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Virtual Rehabilitation of Upper-Limb Function in Traumatic Brain Injury: A Mixed-Approach Evaluation of the Elements System

Peter H. Wilson*, Nick Mumford, Jonathan Duckworth, Patrick Thomas, David Shum, & Gavin Williams

***Abstract*— The aim of this study was to assess the efficacy of the Elements virtual reality (VR) system for rehabilitation of upper-limb function in patients with traumatic brain injury (TBI). A *mixed-approach design* was used. Performance was evaluated at three time points using a within-group design: Preintervention 1 and 2, conducted 4 weeks apart, and Postintervention. Subjective ratings were provided after patients completed exploratory tasks. The intervention consisted of 12 1-hour training sessions over 4 weeks in addition to conventional physical therapy. Nine patients aged 18-48 years with severe TBI were recruited. The Elements system is comprised of a 40-inch tabletop LCD, camera tracking system, tangible user interfaces (i.e., graspable objects), and software. The system provided two modes of interaction with *augmented feedback*: goal-directed and exploratory. Upper-limb performance was assessed using system-rated measures (movement speed, accuracy, & efficiency), and standardised tests. Planned comparisons revealed little change in performance over the pretest period apart from an increase in movement speed. Significant training effects, with large effect sizes were shown on most measures. Subjective data revealed high levels of presence (inc. user involvement/control) and user satisfaction for the exploratory tasks. These findings support an earlier case study evaluation of the Elements system, further demonstrating that VR training is a viable adjunct in movement rehabilitation of TBI.**

I. INTRODUCTION

Overview

Use of virtual reality (VR) in movement assessment and rehabilitation has gathered momentum in recent years. Wilson et al. [1] described the development of a VR system (*Elements*) for individuals with traumatic brain injury (TBI). The Elements system uses low-end technologies to achieve stable movement tracking, flexible presentation of virtual environments (VEs), augmented feedback (AF), and automated recording of performance data. An initial case study demonstrated strong effects on motor learning in three patients with severe TBI [2]. This paper describes a clinical evaluation of the Elements system using a mixed-approach design, combining a quantitative within-group evaluation and subjective questionnaire.

Traumatic Brain Injury

Individuals with TBI commonly experience impaired upper-limb function, including poor timing and accuracy of reaching, and reduced ability to grasp and lift objects [3]. Impaired motor planning is also common due to damage to distributed motor networks including premotor cortex, parietal cortex, basal ganglia and cerebellum [3]. This is manifested by abnormal kinematics: delayed movement latency, poor trajectory control, and so on [4].

VR may provide an effective means for assessing motor control and skill, and for designing and implementing rehabilitation activities. VEs can engage and motivate individuals with TBI, automate data collection, and provide greater control over task constraints [5]. Several researchers have verified the usability of VR systems when re-teaching functional skills [6-8], but only a few studies have assessed the clinical benefits of VR rehabilitation in TBI: e.g., one successfully improved participants' balance [9] and, another, cognitive function [10]. Most other data is drawn from stroke patients [11].

Early Evaluation of the Elements System

The Elements system was first trialed in an ABA case study [2]. Three TBI patients received 12 sessions of VR training on goal-directed tasks involving reach and place actions cued from within the VE, while also maintaining their conventional physical therapies. All three patients showed improvements between baseline and treatment phases in their movement accuracy, efficiency, and

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N. Mumford completed his PhD in Psychology at RMIT University.

J. Duckworth is an artist and recent PhD graduate with the School of Creative Media and Communication, RMIT University, Melbourne Australia.

P. Thomas is with the School of Curriculum, Teaching and Learning, Griffith University, Brisbane, Australia (email: p.thomas@griffith.edu.au).

D. Shum is with the School of Psychology, Griffith University, Brisbane, Australia (email: d.shum@griffith.edu.au).

G. Williams is Senior Physiotherapist at the Epworth Hospital in Melbourne, and VNI Research Fellow.

P.H. Wilson is with the Division of Psychology, RMIT University, Melbourne, Australia. (Phone 613-9925-2906; fax: 613-9925-3587; email: peter.h.wilson@rmit.edu.au). * Corresponding author.

