Virtual Environment Training Improves Motor Performance in Two Patients with Stroke: Case Report

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ABSTRACT

Two subjects with hemiplegia were treated using a computer-generated virtual environment (VE) to train upper extremity reach in the impaired limb. Subjects were evaluated pre- and post-VE training using motor recovery and functional ability tests and a real-world test that required reaching to 9 locations in the workspace. During VE training, subjects practiced a virtual task similar to the real task, trying to imitate a virtual teacher's performance. Post-training, reaching errors during real-world performance were reduced by ~50% (mean across all workspace locations). Both subjects improved in the trained task, indicating transfer of skill from VE to real world performance; reaching also improved in untrained parts of the workspace, indicating some generalization of transfer. Motor recovery and functional scores showed little to no change but one subject acquired the ability to perform several functional tasks (not on the formal test). Our results suggest that VE training holds future promise for stroke rehabilitation.

INTRODUCTION

With the increased focus on cutting costs in health care delivery, new treatment methods are needed that will better facilitate motor recovery following stroke and result in lower costs by shortening the time needed for rehabilitation. One area in need of improvement is upper extremity (UE) rehabilitation following stroke. Recovery of function in the UE following stroke tends to be much less than the recovery seen in the lower extremity. Gowland et al[1] found that only 5% of patients recovered full functional use of the arm and only 25% had good use of the arm for gross motor tasks. Nakayama et al[2] reported somewhat better recovery patterns with 31% of patients having no residual paresis, 37% mild, and 32% severe residual paresis of the upper extremity. In contrast, 70 to 95% of patients with stroke are reported to regain the ability to use the lower extremity to walk.[3]

Despite the discouraging data cited above, untapped potential for improved motor function may exist in the UEs of patients with hemaplegia. Taub has described a phenomenon termed "learned nonuse" in which monkeys "learn" not to use the impaired arm, despite severe sensory deficits but completely normal motor innervation.[4] He has demonstrated that through behavioral training, these monkeys can be taught to use their impaired limb.[4-6] A similar phenomenon may occur in patients with stroke, who "learn" not to use their impaired limb because they find they can substitute use of the nonimpaired limb for many tasks. Several studies, using methods that restrict use of the noninvolved arm, and "force" use of the involved arm have been conducted by Taub et al[7-9] and Wolf and colleagues[10,11] in humans with hemiplegia. Findings in these studies have been quite positive, supporting the idea that learned nonuse may be one factor limiting motor recovery following stroke.

Latent potential for control of the hemiparetic limb may also exist in the noninvolved hemisphere. Brinkman and Kuypers, in a study using monkeys, found that each half of the brain had control of proximal and some complex movements of the *ipsilateral* extremity (in addition to the expected contralateral extremity control).[12] More recently, Nudo and colleagues[13] reported that rehabilitative training of monkeys following experimentally-induced infarcts significantly influenced the character of functional reorganization in the adjacent undamaged motor cortex post lesion. This reorganization was accompanied by behavioral recovery of skilled hand function.

Several studies of humans have shown some success in activating this untapped potential for recovery of function in the hemiparetic UE through techniques such as electromyographic (EMG) biofeedback[14-17] and functional electrical stimulation (FES).[17,18] However, these treatments are based on earlier theories of how the brain controls movements and therefore focus on the activation of certain muscle patterns during treatment.

In contrast, Bizzi and colleagues have developed alternative theories of how the brain controls movements based on experiments performed on intact deafferented animals[19-21] and intact humans.[22] The performance in deafferented monkeys was accounted for by the hypothesis that centrally generated motor commands modulate the stiffness and resting length of muscles that act as flexors and extensors about the elbow joint. As a consequence, the elastic behavior of the muscles—like that of opposing springs—define a single equilibrium position of the forearm, a position that ultimately is reached in spite of externally applied perturbations, without any need for feedback corrections. This result led to a question concerning the execution of target-directed movements. Are these movements executed just by setting the static equilibrium of a limb to the final target? Or does the descending motor command specify an entire trajectory as a smooth shift of this equilibrium? Bizzi, Accornero, Chapple, and Hogan[20] addressed this question in another set of experiments.

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They instructed deafferented monkeys to execute arm movements toward a visual target but with the vision of the arm blocked by an opaque screen. A motor drove the arm right to the target as soon as the EMG activity indicated the onset of a movement. The arm should have remained in place if this were the equilibrium position pecified by the muscle commands at that time. On the contrary, the experimenters could observe an evident motion backward toward the starting position followed by a forward motion toward the target. This finding indicates that the muscular activation does not specify a force or a torque as suggested by the inverse dynamic models, nor a final target position. Instead, the response to the initial displacement suggests that the activation of the muscles produces a gradual shift of the limb's equilibrium from start to end location. Accordingly, at all times the limb is attracted by an elastic force toward the instantaneous equilibrium point. If during a goal-directed movement the limb is forcefully moved ahead toward the target, the elastic force will drive it toward the lagging equilibrium point as observed in the experiment.[20,23] Hogan[24] has called the sequence of equilibrium positions produced during movement by all the muscular activations a "virtual trajectory." The virtual trajectory is a sequence of points where the elastic forces generated by all the muscles cancel each other. By contrast, the actual tarjectory is the result of the interaction of these elastic forces with other dynamic components such as limb inertia, muscle velocity-tension properties and joint viscosity.

These theories suggest that the brain generates movements not by controlling muscles directly, but by controlling the end point trajectory of a moving limb or body part. The end point trajectories (the motor plan or "virtual trajectories") in turn are executed by setting the equilibrium point of muscle tensile forces around the joints used in the movements through the activation of "primitives" (force fields) coded by discrete groups of spinal cord neurons.[25] If these hypotheses are applicable to relearning motor skills, treatment techniques based on training end effector kinematics may be much more effective than methods such as EMG biofeedback, which focus on muscle activation patterns.

These ideas were recently applied to training neurologically intact subjects using a computer generated virtual environment (VE).[26] Todorov et al established in two experiments that arm trajectories learned by imitating an expert's movement in VE transferred well to a comparable real world task. To our knowledge, no one has yet tried to apply the idea of learning by imitation of end-point trajectories to patients who suffer injury to the brain, from stroke or other mechanisms.

We report here results of a pilot study using VE to train movements of the affected UE in two patients with stroke. The study was approved by the Massachusetts Institute of Technology (MIT) Committee on Human Subjects and both subjects signed Informed Consent forms prior to their participation. Our purpose was to answer 3 questions: 1) Can subjects with hemiplegia improve in a virtual task following virtual practice?, 2) Does learning that occurs in a VE transfer to a similar real task?, and 3) Does learning in a VE transfer to related but untrained real tasks, or to functional activities not specifically trained?

