Usability Evaluation and Interface Design:

Cognitive Engineering, Intelligent Agents and Virtual Reality

Volume 1 of the Proceedings of HCI International 2001
9th International Conference on Human-Computer Interaction
Symposium on Human Interface (Japan) 2001
4th International Conference on Engineering Psychology
and Cognitive Ergonomics
1st International Conference on Universal Access
in Human-Computer Interaction
August 5-10, 2001 New Orleans, Louisiana, USA

Edited by
Michael J. Smith
University of Wisconsin-Madison

Gavriel Salvendy
Purdue University

Don Harris
Cranfield University

Richard J. Koubek
Wright State University

2001
LAWRENCE ERLBAUM ASSOCIATES, PUBLISHERS
Mahwah, New Jersey London

NEUROREHABILITATION USING ‘LEARNING BY IMITATION’ IN VIRTUAL ENVIRONMENTS

Maureen K. Holden, Ph.D., P.T.

Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology,
Bldg. E25-526b, 45 Carleton Street, Cambridge, MA 02139

ABSTRACT

This paper describes the theoretical background and key features of a novel virtual environment system for motor re-learning that has been developed in our laboratory. The system has been designed to facilitate the retraining of motor control in patients with neurological impairments, such as stroke or acquired brain injury (ABI). It consists of a computer, specially developed software and an electromagnetic motion-tracking device. During training, the arm movements of the patient and a virtual teacher are displayed simultaneously in the virtual environment. The difference between the two trajectories is used to provide the patient with augmented feedback designed to enhance motor learning. Design considerations relevant to Neurorehabilitation patients are discussed. Preliminary results of recent experiments, in which the device has been used to train upper extremity movements in patients with chronic stroke and acquired brain injury, are also summarized.

1. INTRODUCTION

In recent years, there has been great interest in using VE for learning various types of motor and spatial tasks (Darken, Allard and Achille, 1998; Kozak, Hancock and Arthur, 1993). My interest has been to use a virtual environment as a vehicle in which to combine recent discoveries from the field of neuroscience with established principles of motor learning into a new method for assessing and training motor control. I wanted the method to be particularly useful for patients with neurological problems such as stroke or acquired brain injury. In this article I will first review some of the ideas about motor control, neuroplasticity and motor learning that have been incorporated into the design of the system. Next, I will describe some of the key features of the system, and discuss some design considerations relevant to patients. Some preliminary results from patients who have used the system will then be summarized.

1.1 Theoretical Background

Many studies have revealed that the brain seems to specify movement in term of the goals to be accomplished in the external world. How then does the CNS represent these goals and transform them into signals that activate muscles? It appears there are two stages to this process of motor control - planning and execution (Bizzi and Mussa-Ivaldi, 1998). During planning, the neural representation of the goal is developed by CNS; during execution, the motor plan is transformed into neural commands that drive muscles. This hypothesis separates movement kinematics and dynamics.

In this view, movement planning occurs in extrinsic spatial coordinates, *not* in body-centered coordinates. For example, in planning an upper extremity movement, the brain thinks about the trajectory of the hand (limb endpoint) rather than the trajectories of the individual limb segments. This view is supported by psychophysical evidence which has found certain kinematic invariants (approximate straight segments, bell shaped velocity profiles) of the hand path during arm movements (Morasso, 1981). These invariants were not found in the joint movement profiles. These findings were later developed into the theory of “Minimum Jerk” (Flash and Hogan, 1985) and supported with further psychophysical studies (Shadmehr and Mussa-Ivadi, 1994, Wolpert, Ghahramani and Jordan, 1995). Electrophysiological support for the idea has also been provided by recordings from cells in monkey cortical and subcortical areas which show a correlation between the cell’s firing pattern and the direction of the hand’s path (Georgopoulos, Kettner and Schwartz, 1988).