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bimanual dexterity. While promising, a more rigorous group study is needed to replicate and extend these findings. In addition, several exploratory activities have been recently incorporated into the system. These activities are not cued externally but rather involve a suite of tools that enable the participant to create audiovisual effects. A particularly powerful means for program evaluation is a *mixed-approach design*, involving analysis of both quantitative performance data and subjective ratings from participants themselves.

Within-group evaluation

A within-group study was adopted for a number of reasons. First, more data were needed before embarking on a large randomised controlled trial. Second, within-group designs offer greater statistical power than between-group comparisons because threats to internal validity (e.g., group differences on gender, IQ, etc.) are controlled, and more data analysed [12-13]. Third, training effects can still be calculated using estimates of effect size. Finally, we were better able to control for variations in the conventional therapies that patients received while undergoing VR intervention.

Within-group designs have been used successfully to study the effect of movement rehabilitation on TBI [14-16], including use of VR. For example, these designs have been used by the Rutgers group to show the positive effects of VR training for hand rehabilitation [17], and by others to support use of teacher-animation systems [18-22].

Subjective evaluation of user experience

Surprisingly, we know very little about the experience of brain-injured patients as they engage with VR rehabilitation systems. This type of data has potentially important implications for understanding how training effects are exerted and what system modifications are needed to enhance therapy. Of particular interest to our team is whether exploratory environments can offer a unique form of user interaction, particularly for patients with severe TBI who find conventional therapy quite demanding for physical, cognitive, and emotional reasons. Hence, we also evaluated patients' experience of some new exploratory tasks that have been incorporated into the Elements system.

Aims and hypotheses

The primary aim of this study was to further assess the efficacy of the Elements system by conducting within-group evaluations, as well as assessing how well patients engage with some new exploratory tasks that form part of the system. It was predicted that participants with TBI would demonstrate improved upper-limb function. Moreover, we expected the benefits of VR training to generalise to other aspects of neurobehavioral function. Finally, we predicted high levels of presence/engagement in the exploratory tasks, using an adapted presence questionnaire.

II. METHOD

Participants

Nine participants with TBI (5 males) were recruited from a large metropolitan rehabilitation hospital in Melbourne, Australia, using inclusion criteria identical to those of an earlier case study [2]. Inclusion criteria were age under 50 years and a score of at least 2 on the Oxford scale for muscle activity. Participants were aged 18-48 years (M = 33.0, SD = 11.2). The period of posttraumatic amnesia (PTA) ranged from 28 to 630 days (M = 70). Eight participants were categorised as extremely severe and one very severe based on the length of PTA [23]. Time since injury ranged from 3 to 178 months (median = 9 months). All participants were right handed prior to their TBI. Six participants experienced post-TBI hemiplegia on their left side, one on the right, and two had bilateral ataxia. The level of impairment pre-treatment on the BBT was severe (at least 3 *SDs* below age norms).

Two participants were inpatients during this 8-week study, two were residents at an assisted-living facility, and five were living with relatives. All participants continued their conventional rehabilitation which consisted of weight-based strength and conditioning, gait and mobility training, hydrotherapy swim training, OT, and speech therapy. Each participant had upper-limb impairment and considered this rehabilitation important (evidenced by their voluntary participation in the study). Participants were also required to have the cognitive capacity to provide informed consent and to understand the VR program. The study was approved by relevant institutional Human Research Ethics Committees. All participants were debriefed about the outcomes at its completion.

Materials

Elements system: Hardware. The Elements system runs on off-the-shelf PC hardware. The PC has a Dual Core (2.21GHz) processor, 2GB RAM, and is equipped with an nVidia GeForce 7800 graphics card. The system runs 3D Via Virtools software. The display is a 100-cm LCD panel placed horizontally. Stereo speakers present audio cues. The LCD panel is covered by a sheet of 4-mm non-reflective hardened glass. The movement of the object (e.g., a plastic cylinder) is tracked using a Bumblebee2a camera (PointGrey Inc., Vancouver), precise to 0.1 mm.