SUBJECTS

Subject 1(S1): S1 was a 76- year-old male, 3.5 years post left (L) cerebrovascular accident (CVA) due to thrombotic occlusion of the L internal carotid artery (ICA) confirmed by magnetic resonance imaging (MRI). He had resultant right (R) hemiparesis, significant expressive aphasia, but excellent receptive abilities. This stroke was his first, with no evidence of bilateral or brainstem stroke. He had a history of hypertension and arteriosclerotic heart disease (ASHD) with stable angina, but no history of seizures, diabetes, or other major medical problems. Following his stroke, the patient spent several weeks in acute care and inpatient rehabilitation followed by several weeks of outpatient rehabilitation. He had not had physical therapy (PT) for 1 year at the start of this study. He could ambulate independently with a cane and he did not use a brace. He lived alone in elderly housing but with family nearby who checked on him frequently.

Though he could move his arm in a limited fashion, with some wrist extension, finger flexion, and extension, and a weak lateral grasp, S1 reported essentially no functional use of his R arm. All activities of daily living (ADL) were accomplished by compensatory use of the L arm. He reported that his R UE motor status had been stable for the past 2.5 years. Sensory testing showed intact light touch in R UE, intact proprioception in the R shoulder and elbow, but impaired proprioception in the R wrist and hand. His R UE range of motion was within normal limits (WNL) with the exception of mild limitations in shoulder flexion, abduction and external rotation, and forearm supination (minus ~20° from full range). Right UE motor recovery stage was 3 to 4, using the Brunnstrom scale.[27] His pretraining motor recovery status as measured by the UE portion of the Fugl-Meyer test[28] (2 tests, given 3 months apart) is shown in Table 1. His upper extremity function score assessed using components of the Structural Assessment of Independent Living Skills Test (SAILS)[29] (described in Measures, below) is also shown in Table 1. It should be noted that the patient chose to use his left (nonimpaired) arm for all tasks tested.

Subject 2(S2): S2 was a 76-year-old female, 1.5 years post R CVA, due to thrombotic occlusion of the R ICA, confirmed by computerized tomography (CT) scan. She had resultant left (L) hemiparesis. This stroke was her first, with no evidence of bilateral or brainstem stroke. She had a history of ASHD, carotid endarterectomy, and pulmonary embolus, but no history of other major medical problems. Following her stroke the patient had spent several weeks in an acute care and then a rehabilitation hospital, followed by several months of home care rehabilitation. She had not had PT for 8 months prior to the start of VE treatment. She

Table 1. Summary of Clinical Test Scores

	Pretest 1	Pretest 2	Post 8 Treatment	Post 16 Treatment
Fugl-Meyer				
Subject 1				
UE-Motor (Max = 66)	33	30	34	37
UE-Total (Max = 126)	76	75	78	88
Subject 2				
UE-Motor (Max = 66)	30	33	-	33
UE-Total (Max = 126)	76	79	-	83
SAILS (3 Motor Task Subcomponents; Max = 45)				
Subject 1	30	-	30	30
Subject 2	26	-	-	25

could ambulate independently with a cane inside her residence, but required supervision outside. She did not use a leg brace. She lived in an assisted living facility. She did not cook meals and required daily minimal assistance for bathing/ dressing.

Though she could move her involved L arm with a fair degree of control (ie, active movement in 3-/4- strength range at shoulder, elbow, and wrist joints), functional use of the arm was limited. This was due not only to her motor deficit, but to residual parietal lobe symptoms (significant inattention to L side, poor movement timing, poor movement initiation, poor motor planning ability), as well as a hyperactive grasp reflex and a significant L homonymous hemianopsia. Her R UE motor recovery stage was 3 to 4, using the Brunnstrom scale.[27] Her pretraining motor recovery status, measured by the UE portion of the Fugl-Meyer test[28] (2 tests, given 4 months apart) is shown in Table 1, as is her SAILS score. These scores indicate that her motor status was stable for 4 months prior to training with VE. Sensory testing showed intact light touch in L UE, but impaired proprioception in all joints of the L UE. Her L UE range of motion was WNL with the exception of mild limitations in shoulder flexion, abduction, and external rotation, (minus ~20° from full range), and an elbow flexion contracture of ~30°.

MEASURES

Four types of measures were used for evaluation: 1) motor recovery status of the involved upper extremity was measured using the Fugl-Meyer Test (FM),[28] which has established reliability and validity;[30,31] 2) functional ability of the upper extremities was tested using components of the SAILS which has established reliability and validity.[29] To accommodate testing time constraints, only the three subtests of the Motor Tasks section that assessed UE function were used: Fine Motor Skills, Dressing Skills, and Eating Skills (15 items total); Tests of Gross Motor Tasks (related to standing and gait) and Cognitive Tasks were omitted; 3) anecdotal comments of both subjects about functional use of the arm were obtained; and 4) 3-D kinematics of reaching were measured using an electromagnetic six degree of freedom tracking instrument.* The static accuracy of the device was 0.8 mm root mean squared error (RMS) for position and 0.15° RMS for orientation (within the range of the receivers). The resolution was 0.005 mm, and 0.025°. Sampling rate was 120 Hz/ number of sensors; data were sampled at 30 Hz during pre/post testing, and at 60 Hz during training.[32]

We constructed a foamboard "mailbox" then tested the subjects' ability to place an "envelope" in the slot of the mailbox as the reaching test. The "envelope" was a Styrofoam board (4"x 8"x ¼"), the target slot was 1" high and 5" wide. The goal was to place the envelope in the slot, to a depth of 1" or more. To explore the subject's ability to reach throughout the workspace, the mailbox target slot was positioned in 9 locations: center, right and left, at 3 heights - upper, middle, and lower (Figure 1). For each position, three hand orientations were tested: palm up, palm down, and palm neutral, 3 times each. Both R and L sides were tested (81 trials total/arm). Reaching straight ahead in a shoulder-centered frame of reference (ie, 90° shoulder flexion, neutral abduction), corresponded to a center - middle position. Upper and lower reaches were 12" above and below this height; abducted and adducted reaches (right and left) were 45° to the right and left of the acromion for each side.

Palm up, down, and neutral corresponded mainly to forearm supination/pronation position but also had components of wrist flexion/extension and radial and ulnar deviation. The target distance was adjusted for each workspace position, using the nonimpaired side as a guide so that the envelope was 2 inches into the slot with the elbow fully extended and the scapula in neutral protraction/retraction. Sensors were attached to the a) anterior trunk, just below the sternal notch; b) upper arm on the lateral aspect of humerus, midway between the olecranon and acromion; c) envelope, in line with the patients thumb; and d) real world target at one end of the slot.

