A Virtual Environment-Based Paradigm for Improving Attention in TBI

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***Abstract*—Attention deficits are one of the most profound problems facing the traumatic brain injured individual. The Traumatic Brain Injury (TBI) inpatient population in the rehabilitation unit is difficult to study with new technology because it is often very difficult to render and evaluate such interventions in the short time span when a patient is still in the hospital, even though that is precisely the time when clinical attentional therapy is considered most critical. We developed and performed a preliminary test of a haptic/graphic paradigm for improving attention and concentration in early stages of recovery in the TBI inpatient population. Six TBI patients and three healthy controls were exposed to a minimal distraction/minimal interaction environment while reaching for a visual target. Our initial results showed (1) the subjects tolerated the experience, (2) the number of targets acquired in successive one-minute intervals indicated a sustained attention for the task, and (3) haptic interaction in such an environment was well tolerated, engaging, and enjoyable -- often considered a game. These findings have provided the foundation for a larger, intensive, protracted study with repeated treatment.**

I. Introduction

Severe sensory and motor deficits that result from head trauma, stroke, or spinal cord injury can include motor impairment, perceptual difficulties and cognitive impairment. Consequently rehabilitation of patients is a complex process, with the added difficulty that improvement beyond the achievements in the clinical setting must transfer to real life activities.

Attention deficits are frequently observed after traumatic brain injury (TBI). Because of its importance, attention has been the target of various types of treatment and rehabilitation programs for survivors of TBI [1]. Attention rehabilitation in patients with TBI and stroke includes a variety of approaches, for example, the direct attention process training [2], [3]. Previous studies which used paper-and-pencil and performance-based neuropsychological measures have investigated the effectiveness of attention training after TBI and demonstrated an improvement of acquired deficits of attention after training [2]-[6]. Yet, evidence was based on a limited number of studies with small samples [6], [7]. The most common group of TBI patients that has been tested in these studies was the outpatient population. However, higher cancellation rates and failure to attend therapy can frequently confound the science in this population.

In contrast, there are few inpatient studies in spite of the fact that this population tends to have the greatest problems with attention (i.e. lower Rancho Cognitive Level), stand to show a greater degree of improvement and are a captive audience. Studies that did test this population most commonly assessed the attention deficits associated with TBI, compared patients and control performance, and tested various clinically useful scales for measurement of different types of attention dysfunction [8], [9]. Considering that attention plays a major role in many cognitive functions, the need to remediate attention in early stages is crucial. One solution may be a technology that can facilitate therapy.

Virtual reality (VR) has been shown as an effective tool in many domains of therapy and rehabilitation in TBI and stroke [10]-[12], and has been shown to enhance patients' motivation and enjoyment [13], [14], important factors in successful rehabilitation [12]. VR typically refers to the use of a human-computer interface that allows the user to experience and interact with a computer-generated virtual environment. The use of VR enables both easy relocation of an object in space and alterations to the object's characteristics (e.g., its size and shape). It allows the researcher to readily customize experimental scenarios to specific investigations (e.g., specific controlled scenarios for attention training that may introduce distractions as and when required), and to simulate real-life environments that would be difficult or even impossible to create with conventional, real-world set-ups. This capability is especially important for clinical studies, in order to provide a patient with the ability to practice performance in a safe and ecologically valid interactive environment.

VR has already shown to be effective in assessing the severity of attention in TBI and in helping restore cognitive and motor functions to individuals who are recovering from

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TBI or stroke. In general, virtual environments offer several advantages over conventional therapies. VR has been used as a medium for functional evaluation as well as for the assessment and rehabilitation of cognitive processes, such as visual perception, attention, memory, and executive functioning in individuals with TBI [10], [15]-[18]. These studies provided evidence in support of the validity of VR tasks as a measure of cognitive function. They found strong concordance between real-world and VR-based performance, and showed that VR-based assessment measures, which were compared to traditional neuropsychological measures, reliably distinguish between individuals with TBI and healthy individuals. Moreover, a previous study showed that the use of VR in rehabilitation is not only useful as an assessment tool, but also has the potential to offer a useful training method and that training in a virtual environment does transfer to improved real world performance [19].

Our lab has spent several years developing a large-workspace, three-dimensional haptics/graphics system (VRROOM) with software that allows for selective manipulation of the virtual environment. A novel practice paradigm has already shown preliminary evidence that it allows for rapid restoration of function in the stroke survivor [20], [21]. The purpose of this study was to develop and test a VR-based paradigm to enhance attention and concentration in early stages of recovery in the traumatic brain injury inpatient population using state of-the-art virtual reality and robotics. We hypothesized that in the testing during two single successive visits the VR haptics/graphics system will be well-tolerated by the patients, improve time-on-task, targets acquired per one-minute period, and a willingness to return for treatment.

II. Materials and Methods

A. Subjects

Six TBI patients (recruited from the inpatient population of the Rehabilitation Institute of Chicago) and three neurologically healthy controls participated in the study. Five of the six patients were tested twice (on consecutive days). Personal and clinical data for the patients and controls are shown in Table 1. Subjects gave informed consent in accordance with the Institutional Review Board of Northwestern University.