The Elements system provides two modes of user interaction: one goal-oriented and the other exploratory. Both modes have been described previously [2, 24]. Task 1 (Bases) consists of the home base and three potential movement targets, all 78 mm in diameter. The circular targets are cued in a fixed order (west, north, east) using an illuminated border. Task 2 (Random Bases) has the same configuration of targets, but they are highlighted in random order. Task 3 (Chase Task) begins with a blank screen. A target circle then appears randomly in each of nine locations, distributed over the display. Task 4 (Go-No-Go) uses the same target positions as Task 3 but additional distractor targets (viz., a pentagon, triangle, & rectangle) appear. Participants are instructed to move and place the object on the circular targets only.

The exploratory tasks were designed to encourage participants to explore and discover different ways of interacting with the VE using visual and sound effects. Task 1 (Mixer) consists of nine circles in a 3x3 pattern, each with a white border. The participant places the object on a circle to activate its sound and start the border animation spinning. The pitch and tone of the sound vary according to the object's proximity to the circle. Participants can activate different combinations of circles at any time to produce an overall sound effect in the VE. Task 2 (Squiggles) encourages participants to draw lines and shapes on the display using a combination of four objects (original cylinder, pentagon, triangle, and rectangle). As each object is placed and moved across the screen a coloured trail is drawn along its path, and a musical tone plays. If the object is lifted, the trail animates and moves across the screen. Each object has a unique trail and sound (Figure 1). Task 3 (Swarm) encourages bimanual control to explore the audiovisual relationships between the four objects. When placed on the screen, multiple coloured shapes slowly gravitate toward and swarm around the base of each object. As an object is moved its swarm follows. The movement, colour, size and sound characteristics of each swarm change when the distance between objects is altered.

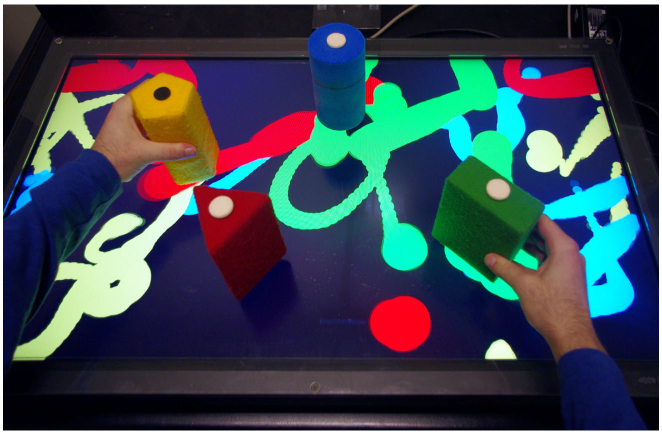

Figure 1. Sample configuration for the Squiggles exploratory task.

Augmented feedback (AF). Both the goal-directed and exploratory tasks utilise AF which serves two purposes. First, AF provides participants with additional knowledge of the outcomes of their actions to assist movement planning in the future. Second, AF enables participants to focus their attention on the effects of their movement, rather than on the movement itself, which has been shown to benefit motor learning [25]. In this system, each AF feature is related to one or more of the three movement variables (see [2]). During training, each participant was instructed to focus on the AF appropriate to the performance variable that was targeted. For example, an increase in the luminance of the on-screen target as the object approached indicates improved placement accuracy.

Outcome Measures

System-measured variables. *Accuracy* of object placement is measured as a percentage score, and represents the overlap between the base of the object and the target area; thus 100 percent would be perfect overlap. *Movement speed* is given by the rate of object movement during task performance, measured in m/s. *Movement efficiency* is the deviation from the straight-line path between targets. This variable is measured as a percentage score: (total straight-line distance between the sequence of targets ÷ distance moved) x 100. In addition to training, Task 1 and 3 were used as assessment tasks (administered without AF).