Three measures were derived from the sensor data. 1) Distance errors were assessed by calculating the straight-line distance from the endpoint ("mail") sensor at the furthest extent of reach to the target sensor. (The target sensor location was first transposed in software to be at the "center" of the slot.) This method combined linear translation errors in all three planes. 2) Orientation errors were measured by assessing the angular difference of the "envelope" orientation compared to the slot orientation. 3) Peak velocities of the "mail" (endpoint) sensor were measured.

The FM test was administered twice prior to training

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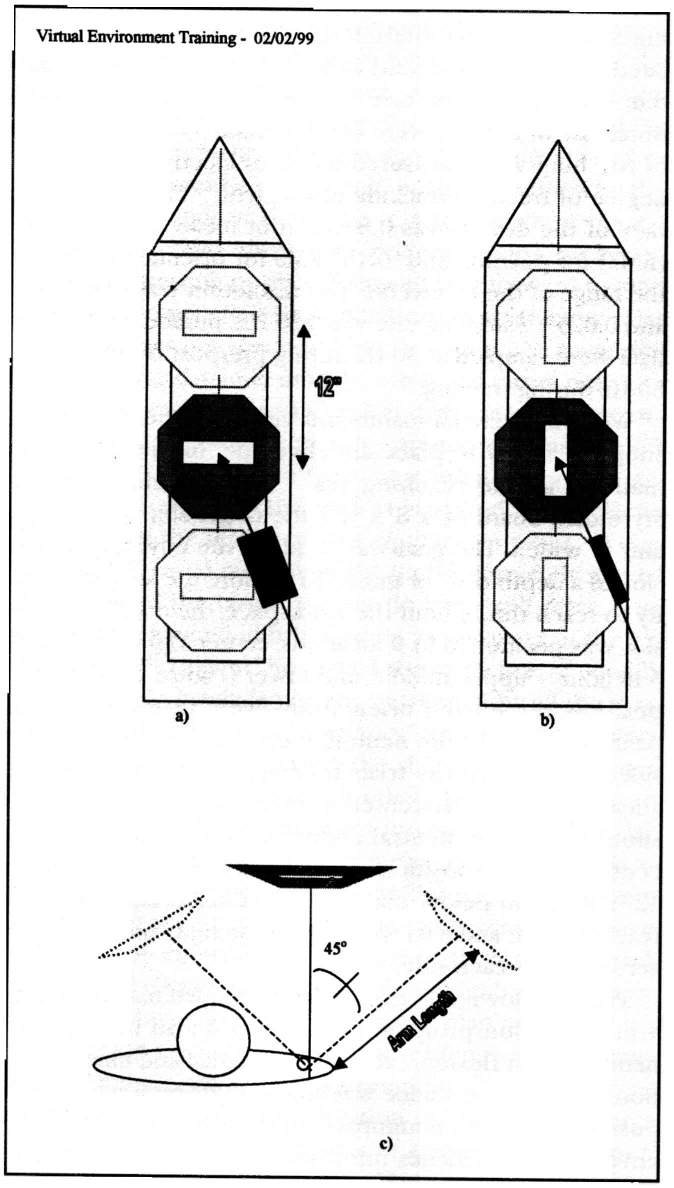

Figure 1. Schematic of real-world reaching set-up used to test subjects before and after training in a similar virtual task. a) 3-D "mailbox" with movable target slot (1"x5"); horizontal orientation was used for supinated and pronated reach attempts. "Envelope" (4"x 8"x ¼") is shown moving toward target. Center target was positioned at a location corresponding to hand position when UE was in 90° shoulder flexion/neutral abduction and elbow fully extended (ie, distance equal to arm length and height equal to height of acromion in sitting position). For testing upper and lower workspace reaching, the slot was positioned 12" above and below center position. Target positions later trained in VE are shown in grey; untrained locations are shown in white; b) vertical slot orientation was used for reaching with forearm in neutral position; c) testing in transverse plane (view from above); slot was positioned 450 medial (adducted reach) and lateral (abducted reach) to the center position (shoulder-centered frame of reference). Only center forward position (grey) was trained in VE.

and once after 16 sessions of training. The SAILS test was administered once before training and once after 16 sessions of training. The kinematic reaching test was administered at approximately 1-week intervals 3 times prior to training and 3 times after 16 sessions of training. For S1, FM, and SAILS tests were also administered once, and the kinematic test twice, after 8 training sessions. Data for the last of the final post-test sessions for S1 were lost due to technical problems.

Both subjects were informally questioned on an intermittent basis after the first few weeks of training as to whether they noticed any difference in their tendency to use the involved arm outside the laboratory setting for any functional activity.

Treatment Method

We selected only one movement for training in the VE, with the criterion that it be a functional, goal-oriented movement that highlighted typical motor control problems seen in patients with stroke. Assuming patients could "learn" this movement in the VE we wanted to test whether such learning transferred to the same movement performed in the real world or generalized to other real-world movements that were untrained. We devised a reaching task in which the subject held an "envelope" (using a lateral grasp) then extended the arm to place the "envelope" in a "mailbox" slot. To accomplish this task, the UE moved from a starting position resting on the lap in shoulder neutral, slight elbow flexion, forearm neutral and hand grasping "envelope" with a lateral grasp, to a position of shoulder flexion to 90°, neutral shoulder abduction, ~20° of shoulder external rotation, scapular protraction, full elbow extension, full supination, and continued lateral grasp. At this point the envelope would be in the slot. Real-world movements made by the subject during training were monitored by the same electromagnetic tracking device used for pre/post testing (see Measures) and displayed within a 3D VE in real-time (delay ~ 30 msec) on a desktop computer.