B. Apparatus and data collection

A three-dimensional, large-workspace haptics/graphics system called the Virtual Reality and Robotic Optical Operations Machine (VRROOM) was used in this study (Fig. 1a). VRROOM's visual display subsystem, the Personal Augmented Reality Immersive System (PARIS), developed at the University of Illinois at Chicago, is the highest quality system available, allowing users to view virtual objects superimposed onto the real world. A cinema-quality digital projector (Christie Mirage 3000 DLP) displays the images over five-foot-wide 1280x1024 pixel image resulting in a 110º wide viewing angle. A 6-degree of freedom PHANToM Premium 3.0 robot (SensAble Technologies) is capable of generating 3 Newtons (N) with transient peaks of 22 N and provides a workspace measuring 900 x 900 x 300 mm. Its hardware-resident controller runs asynchronously with the computer for stable, uninterrupted control. The correct perspective and stereo projections for the view of the scene were computed using values for the current position and orientation of the head (6 DOF) supplied at 100 Hz by a tracking sensor ('Flock of birds', Ascension Technology) attached to the stereo shutter glasses worn by the subject (Crystal Eyes, StereoGraphics Inc.). The immersive virtual environment consisted of a minimal environment with no background textures and only a cursor and a target (generated as 3D virtual ball-shaped targets with a 1 cm radius) in the field of view. Targets could be both seen (using VR technology) and felt (using robotics to render haptic sensation) (Fig. 1b). Subjects sat in a dark room on a chair placed in front of the VRROOM system, grasping the handle of the robot with their right hand.

TABLE 1 Personal and clinical details for TBI patients and healthy (H) controls

Subject no.	*Sex*	*Age (yr)*	*Weeks since injury*	*Rancho level*
TBI 1	M	35	13	VI/ VII
TBI 2	M	52	10	VII
TBI 3	M	27	4	IV
TBI 4	M	24	3	VII
TBI 5	M	32	4	VI
TBI 6	M	30	16	IV
H1	M	39	NA	NA
H2	F	32	NA	NA
H3	M	27	NA	NA

NA: not applicable; Rancho level: score on the Rancho Los Amigos scale pre-VR experiment based on clinical evaluation.

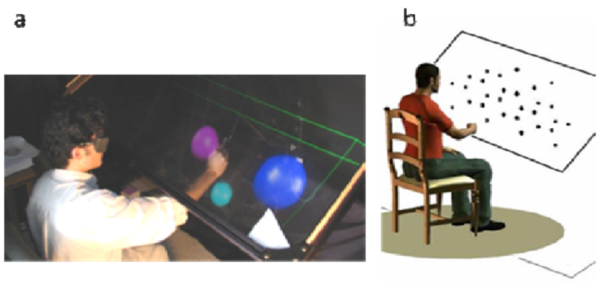

Fig. 1. The VRROOM system. (**a**) User seated at the apparatus with virtual spheres rendered both haptically and graphically. (**b**) An illustration of an experimental subject sitting in front of the VRROOM system, and the spatial arrangement of all possible virtual targets appearing within the 3D virtual environment.

C. Procedures and data analysis

Subjects were required to hold the handle of the robot and move the handle toward spherical targets that appear within a minimal interactive virtual environment. Only one target and the cursor (representing the location of the tip of the robot) appeared within the scene at a time. Each target appeared randomly at a point located in the three-dimensional space (Fig. 1b). On half of the trials the robot exerted forces according to the gradient of a three-dimensional (trivariate) Gaussian function, designed in such a way so that the forces begin at approximately 3 cm from the target, were maximum at approximately 1.5 cm from the target, and then approach zero at the target center. In this fashion, we created a smooth attractor that draws the patient's hand to the target. Similarly, on the other half of the trials the robot exerted the opposite of this, a repulsor that pushed the hand away from the target. When the subject entered the cursor to the target, the target disappeared and the next target appeared in the scene. In total, the experiment included 160 trials, of which after every 20 trials the force condition (i.e., attractor or repulsor) was changed.

The VRROOM system is capable of recording events occurring in the scene (e.g., appearance of a target), as well as the subject's arm position in space at any given time (via the robotic arm) at approximately 100 Hz. The arm position during each trial was analyzed. Here we present the calculated total number of targets to which the patient was able to reach per one-minute interval, (which indicate the level of concentration during the task), as well as the patient's tolerance that was measured by means of the total time in which the patient was able to interact with the environment.

III. Results

Though we anticipated that some or all of the TBI patients would not readily tolerate the intervention and hence would not complete the task, every subject except for one completed the task. Patient TBI6 completed only 105 trials on the first test (day 1) due to fatigue. However, he was anxious to return and easily completed the entire task on day 2. Most fundamentally, the patients tolerated the intervention with no signs of discomfort or intimidation from the technology. Further, no one requested that the intervention be discontinued. The subjects perceived the intervention as a game, and perceived use of VR/haptics as a unique "high tech" medical approach. It is important to note that all were highly motivated throughout the experiment and eager to return for more the next day. Five of the six patients (TBI2-TBI6) did return the next day, tolerated the intervention equally well, and all requested additional visits.

