1983;54:115-130.
- Morasso P. Spatial control of arm movements. *Exp Brain Res.* 1981;42:223-227.
- Rizzolatti G, Fadiga L, Fogassi L, Gallese V. Resonance behaviors and mirror neurons. *Arch Ital Biol.* 1999;137:85-100.
- Iacoboni M, Woods RP, Brass M, Bekkering H, Massiotto JC, Rizzolatti G. Cortical mechanisms of human imitation. *Science.* 1999;286:2526-2528.
- Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: A review and critical reappraisal. *Psychol Bull.* 1984;95:355-386.
- Georgopoulos AP, Pellizzer G. The mental and the neural studies and mental rotation and memory scanning. *Neuropsychologia.* 1995;33(11):1531-1547.
- Cobb SVG. Measurement of postural stability before and after immersion in a virtual environment. *Applied Ergonomics.* 1999;30:47-57.
- Nichols S. Physical ergonomics of virtual environment use. *Applied Ergonomics.* 1999;30:79-90.
- Stanney KM, Kennedy RS, Drexler JM, Harm DL. Motion sickness and proprioceptive after effects following virtual environment exposure. *Appl Ergonomics.* 1999; 30:27-38.
- Stanney K, Salvendy G. Aftereffects and sense of presence in virtual environments: Formulation of a research and development agenda. *Int J Hum Comput Interact.* 1998;10:135-187.
- Durlach N, Mavor AS, eds. *Virtual Reality: Scientific and Technological Challenges.* Washington, D.C.:National Research Council, National Academy of Sciences Press; 1995:111-133.
- May JG, Badcock DR. Vision and virtual environments. In: Stanney KM, ed. *Handbook of Virtual Environments: Design, Implementation and Applications.* 2002:29-63.
- Mon-Williams M, Wann JP, Rushton S. Binocular vision in a virtual world: Visual deficits following the wearing of a head-mounted display. *Optthalmic Physiol Opt.* 1993;13:387-391.
- Meyer K, Applewhite HL, Biocca FA. A survey of position trackers. *Presence.* 1992;1:173-200.
- DiZio P, Lackner JR. Altered loading of the head exacerbates motion sickness and spatial disorientation. *Paper presented at: Aerospace Medical Association Meeting.* 1992; Miami, Fla.
- Bizzi E, Mussa-Ivaldi FA, Shadmehr R. System for Human Trajectory Learning in Virtual Environments. *US Patent No. 5,554,033, Massachusetts Institute of Technology.* 1996.
- Holden MK, Todorov E. Use of virtual environments in motor learning and rehabilitation. In: Stanney KM, ed. *Handbook of Virtual Environments: Design, Implementation, and Applications.* Mahwah, NJ: Lawrence Erlbaum Assoc. 2002:999-1026.
- Holden MK. NeuroRehabilitation using 'Learning by Imitation' in virtual environments. In: Smith J, Salvendy G, Harris D, Koubek RJ, eds. *Usability Evaluation and Interface Design: Cognitive Engineering, Intelligent Agents and Virtual Reality. Proceedings of HCI International 2001.* London, England: Lawrence Erlbaum Assoc.; 2001:624-628.
- ²⁵ Nudo RJ, Milliken GW, Jenkins WM, Merzenich MM. Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. *J Neurosci.* 1996;16:785-807.
- ²⁶ Schmidt RA. Frequent augmented feedback can degrade learning: Evidence and interpretations. In: Stelmach GE, Requin J, eds. *Tutorials in Motor Neurosci.* Dordrecht, The Netherlands: Kluwer Academic Publishers; 1991:59-75.
- Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: A review and critical reappraisal. *Psychol Bull.* 1984;95:355-386.
- ²⁸ Winstein CJ, Pohl RS, Lethwaite R. Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Res Q Exer Sport.* 1994;65:316-323.
- Bilodeau EA, Bilodeau IM. Motor skills learning. *Ann Rev Psychol.* 1962;13:243-280.
- ³⁰ Holden M, Todorov E, Callahan J, Bizzi E. Case Report: Virtual environment training improves motor performance in two stroke patients. *Neurol Rep.* 1999; 23:57-67.
- Holden MK, Dyar T, Callahan J, Schwamm L, Bizzi E. Motor learning and generalization following virtual environment training in a patient with stroke. *Neurol Rep.* 2000;24:170-171.
- Holden MK, Dyar T, Callahan J, Schwamm L, Bizzi E. Quantitative assessment of motor generalization in the real world following training in a virtual environment in patients with stroke. *Neurol Rep.* 2002;25:129-130.
- Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Stegling S. The post-stroke hemiplegic patient: A method for evaluation of physical performance. *Scand J Rehabil Med.* 1975;7:13-31.
- Wolf SL, Catlin PA, Ellis M, Archer AL, Morgan B, Piacentino A. Assessing Wolf Motor Function Test as outcome measure for research in patients after stroke. *Stroke.* 2001;32:1635-1639.