We next created a series of 6 "scenes" in the VE using a prototype of software currently under development.* The scenes had a one to one spatial correspondence with the real world, and were displayed on a desktop computer (Figure 2). They were simple, containing only the virtual "mailbox" and two virtual "envelopes." One envelope was a "teacher" who performed the correct movement over and over again. The teacher animation was a recording of a well practiced normal subject performing the virtual task. The second envelope was a virtual representation of the real envelope that the patient held and moved during practice. Thus, the patient could match the endpoint trajectory of his/her movement with that of the teacher during training, in real time. The scenes progressed from easy (Level 1) to more difficult (Level 6) in order to train the movement in a sequential fashion. The sequence used was near and far reach with forearm pronation, neutral position, and supination, respectively. The endpoint of the near reach

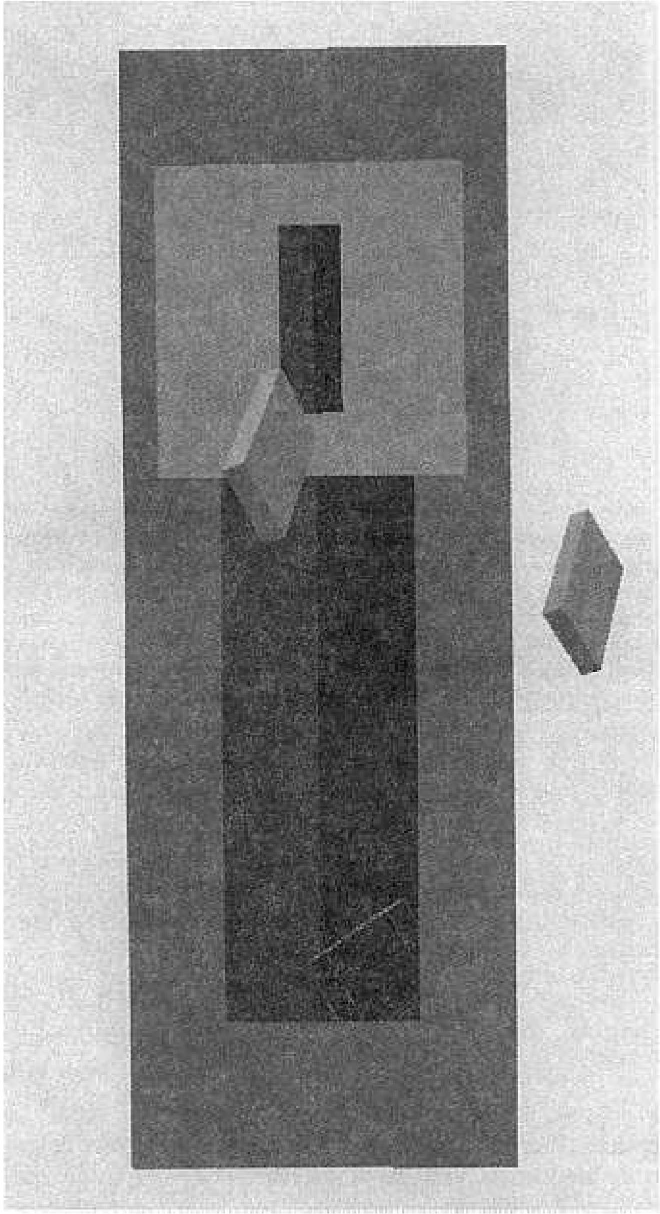

Figure 2. Example of a "mailbox" scene used for VE training. The "teacher" envelope is shown approaching the target slot. (In VE the entire trajectory is animated and objects appear in color against a black background.) Off to the right the "patient" envelope is shown; this envelope moves when the patient moves his/her hand. Below, a wire-frame rectangle identifies the "start" position used to align the teacher and patient trajectories at movement onset. This scene is Level 4 – far reach with forearm in neutral position.

was set at the distance midpoint of the normal trajectory for the far reach.

The "teacher" movement could be altered in a number of ways designed to facilitate learning. The animation could be adjusted in speed to any level slower or faster than the original, it could be paused at any point, displayed as a trace (solid line vs. moving object), or hidden from view entirely. The teacher could also be made to "follow" the trajectory of the subject (ie, temporal information could be eliminated and the learner could focus exclusively on learning the spatial elements of the movement. Additional features (audio and visual) were designed to assist the patient with error detection, timing, and positioning. A model of the entire arm and the held object could also be displayed on the screen in real time, if desired. This was used intermittently in training, to correct the subject's tendency to try to achieve the task with ineffective compensatory movement patterns such as excessive shoulder abduction with elbow flexion.

During training, subjects sat in a chair at a comfortable distance from the computer screen and moved their arm in the real world while watching a display of their trajectory in the virtual world on the computer screen. Subjects could still see their arms move in the real environment but once the program was running, their attention immediately focused on the screen. This focus occurred automatically and did not require any direction from the therapist. However, guidance from the therapist was required to help the patient focus on selected aspects of movement and teacher feedback during each trial.

A protocol was developed that specified the scene sequence, number of repetitions, and types of feedback (teacher features, manual assistance by the therapist, verbal instructions) to be provided on each trial. In practice, this training guide was altered somewhat by the therapist in order to adapt to the needs displayed by the patient during training. In general, a session began by displaying the subject's own attempted movements on the screen in virtual reality so that he/she could become perceptually adjusted to the VE. Next, the "teacher trajectory" was displayed and the patient observed the teacher for several trials without attempting to move. Then the subject attempted to perform the desired movement by imitating the "teacher" trajectory as closely as possible. During these trials, the subject's trajectory was displayed in real time as well so that the magnitude and direction of the mismatch from self-generated motion versus "teacher" motion could be seen on the screen. A variety of feedback features were used depending on the subject's response during this part of the practice. After each 10 to 20 trials with "teacher" guidance, the teacher animation was hidden and the patient practiced in the scene without any feedback (other than seeing their self-generated virtual trajectory). Subjects progressed to the next more difficult scene after they had performed 3 consecutive successful reaches (defined here as getting the mail in the slot, not perfect trajectory matching) or had practiced in that scene for 30 to 45 minutes without 3 consecutive successes. The subjects were closely monitored by the therapist during treatment and received manual assistance where necessary (approximately 5 to 10% of trials). The goal of this manual assistance was to prevent shoulder pain secondary to muscle fatigue, to prevent establishment of ineffective movement strategies, to give the patient the "feel" of performing the full movement in a more coordinated fashion, and to avoid excessive frustration on the part of the patient as he/she attempted to move but repeatedly did not reach the goal.

Each subject received a series of 16 treatment sessions of 1 to 2 hours duration conducted by a licensed PT. The planned treatment frequency was 2x/week, but absences occurred due to inclement weather and unrelated medical problems. Subject 1 was treated 2x/week for 4 weeks, then had a 1 month hiatus; after 3 additional treatments he had a 5 week absence, followed by 5 additional sessions. Subject 2 was treated 1-2x/week over 11.5 weeks for a total of 16 sessions. (The schedule for pre/post evaluations is described in the Measures and Subjects sections.)

RESULTS

Clinical Tests

Pre-and post-training values for the FM (both UE-motor and UE-total) and SAILS tests are shown in Table 1. S1 showed a slight improvement in UE-total FM score (+12 or 17% increase) and UE-motor (+5 or 17% increase) but no change in SAILS. S2 had essentially no change in UE-total FM (+5 or 7% increase) and UE-motor (+1 or 5% increase), and no change on SAILS.