Once the movement has been planned, the execution phase begins. The end-effector trajectory is tranformed from extrinsic to intrinsic (body-centered) coordinates, and the movement dynamics are generated. How this transformation occurs is the subject of some debate, largely because the solution to this transformation is not unique. That is, any given kinematic trajectory can be achieved by multiple joint movement combinations and/or muscle activation patterns. The brain must find a way to quickly simplify the mechanical complexity of the task, so that the goal can be achieved in a reasonable amount of time. Several theories exist to explain how the nervous system might accomplish this (Hollerbach and Atkeson, 1987; Bizzi et al. 1992; Gandolfo et al., 2000).

Research in robotics has found that artificial neuronal networks exposed to repeated motor commands paired with their sensory consequences are capable of learning fairly complex motor tasks without the need for explicit programming. This learning results from a change in the internal structure of the artificial network, specifically a change in the connectivity among the elements in the network. Based on these results, scientists have proposed a similar process in the CNS. The hypothesis is that learning is the result of repeated exposures to sensory signals coming from the moving limbs as they interact with the environment. The actions produced by the motor areas are initially imprecise, but feedback produces a gradual convergence on the correct solution. Ultimately, this practice leads to an *internal model*, which is embedded in newly formed connections among a group of neurons in the motor areas. The idea is that the brain centers responsible for generating motor commands also serve as sites for storage and retrieval of motor memory. Thus, the brain center that has learned the task becomes the center for expressing the task. There is physiological evidence to support this idea of a neural substrate for internal models (Gandolfo et al., 2000; Grafton et al 1992).

1.2 Implications for Motor Recovery via Plasticity or Relearning:

This cortical link to learning implies a capacity for functional re-organization that may play a significant role in motor recovery following injury to the brain. Because learning and implementation seem to be intermingled in the same cortical areas, it is likely that the mapping of the cortex is probably much more fluid and dynamic than we previously thought. And the remapping seems sensitive to and influenced by practice. In fact, Nudo and colleagues (1996) have found use-dependent alterations of cortical organization in the primary motor cortex (M1) of adult intact primates. Following focal ischemic infarcts, these primates also showed substantial functional reorganization of the motor cortex if they were exposed to a retraining program. However, in the absence of training, such reorganization did not occur. These finding support the idea that the capacity for re-organization is dependent on formation of new synapses, which in turn are dependent on motor training and practice.

The cortical mechanisms which may account for motor learning by imitation of visually observed movement have recently been investigated in both animal and human models (Rizzolatti, Fadiga, Fogassi, et al., 1999; Iacoboni, Woods, Brass, et al., 1999). In the premotor cortex of the monkey (area F5), so called 'mirror' neurons have been discovered. These neurons fire *both* when the monkey *performs* an action and when it *observes* an individual making a similar action. 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). This suggests that humans too, may have a mechanism which directly maps visually observed movements onto cells responsible for movement.

2. METHODOLOGY

My goal was to incorporate the discoveries outlined in the Introduction section into the design of a motor re-training system for use in Neurorehabilitation. I wanted the system to serve two purposes: 1) as a research tool, allowing in depth study of motor learning, motor recovery, and the effectiveness of different training techniques.; and 2) as a motor retraining device, useful for therapists treating patients in clinical settings.

2.1 System Description

The VE training system consists of a computer, specially developed software (MIT Patent No. 5,554,033), and an electromagnetic motion tracking device[1]. The tracking device allows the movements of the patient to be

---

[1] Polhemus 3SPACE FASTRAK, Polhemus Inc., PO Box 560, Colchester, VT 05446

monitored and displayed within the context of a virtual environment displayed on the computer. The software provides the tools to create training scenes, and virtual teachers whose trajectories are displayed on the computer screen. A variety of additional features allow the user to receive feedback about his/her performance during practice, and a score following each trial. The score is based upon a comparison of teacher and patient trajectories. Both patient and teacher movements are displayed in real time on the computer screen in the same coordinate frame of reference using 3D graphics. The graphics may be displayed in stereo 3D through the use of head mounted glasses or a stereo screen projection, or as enhanced 2D on a standard desktop or wall-projected display. A subject using the device with a standard desktop display isshown below in Figure 1.