TBI patients' completion times (except for TBI4) were slower than three healthy controls (Fig. 2). Furthermore, results indicated that all five TBI patients that returned the next day exhibited reduced completion times on day 2. In spite of the attention deficits that might be present in these patients, we found no noticeable evidence of any loss of attention to the task during the intervention. Quantitatively, we found that all subjects (both healthy and TBI) exhibited variation in number of targets acquired per one-minute interval. However, the variations seen for the TBI patients suggest no clear evidence of any deterioration in attention during the task (Fig. 3). Overall, patients TBI2-TBI6 showed improvement from day 1 to day 2, acquiring more targets per one-minute interval.

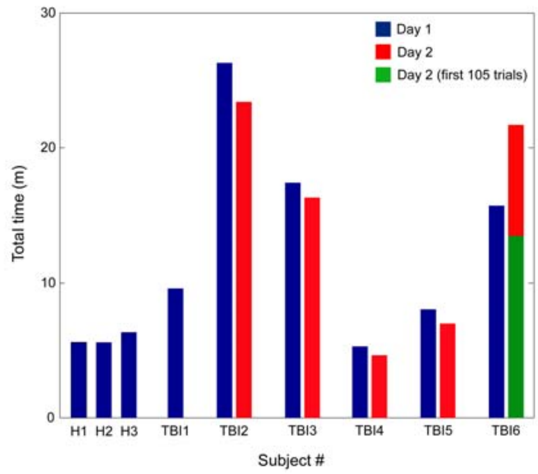

Fig. 2. Overall experiment completion time (in minutes) for three healthy subjects and six TBI patients. Each bar represents an individual's completion time. Patients TBI2-TBI6 returned the next day for a repeat test. Note that TBI6 completed 105 trials on day 1, thus, the completion time for the first 105 trials on day 2 is also presented for comparison.

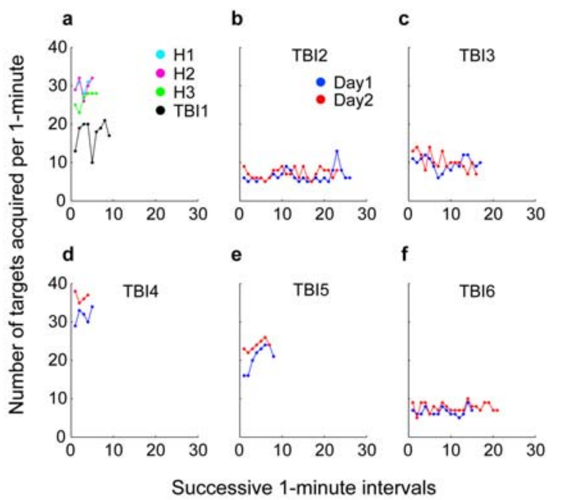

Fig. 3. Subjects' number of targets acquired in each 1-minute interval. (**a**) Three healthy subjects and patient TBI1, (**b**)-(**f**) Results from day1 and day2 are shown for patients TBI2-TBI6. Note that shorter completion times included less 1-minute intervals.

Finally, we found that the designed haptic forces were easily tolerated and intriguing to the patients. There was no detectable difference between attractor and repulsor force conditions at these mild levels, though these forces were noticeable by the patients, particularly when they changed from attractor to repulsor. Although no differences in one-minute target acquisition rate were found, we were able to show that the attractor and repulsor were neither unpleasant, nor difficult or overly distracting to these patients. In fact, they all were intrigued and motivated by the experience, and wanted to come back. This is supported by the fact that there was no measurable loss of attention.

IV. Discussion

We hypothesized that isolated training with a focused task would be best for restoring attention for the TBI inpatient population. This approach is in contrast to other virtual reality paradigms applied to the TBI population. The novelty of the developed VR-based technique is that it uses an extremely minimal environment with minimal distractions, and also uses the feel of unique forces that engage the subject. While more subjects with prolonged and repeated testing are needed, the results of this initial study are encouraging. While not yet providing any solid conclusion regarding the efficacy of this treatment approach, this study demonstrates that all subjects choose to return on a second day, and that the intervention is tolerable and engaging.

The approach builds on recent efforts by our group and others that leverage neuroplasticity to beneficially alter movement patterns in individuals recovering from brain injury [21]. It provides more foundation for the wider family of applications that benefit from interactive physical training (therapy, prosthetic control, hazardous material handling, haptics, pilot training, sports training, telesurgery, learning to operate a brain machine interface, space exploration and military). This study also represents a first step in understanding movement recovery characteristics that can provide insight for future studies and data for models.

In a clinical context, this data suggests that a VR-haptics intervention might be an effective, well-tolerated and highly motivating adjunct to current conventional treatment approaches designed to address attention impairments in TBI. Our lab is currently engaged in a head-to-head randomized comparison of this haptic/graphic paradigm to a conventional attention-based cognitive rehabilitation.

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