Anecdotal Reports

S1 reported that following the VE training, he was able to use the R arm in several functional activities that were previously impossible for him; specifically, to open the refrigerator door, use a can opener to open canned goods, and to pull pants up/down when using the bathroom. (Unfortunately, none of these specific items appear on the SAILS test, thus his post-test score on that test shows little change.) S2 reported little change in her day to day use of the arm.

Virtual Performance

Virtual performance improved over the 16 sessions. Progress was measured only informally by assessing how many scenes a subject could progress through in a session. At the start of training, both subjects were spending all their time on the Level 1 or 2 (easy) scenes. By the end of training, however, they were both consistently progressing to scene Level 5 or 6 (most difficult). This meant they had progressed from performing the near reach in a pronated position to performing a far reach in a neutral or supinated position. Neither subject was able to perform 3 consecutive successful reaches in scene 6 (far reach with full supination) by the end of 16 training sessions.

Real-world Performance

Distance errors

Real world performance in the "mailbox" task showed improved reaching in both the trained and untrained parts of the workspace for both subjects. Figure 3 shows S1's raw data for hand (envelope) trajectories pre- and post-training for the trained task on the involved arm. Post-test trajectories for the noninvolved arm are also shown for reference (pre/post graphs for noninvolved arm were essentially identical). Not only is the extent of reach improved, but one can see that qualitatively, the trajectory path post-training is beginning to resemble that of the noninvolved side.

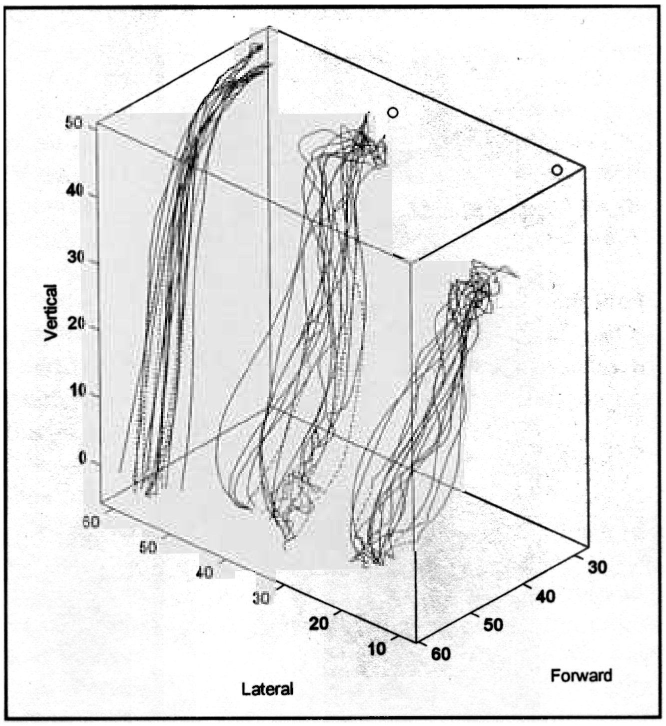

Figure 3. Raw data graphs for end point trajectory (envelope path) for S1 during 8 repeated reaching movements with different hand orientations in the trained task (forward reach to 90° shoulder flexion/neutral abduction with full elbow extension). Circles represent location of targets subject was reaching toward. The most forward trajectories (right side of graph) are pre-training, involved arm; middle are post-training, involved arm; farthest back (left side of graph) are from noninvolved arm. (Pre/post graphs for noninvolved arm not shown separately but were essentially identical). Note that post-training, the involved side trajectory is beginning to resemble that of the noninvolved side.

Figure 4 shows the mean error scores pre-and post-training, by session number, for the involved arm of each subject. Note that performance is fairly stable in both the pre- and post-training periods. For S1 (bottom panel), post-test performance (dotted lines) appears less variable than pretraining performance (solid line). S1 showed an average pre/post decrease in error of 18 cm (ie, 64% reduction in error); S2 showed a decrease of 9 cm, representing a 50% reduction in error. The 9 and 18 cm gains represented roughly a 25% improvement in reach excursion.

Figures 5 and 6 show mean distance errors plotted by target location in the workspace for Subjects 1 and 2, respectively. Note that for both subjects, some of the largest improvements occurred in *untrained* parts of the workspace. S1 showed better transfer to upper regions of the workspace; S2 showed better transfer to lower regions.

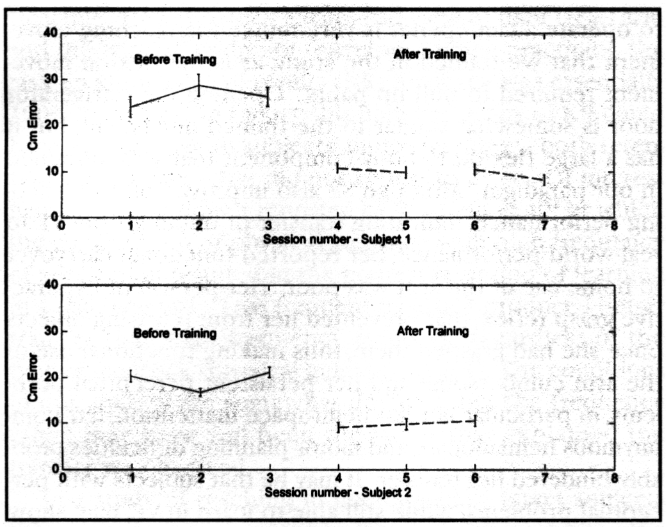

Figure 4. Performance on real-world reaching task pre/post virtual training. ***Top Panel:*** **Mean error scores for distance (cm) from target (averaged across all 9 target positions) plotted by session number for subject 1, involved arm. Sessions 1 to 3 (solid line) = pretraining scores; session 4 to 5 (dotted line) = scores after 8 training sessions; session 6 to 7 (dotted line) = scores after 16 training sessions. Magnitude of the pre/post differences would be considered statistically significant, based on nonoverlap of the standard deviation values. Values for noninvolved arm are not shown, but were ~ 1 cm with little variability for all sessions, with the exception of session 1, when error value was ~ 5 cm with ± 2 cm standard deviation.** ***Bottom Panel:*** **Mean error scores for distance (cm) from target (averaged across all 9 target positions) plotted by session number for subject 2, involved arm. Sessions 1 to 3 (solid line) = pretraining scores; session 4 to 6 (dotted line) = scores after 16 training sessions. Values for noninvolved arm are not shown, but were ~ 1 cm with little variability for all sessions. (The values for the noninvolved arm do not represent true "errors," ie, subjects could readily perform the task; rather they result from the sensor position on the envelope.)**

Orientation errors and velocities

Subject 1 showed significant improvement in hand orientation errors during reaching to targets in the trained location, and in 5 of the 8 untrained work space locations (Figure 7). Subject 2's hand orientation errors did not improve significantly. Peak velocities did not change significantly for either subject following training.