Standardised Measures

Box and Block Test (BBT). The BBT is an assessment of general upper-limb function. The goal is to move as many (2.5-cm) blocks as possible from one container to another, one at a time, in 60 s using one hand. The BBT has excellent test-retest reliability and predictive validity, and has been used frequently to assess patients with TBI [26].

McCarron Assessment of Neuromuscular Dysfunction (MAND). Research has indicated that unilateral upper-limb training can improve bimanual coordination [27-28]. Thus, the nuts-and-bolts task from the MAND was used to assess bimanual dexterity. This task requires participants to hold a metal nut in their non-preferred hand and screw either a large or small bolt into the nut as quickly as possible with their preferred hand, with no time limit. The MAND tasks show good reliability and validity and are recommended for assessing brain-injured patients [29].

Neurobehavioral Functioning Inventory (NFI). The NFI assesses general neurobehavioral symptoms and problems commonly encountered by patients with TBI and other neurological disabilities. We used it to assess whether Elements training had any effect beyond upper-limb function. The NFI has 76 items and six subscales: Depression, Somatic, Memory/Attention, Communication, Aggression, and Motor. Each item is rated on a 5-point Likert scale from 1 (*never*) to 5 (*always*). Higher scores indicate poorer outcome. The NFI has good reliability and construct validity [30].

Subjective Measure: Presence Questionnaire. The patients' experience of performing the exploratory tasks was assessed using an adapted version of the *Presence Questionnaire* [31]. We used items from the Involvement/Control and Interface Quality sub-scales, and items loading on Distraction and Sensory factors. Involvement/Control relates to one's meaningful engagement with the learning environment and ability to exert control over it. Distraction relates to virtual systems that isolate users from the external, physical environment and enlist their selective attention. The sensory factor relates to the richness of the VE and the presentation of multimodal information. All items were rated on a 5-point Likert scale (1=*not at all*; 5=*a great deal*). Average ratings were calculated for each subscale/factor, with higher scores indicating more optimal experience.

Procedure

Performance was assessed at three time points. Preintervention 1 (Pre1) and Preintervention 2 (Pre2) measures were conducted 4 weeks apart before introduction of VR; during this time participants continued their conventional physical therapy. The 4 weeks of VR training were then conducted in conjunction with physical therapy, followed by Postintervention (Post) assessments.

The four goal-oriented tasks were presented an equal number of times in each session for both hands; these took 40 min per session. Following this, participants received graphical feedback on their performance, and then interacted with one of three exploratory VEs during the last 5-10 mins of the session. All sessions were administered by Mumford using standardised procedures.

Data analysis. The primary analyses compared participants' performance on the six DVs (accuracy, speed, efficiency, BBT, MAND, NFI scores) before and after intervention. To test our predictions, two sets of planned comparisons (referred to as pretest and treatment contrasts) were conducted in order to maximise power [32]. In the first set, the two preintervention scores were compared on each measure. In the second, each postintervention score was contrasted with the average of the preintervention scores. In order to interpret the results, we also calculated effect sizes (partial η^2) for each contrast.

III. RESULTS

The participants' levels of performance on all outcome measures are summarised in Table 1. Effect sizes are represented in Figure 2.

Table 1. Group Performance on System Variables and Standardised Tests Before and After VR Training.

Variable		Pre1 *M* (*SD*)	Pre2 *M* (*SD*)	Post *M* (*SD*)
Accuracy	L	46.3 (22.0)	51.3 (22.9)	64.3 (19.8)
(%)	R	56.9 (21.0)	59.2 (16.6)	73.6 (9.2)
Speed	L	0.20 (0.08)	0.26 (0.09)	0.24 (0.06)
(m/s)	R	0.23 (0.06)	0.28 (0.07)	0.31 (0.08)
Efficiency	L	81.0 (20.3)	91.1 (5.2)	94.3 (4.8)
(%)	R	92.6 (2.4)	93.5 (4.1)	97.7 (1.3)
BBT (no.	L	30.4 (19.6)	33.0 (17.5)	35.9 (15.8)
blocks)	R	46.7 (12.1)	47.3 (10.2)	53.3 (12.6)
MAND (s)	Small	26.2 (17.5)	22.0 (10.8)	21.6 (10.0)
	Large	33.7 (22.2)	26.8 (11.1)	25.1 (6.3)
NFI (total)		128.7 (40.1)	128.6 (38.7)	112.9 (40.9)