Figure 1. Subject using the VE device

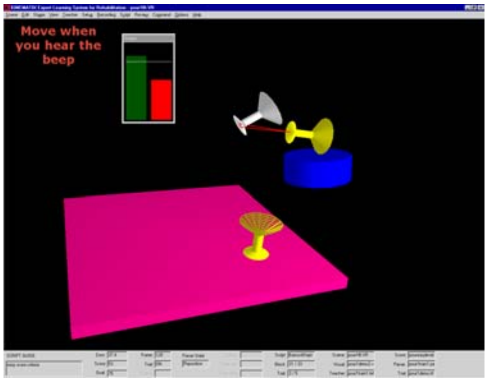

Figure 2. Example of scene used to train a pouring task. Teacher in yellow on right; patient in white to left of teacher. Score and displacement error (red line) are displayed.

***Scenes**:* Training scenes are the 3D 'pictures' (virtual environments) that the patient sees on the computer screen. An example of a scene used to train the functional task of pouring from a cup is shown in Fig. 2. The scenes allow us to create an environmental context with a purpose – one that will elicit a particular movement by providing a goal for that movement. This mimics the way movements are planned in the natural world. The scenes give us a mechanism to control and monitor exactly which movements are being trained during the experimental session. They also provide a vehicle for adjustment of the task difficulty. Scenes also provide a convenient way to set up a particular practice sequence. We have developed a software feature ('Script') that allows us to specify a sequence of scenes (with associated training settings) that will play automatically one after the other, thus simulating a typical rehabilitative therapy session. Both teacher and patient movements may be displayed on the screen as movement of the endpoint only, or as whole arm movement (i.e., the shoulder, elbow, forearm, and wrist movements are rendered in 3-D). In VE the task can be simplified in the early stages of learning, allowing the learner to focus on key elements of the task.

***Teacher**.* The virtual environment provides a mechanism for display of a 'teacher' movement which shows the patient the actual kinematics of hand (end-point) path (i.e., the same way the brain plans the movement). In theory, this should facilitate motor learning by assisting the patient's motor planning process in a natural way. The virtual teacher also affords the patient an opportunity to practice 'learning by imitation'. As discussed in the introduction,, this may facilitate the execution phase of motor control by activating direct links to output neurons associated with task execution. The teacher speed and appearance can be altered in a variety of ways to enhance learning (e.g., whole arm movement may be displayed). The teacher may also be removed from the display so that the subject does not become overly 'dependent' upon guidance to perform the movement. Imitating the teacher in the context of a virtual environment offers some advantages over practice with a real or videotaped teacher. In VE, the patient's and the teacher's limb movements are displayed on the computer screen in real time and in the same coordinate frame of reference. The patient can thus 'get inside' the virtual teacher and imitate the movement exactly. No mental rotations or translations are required. Experimental findings have revealed that cells of the motor areas of primates are involved in mental rotations of the direction of voluntary movements (Georgopoulos et al. 1989). Conceivably, for some patients with cortical motor stroke, the mental rotation of movements required to copy movements demonstrated by the therapist may be difficult.

***Augmented Feedback**.* As described in the Introduction, motor learning occurs when internal models develop as a result of synapse formation following repeated practice of movements that result in at least some success at task completion. It is this trial and error process that we target with our system by providing enhanced feedback about error during practice. This augmented feedback may be applied during the actual movement practice (concomitant), or following completion of the movement (knowledge of results), and is based on a comparison of the patient and teacher trajectories. Presumably, by helping the patient identify the motor strategies that are successful, the development of these internal models can occur more rapidly. And practice, essential to the development of these internal models, seems to be facilitated in VE. This may be because the task practice is experienced by the patients as being 'fun'. In studies on normal subjects, highly augmented and frequent feedback has been found to be effective in improving performance (task 'acquisition') but to lessen task retention and generalization (Schmidt 1991). Thus, our system allows us to vary feedback frequency so that we can provide our subjects with the optimal feedback frequency for learning.