DISCUSSION

Several findings in this study have important clinical implications presuming that our results can be replicated in larger sample of subjects with hemiplegia. Our subjects' ability to improve their motor performance in a VE is encouraging because although normal subjects have shown the ability to learn in VE,[26,33-35] hemiplegic subjects' ability to do so has not been reported. Patients with stroke suffer from many problems that conceivably might preclude their success on such a perceptually complex task. The present results suggest that factors such as advanced age, aphasia, and even perceptual impairments may not necessarily prevent success with this "high-tech" intervention.

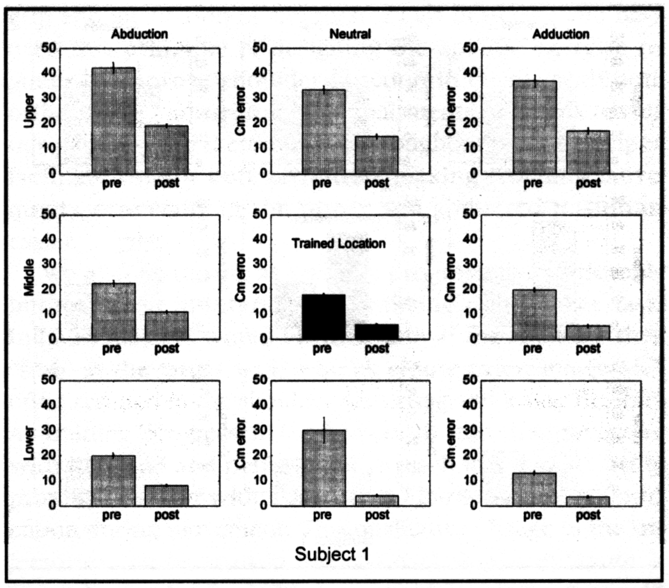

Figure 5. Distance errors (cm) for real-world reaching task, plotted by target location in the workspace, for subject 1, involved arm. Values are means across 3 sessions pre- and 4 sessions post-training on a similar virtual task. Error scores for the trained movement are in the center of the middle row. Note that all locations show a reduction in error, despite no specific training in those locations. Note better transfer to upper parts of the workspace for this subject. Values for noninvolved arm (not shown) were close to 1 cm and were nearly identical pre/post, with the exception of upper-adduction, which had a 10 cm mean error pretraining, 1 cm post. (The 1 cm error score for noninvolved arm was a function of the sensor position on the "mail" piece, and not due to inability of the subject to perform the task.)

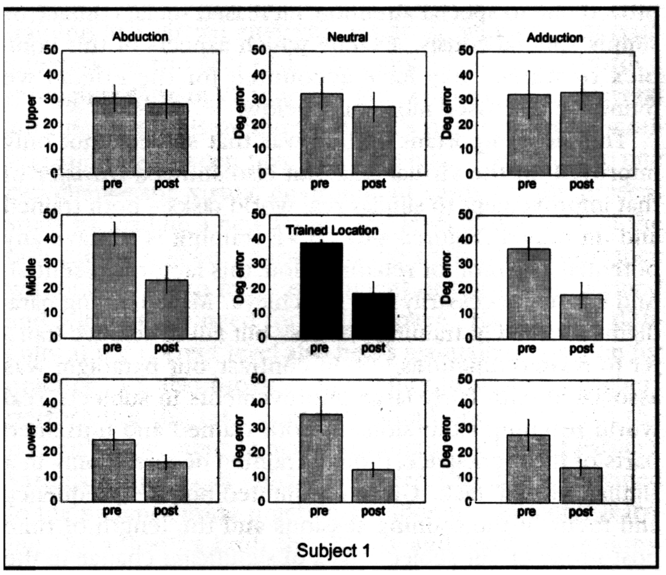

Figure 6. Distance errors (cm) for real-world reaching task, plotted by target location in the workspace, for subject 2, involved arm. Values are means across 3 sessions pre- and post-training on a similar virtual task. The trained movement is in the center of the middle row. However, most locations show a reduction in error, despite no specific training in those locations. Note better transfer to lower parts of the workspace for this subject. Noninvolved arm values are not shown, but were ~1cm for all locations and essentially identical for pre/post tests.

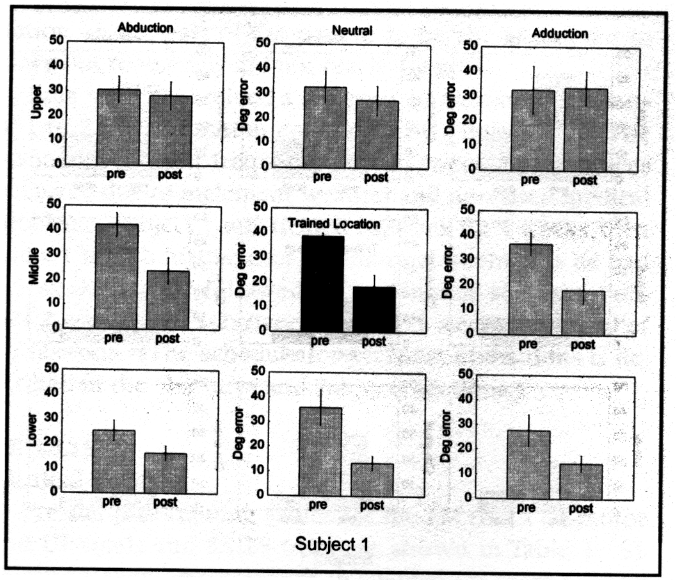

Figure 7. Orientation errors (degrees) for real-world reaching task, plotted by target location in the workspace for subject 1, involved arm. Values are means across 3 sessions pre-and post-training on a similar virtual task. Performance improved in the trained location and 5 of the 8 *untrained* workspace locations.

We believe it is reasonable to attribute the success demonstrated by our subjects to the VE treatment, as both were long enough post stroke to be well past the expected time of spontaneous recovery[1,2,36] and both had completed their rehabilitation programs. Of course controlled studies are needed to rule out the possibility that the subjects improved due to special attention, increased social contact, or simply spontaneously. Exactly which aspects of this complex treatment may have accounted for the effects we found are discussed more fully below.