A. System-measured performance

Pretest contrasts. On accuracy and efficiency measures, no significant change between the Pre1 and Pre2 assessments were shown for either the left or right hand (each $p > .05$). However, on movement speed, pretest contrasts were significant for both their left, $F(1,8) = 12.82$, $p = .01$, and right hands $F(1,8) = 13.08$, $p = .01$.

Treatment contrasts. On accuracy, treatment contrasts were significant for both left, $F(1,8) = 13.69$, $p = .01$, and right hand $F(1,8) = 9.45$, $p = .02$. Significant improvement was also shown for participants' right hand efficiency, $F(1,8) = 22.22$, $p = .002$, and that for the left hand approached significance ($p = .06$). On movement speed, a significant change was found for the right hand, $F(1,8) = 11.5$, $p = .01$, but not the left ($p = .30$).

B. Standardised measures

Pretest contrasts. No significant changes were shown between pre1 and pre2 on the BBT, nuts-and-bolts task from the MAND, and NFI total score (each $p > .05$). The NFI communication subscale did show improvement, $F(1,8) = 5.57$, $p = .046$.

Treatment contrasts. On the BBT, significant improvement was noted from the treatment contrast for left, $F(1,8) = 5.68$, $p = .04$, and right hands, $F(1,8) = 12.61$, $p = .007$. However, no significant improvement on the nuts-and-bolts task was found for either the large or small bolt (each $p > .10$). On the NFI, a significant reduction on total scores was found, $F(1,8) = 14.52$, $p = .005$. Although each of the subscales showed a tendency to improve during treatment, only the memory/attention subscale improved significantly, $F(1,8) = 5.39$, $p = .049$.

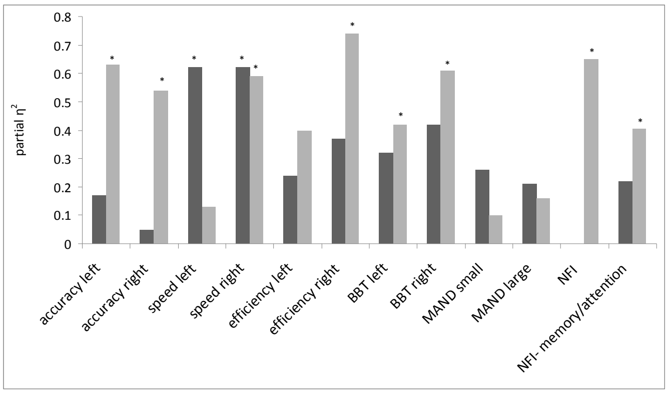

Figure 2. Effect size (η^2) for each pretest and treatment (light bars) contrast. *denotes statistical significance at $p < .05$.

C. Subjective evaluation of the exploratory VEs

Averaged over the three exploratory environments, mean ratings for the Involvement/Control and Interface Quality subscales were 3.90 (*SD*=0.54) and 4.13 (*SD*=0.06), respectively. Mean scores for the Distraction and Sensory factors were 4.84 (*SD*=0.15) and 4.00 (*SD*=0.18), respectively.

IV. DISCUSSION

The primary aim of this investigation was to further assess the efficacy of the Elements system using a within-group design. First, the pretest contrasts revealed no significant improvement in performance on most measures over the 4-week period of conventional rehabilitation alone. The one exception was an increase in movement speed on the system. By comparison, treatment contrasts supported the effectiveness of the system across a range of measures. Taken together, the effects of training were a function of the VR system and not just repeated exposure. The patterns of performance on the system-rated and standardised assessments, implications of the results, the impact of the exploratory environments, limitations of the study, and future directions are discussed below.