2.2 Design Considerations for Neurorehabilitation

In contrast to healthy subjects, where the focus of VE training is often complex perceptual-motor skills, such as flying a plane, in rehabilitation the goal is usually to re-learn very simple motor tasks. Such tasks as pulling on the sleeve of a jacket must now be practiced in the face of a variety of sensory, motor and cognitive deficits. The exact type of deficit can vary tremendously from patient to patient, even with the same diagnosis. Thus, the system must be flexible, so that the training can easily be adjusted to the needs of different patients. Another major focus is to facilitate transfer of motor learning that occurs in the virtual world to performance in the real world. Flexibility in system design helps us to ensure that the virtual tasks we create resemble the real tasks as much as possible, particularly in terms of the movement required to perform the task.

While very complex, realistic or fanciful graphics and fast-paced game formats are appealing to normal subjects for VE training, they may be overwhelming for patients. When the brain itself has been affected, as in stroke or acquired brain injury (in contrast to disabilities where the brain is intact, like spinal cord injuries), processing of all this information may be too difficult. In contrast, a very simple display, with few movements, may help a patient to focus on the task at hand, and enhance learning.

The issue of possible negative side effects such as cybersickness, altered eye-motor coordination, and postural disequilibrium must be carefully considered. To date, there seem to be no reports of negative side effects using desktop display systems for VE. Most of the problems seem related to the immersive environment created in head mounted displays (HMD) (Stanney, Kennedy, Drexler et al., 1999). It seems obvious that feelings of disorientation, postural disequilibrium, or aftereffects in arm control that produce past-pointing, could be much more dangerous for disabled subjects, in whom a fall and injury could more easily be elicited than in normal subjects. Because trunk and postural control muscles are often adversely affected by neurological impairments, the extra weight imposed on the head by HMD's may be a problem.

Finally, practical issues are important. Keeping costs down, making systems easy to use, and minimizing the amount of equipment attached to the patient, will offer the greatest potential for success and acceptance of VE as a standard treatment procedure in rehabilitation clinics.

Because of many of the factors listed above, we have initially used our system with a desktop display. The display can also be projected on a large screen instead of a monitor, to give a greater feeling of immersion. A significant disadvantage of the desktop display is poor depth visualization. A solution to this problem would be to use a stereo projector - which can project true stereo 3-D onto a wall screen and be seen without glasses or a headset by both the patient and the therapist. Our software has the capability to be used with such a projector, and we plan to try this with patients in the future.

3. RESULTS

Stroke. To date we have used the first prototype of the system to achieve improvements in the reaching ability of 2 stroke patients who were several years post stroke and had shown no improvement in the prior 6 months (Holden, Todorov, and Callahan, et al., 1999). Based on those results, we developed several new features which are in the present system (scoring function, scripts). We have recently begun a study of motor generalization. Results from the first subject in that study are promising in that he improved not only in the task trained in VE, but in related untrained tasks, and on standard clinical measures of motor recovery and function (Holden, Dyar and Callahan, et al., 2000).

Acquired Brain Injury. We are currently studying the relearning of a pouring movement in subjects with chronic acquired brain injury (3-18 yr. post injury). To date, we have found improvement for 3 of the 4 subjects in the trained virtual task, on similar and related tasks in the real world, and on standard clinical tests of upper extremity motor recovery and function (Holden, Dettwiler, Dyar, et al., 2001).

4. CONCLUSIONS

Our preliminary results to date indicate that the system shows promise for use in research and clinical applications.

Acknowledgement: This work was supported by the Charles A. Dana Foundation

REFERENCES

Bizzi, E., Hogan, N., Mussa-Ivaldi, S., and Giszter, S. (1992). Does the nervous system use equilibrium- point control to guide single and multiple joint movements? *Behav. Brain Sci. 15*: 603-613.