The most important finding was that subjects not only improved on the virtual task, but also showed *transfer* of that improvement to similar real world tasks - both trained and untrained (Figures 4-6). If VE training is to have any potential as a tool for rehabilitation, this factor is essential. And it is not necessarily easy to achieve. Many training paradigms succeed in training one task but fail to achieve transfer to related functions.[37-39] In contrast, our paradigm was associated with fairly large improvements in subjects' real world reaching excursions in both trained and untrained parts of the workspace, though training occurred only in a similar "virtual" task. Given the limited number, frequency and focus of the training sessions and the length of time post-stroke of our subjects, lack of significant change in the hand orientation error (except for the improvement of S1 in the trained location; see Figure7) and on the FM and SAILS tests is not too surprising. Our assumption that continued or more frequent training would lead to greater changes in orientation error and standard clinical tests remains to be tested. However, the kind of functional improvements anecdotally reported by S1 are encouraging in this regard. Most therapists would agree that using a hand to operate a can opener is very unlike the reaching movement that we trained in the study, as is the flexion movement required to pull up pants. Opening the refrigerator door is somewhat similar to the trained movement, but it has a large flexion to body component that was untrained in our paradigm. Although S2 also improved on her reaching performance, indicating transfer of training from VE to real-world performance, her reported functional carryover to home use of the arm was poor. Her persistent hyperactive grasp reflex, that prevented her from releasing objects once she had grasped them, thus making functional use of the arm cumbersome and her persistent perceptual problems, in particular her left hemi-space inattention, left homonymous hemianopsia, and motor planning difficulties probably hindered her transfer. It may be that subjects with perceptual problems, while still able to learn in VE, may show transfer only to fairly similar tasks in the real world, as did our subject. If so, this may mean that training for such subjects will require a different approach; perhaps direct practice of the desired functional task (sequenced and graded over several "scenes" to make learning easier and faster). We believe it is too early to say which subjects will not benefit from VE training; the issue requires further study.

What allowed our subjects to "learn" a new movement in the VE then transfer this improvement to real world performance of reaching movements in both trained and untrained parts of the workspace? A key factor was likely the patients' imitation of the "teacher" in *real time* and the *same frame of reference*. Thus, practice in VE could be accomplished without the need to perform a spatial transformation as is required when imitating real teacher motions in the real world. Something akin to this happens when a therapist moves or assists a patient during therapy (ie, the patient does not have to perform the spatial transformation that is necessary when observing, then imitating, a movement). However, in manually assisted performance, the motor program being generated by the patient will not be the same as if he/she were doing the actual movement without the help. If manually assisted practice is too frequent, one concern is that the patient may learn to associate the "wrong" motor output with the "right" kinematic feedback. Practice in VE obviates this problem. Practice with the "teacher" may help the subject identify errors in their movements more rapidly and to hone in on a successful strategy faster.

Another factor we believe enhanced transfer was the way we structured our training sessions. In motor learning studies on normal subjects, it has been found that training schedules which provide highly augmented and frequent feedback are effective in improving performance (during the task acquisition), but are detrimental to task retention and transfer of that skill to other tasks, once the feedback is removed (ie, learning).[40,41] Since the VE we provided would be considered "highly augmented" feedback, we were careful to limit "teacher" feedback to about 50% of trials so that the patients would have some practice without the "teacher." However, they always had view of their (real) arm and the "virtual" endpoint (envelope) when practicing the task, so knowledge of results (KR) feedback was essentially 100% frequency. In theory, this high frequency of KR could have interfered with subjects' motor learning - both retention and transfer - but did not appear to do so. Of interest here is an experiment reported by Winstein et al[42] in which the combination of physical guidance with high frequency of application resulted in the poorest retention of learning in a reaching task. Less frequent feedback produced better transfer than high frequency feedback, regardless of the type of feedback (physical guidance or KR). The conditions in our study were somewhat different, but the frequency effect may have still been the factor that explained the transfer we observed.

In a study of reaching in nuerologically intact subjects who were trained to adapt to forces which perturbed the movement during motion, Gandolfo et al[43] found some transfer of the learned adaptation to neighboring workspace (~20° to either side of the trained task), but the transfer was not complete and decayed smoothly and quickly with distance from the trained trajectories. In our study, the transfer occurred over at least 45° in the coronal plane and ~30° in the saggital plane; further extremes of movement were not tested. The task in the present study also differed from Gandolfo et als, as subjects were not exposed to perturbing forces during the execution of their trajectories.

Was it is possible that our subjects simply "learned" the real-world test task, independent of the VE training, especially since it was repeated multiple times? The stable performance pretraining and improved but stable post-training performance (Figure 4), argues that the pre/post improvement did not result from practice on the actual task but from the VE intervention.

Repetition of the virtual task, though, was likely a factor in the improvements we found. It is possible that the VE treatment simply encouraged the subject to move the involved arm more and the repetition alone was the factor accounting for success rather than the virtual "teacher" and feedback about error. Controlled studies are needed to determine this. But even *if* repetition were found to be the key factor, VE may still be a useful way to motivate patients to continue with the long practice required for motor learning by making practice more fun. In fact, both patients reported that the sessions with VE were fun and neither found interacting with the computer problematic.

Biomechanical factors may have had an influence. Simple strengthening of muscles from repeated movement practice may have contributed to success. However, both patients reported having had strengthening regimes in their PT treatments prior to this study but did not report a similar gain in smoothness and excursion of reaching movements. A definitive answer to this issue will require further study. We also suspect improved rotator cuff function may have been a factor in our subjects' improvement. Therapists have long known that there is a link between active hand grip and facilitation of the rotator cuff muscles[44] and have used this principle in designing therapeutic exercise regimes to improve shoulder function in clients with both orthopaedic and neurologic impairments. Perhaps having our patients grip the envelope throughout practice helped facilitate rotator cuff activation, making reaching movements, especially in the upper and abducted positions, easier.

We also observed, as training progressed, a noticeable improvement in interjoint coordination during the task. Initially, subjects would lift their arm at the shoulder then "stab" at the target with a quick elbow extension (which often resulted in the shoulder adducting and losing flexion). As training progressed, they began to lead the movement with the hand and performed the reach in a more distal to proximal fashion with a smoother elbow/shoulder coordination during movement. This qualitative change in the trajectories can be seen in the raw data shown in Figure 3. The trajectories after VE training (middle) are beginning to resemble those of the nonimpaired side (left). In our study, imitation of the endpoint (hand path) trajectory was a strong influence on altering the patients' kinematics, but both subjects also needed coaching on the interlimb coordination of the UE joints during training. This was accomplished with verbal and manual guidance from the therapist and with visual feedback (from virtual display of the whole arm) during training. Future studies will help us tease apart more carefully exactly which elements of the training are the most useful for motor relearning in patients with stroke.

One question the reader may ask is why bother with training in a virtual environment at all; why not just train subjects on the real task? Are any advantages afforded through the use of VE training? We believe there are several advantages to this method. First, it's fun! This helps motivate subjects to keep practicing the task. Also, because one can change the virtual environment easily (in the present study by loading a new scene), the level of difficulty of the task can be quickly adjusted to the subject's performance without having to move equipment or the subject around and without the need for added space. Having task difficulty at the correct level also helps maintain motivation for practice. VE also provides the ability to show a "teacher" performing the task correctly simultaneously with the patient's movement (a major advantage, discussed earlier). Various features can enhance the error feedback provided to the patient during practice, another aide to motor learning. By adjusting both the display and feedback options, one can limit information in such a way as to focus the learner on specific key points of the movement being learned. Finally, when a patient makes a mistake in VE the consequences are also "virtual." This can be an advantage for safety (eg, if pouring from a glass, no "real" liquid would be spilled, nor would the glass 'really' break if an error were made).

CONCLUSION

Two subjects with hemiparesis have demonstrated improved reaching ability on a real-world task, following training in VE on a similar virtual task. Reaching improvements also occurred in parts of the workspace that were not trained in VE (45° to the right and left, and 30° above and below the trained location). In addition, one subject gained the ability to perform 3 functional tasks that were not directly related to the trained reaching task. The subject had been unable to perform these tasks since his stroke (3.5 years earlier).

Our results show that VE motor training may hold promise as a new technique for rehabilitation in neuromotor disorders, particularly stroke. The improvements in motor performance that were found may be due to unique attributes of our VE paradigm which allowed "learning by imitation" of a virtual teacher, as well as other factors such as increased motivation to move the involved arm, task repetition, type and frequency of feedback during training, and biomechanical and neurophysiological considerations. Further studies with control group comparisons will be needed to clearly elucidate the role each of these factors may play in motor relearning following stroke.

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Correction for p. 63, Figure 6.

The graph for Figure 6 was inadvertantly omitted; the graph which appears on p. 63 for Figure 6 is actually the Figure 7 graph, but with the Figure 6 legend. The correct version is shown below.

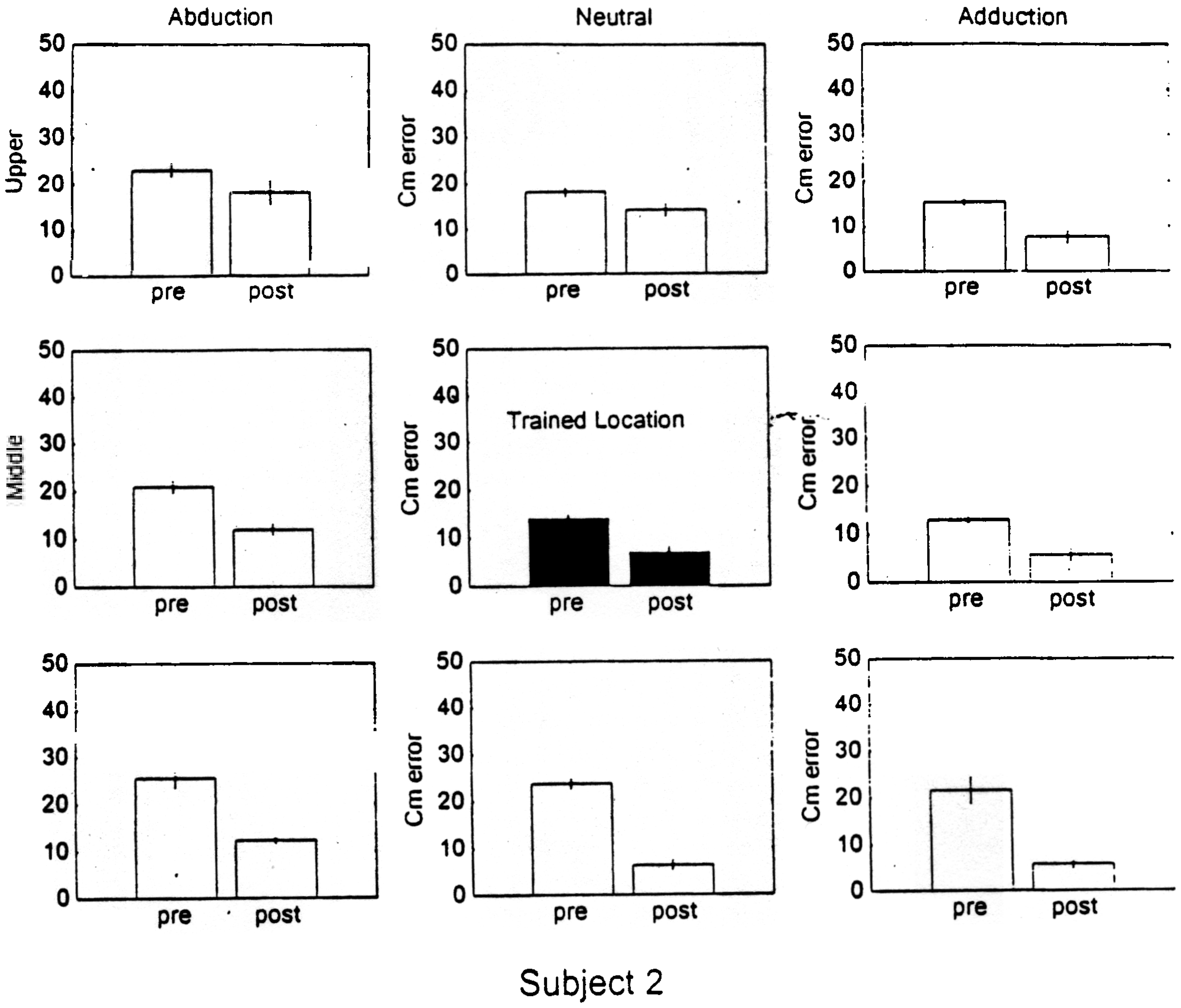

Figure 6. Distance errors (cm) for real-world reaching task, plotted by target location in the workspace, for subject 2, involved arm. Values are means across three sessions pre and post training on a similar virutal task. The trained movement is in the center of the middle row. However, most locations show a reduction in error, despite no specific training in those locations. Note better transfer to lower parts of the workspace for this subjet. Non-involved arm values are not shown, but were ~1 cm for all locations and essentially identical for pre/post tests.