Bizzi, E., and Mussa-Ivaldi, S. (1998). The acquisition of motor behavior. *Daedalus, 127(2),* 217-232.

Darken, R.R., Allard, T., & Achille, L. B. (1998). Spatial orientation and wayfinding in large-scale virtual spaces: An introduction. *Presence, 7(2),* 101-107.

Flash, T., and Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *J. Neurosci. 5*: 1688-1703.

Gandolfo, F., Li, C.-S. R., Benda, B., Schioppa, C.P., and Bizzi, E. (2000). Cortical correlates of learning in monkeys adapting to a new dynamical environment. *Proc. Natl. Acad. Sci. 97*: 2259-2263.

Grafton, S., Mazziotta, J., Presty, S., Fristion, K., Frackowiak, R., and Phelps, M. (1992). Functional anatomy of human procedural learning determined with regional cerebral blood flow and PET. *J. Neurosci. 12(7):* 2542-2548.

Georgopoulos, A. P., Kettner, R. E., and Schwartz, A.B. (1988). Primate motor cortex and free arm movements to visual targets in three-dimentional space: I. Coding of the direction of movement by a neuronal population. *J. Neurosci. 8*: 2913-2927.

Georgopoulos, A.P., Lurite, J., Petrides, M., Schwartz, B., and Massey, J. T. (1989). Mental rotation of the neuronal population vector. *Science, 243*: 234-236.

Holden M, Dettwiler, A, Dyar, T, Niemann G, Bizzi E: (2001). Retraining movement in patients with acquired brain injury using a virtual environment. *Proceedings of Medicine Meets Virtual Reality 2001, J.D. Westwood et al. (Eds.)*, IOS Press, Amsterdam , pp. 192-198.

Holden, M., Todorov, E., Callahan, J., and Bizzi, E. (1999) Virtual environment training improves motor performance in two patients with stroke: Case report. *Neurology Report 23(2)*, 57-67.

Holden, M.K., Dyar, T., Callahan, J., Schwamm, L., Bizzi, E. (2000). Motor learning and generalization following virtual environment training in a patient with stroke. *Neurol. Report 24 (5),* 170-171.

Hollerbach, J. M., and Atkeson, C. G. (1987). Deducing planning variables from experimental arm trajectories: Pitfalls and possibilities. *Biol. Cybern. 56*: 279-292.

Iacoboni, M., Woods, R.P., Brass, M., Bekkering, H., Massiotta, J.C. and Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science 286*: 2526-2528.

Kozak, J.J., Hancock, P.A., Arthur, E.J., & Chrysler, S.T. (1993). Transfer of training from virtual reality. *Ergonomics, 36*, 777-784.

Morasso, P. (1981). Spatial control of arm movements. *Exp. Brain. Res. 42,* 223-227.

Nudo, R.J., Milliken, G.W., Jenkins, W.M., and Merzenich, M.M. (1996) Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. *Journal of Neuroscience, 16,* 785-807.

Rizzolatti, G., Fadiga, L., Fogassi, L., Gallese, V. (1999). Resonance behaviors and mirror neurons. Arch. Ital. *Biol. 137(2-3):* 85-100.

Schmidt, R.A. (1991) Frequent augmented feedback can degrade learning: Evidence and interpretations. In: GE Stelmach and J Requin, eds., *Tutorials in Motor Neuroscience*. Dordrecht, The Netherlands: Kluwer Academic Publishers, p. 59-75.

Shadmehr,R. & Mussa-Ivaldi, S. (1994). Adaptive representation of dynamics during learning of a motor task. *Journal of Neuroscience 14*, 3208-3224.

Stanney, K.M., Kennedy, R.S., Drexler, J.M., & Harm, D.L. (1999). Motion sickness and proprioceptive after effects following virtual environment exposure. *Applied Ergonomics, 30*, 27-38.

Wolpert, D., Ghahramani, Z. and Jordan, M. (1995). Are arm trajectories planned in kinematic or dynamic coordinates? An adaptation study. *Experimental Brain Research 103*, 460-470.