System-measured performance

Our participants demonstrated significant improvements in movement accuracy based on the treatment contrasts. In line with case-study findings, this improvement in accuracy was not to the detriment of movement speed. Furthermore, the large effect sizes support the system's benefits to movement accuracy of patients with TBI.

Movement speed data need to be interpreted with reference to accuracy, specifically the trade-off defined by Fitts Law. This principle would predict that in the absence of motor learning, an increase in speed would result in a reduction to accuracy [33]. In our study, however, significant improvements over treatment (with large effects) were noted for both speed and accuracy using the right hand. For the left hand, significant improvement in accuracy (with large effect) was observed in conjunction with no change in speed. This pattern of results suggests genuine improvements in motor control [2].

The movement efficiency results also support the efficacy of the Elements system. Both left and right hands demonstrated no change from conventional rehabilitation alone (pretest contrast), followed by improvement after the VR training (treatment contrast) for the right hand. Although the left hand treatment contrast just failed to reach significance, $p = .06$, effect size was moderate (Cohen, 1992). The improvement in right hand performance is interesting in view of the fact that all participants scored highly on this variable prior to intervention (generally over 90%). This is an important finding because rehabilitation normally targets areas of limited function [34-35], and little evidence has been reported for improvement at higher levels of function. Future interventions (both VR and non-VR) should target areas of high and minimal impairment to ascertain whether training effects in both are related to changes in functional skill.

Standardised assessment performance

In addition to the system-generated measures, it is important to report performance on standardised measures in order to assess the generalisability of the intervention. Participants' general upper-limb function as assessed by the BBT showed little change prior to the intervention but significant improvement after VR training with medium to large effect sizes. The BBT has excellent predictive validity[36-37] and its scores are seen to accurately represent participants' functional abilities [36, 38]. This indicates that the Elements training is likely to benefit participants' daily function.

Like our earlier case study [2], MAND data show that bimanual coordination did not change significantly over one month of conventional rehabilitation alone or after the introduction of VR therapy. Since the majority of training was with the goal-based tasks which involved unilateral movement, these results suggest task-specific benefits. However, previous research indicates that combining bimanual and unimanual training may lead to more generalised improvement [39]. Although the Squiggles and Swarm tasks did afford a degree of bimanual movement, four weeks of training may not be sufficient to significantly improve bimanual skill. The length of treatment is an issue of current investigation.

The NFI was included in the present study to explore whether the Elements training led to functional benefits that extend beyond upper-limb performance. Results showed no significant change prior to the intervention, but fewer symptoms of dysfunction after treatment. It has been theorised that the enjoyment and novelty of VR may have a general therapeutic benefit by improving motivation and engagement [5, 40]. In particular, task involvement/engagement may enhance aspects of memory/attention, a subscale showing significant change. This is supported by our subjective data which shows high levels of presence, specifically involvement/control. These indirect effects are not trivial since memory and attention are commonly disrupted after TBI [41].

Subjective evaluation of the exploratory VEs

Subjective evaluations by the patients showed that the exploratory VEs help engender high levels of presence, specifically task involvement/control. Patients found the VEs stimulating at a sensory level, and were able to engage with the system and exert control without being distracted by the visual and auditory effects. There appears to be a strong motivational incentive for participants in being able to create their own feedback effects (visual and auditory). The benefits of playful interaction on engagement and motivation have been found in earlier work (e.g. [5]). Taken together, participants might have experienced greater gains in motor function by being exposed to both the goal-based and exploratory VEs.

Furthermore, the questionnaire confirmed that participants enjoyed using the exploratory VEs, and found them a positive change from conventional rehabilitation. This finding is in line with previous studies (e.g., [42-43], which viewed patients' enjoyment of VR rehabilitation as a central contributor to their motivation and motor recovery.

Study limitations and future directions

Although our subjective data support the use of exploratory tasks, our study does not permit evaluation of these tasks in isolation. This issue is important because it goes to the heart of user engagement—the extent to which treatment effects are simply a function of time on task, which is leveraged by the patient's level of engagement in novel, stimulating tasks.

The sample size used here may limit the generalisability of our findings. Thus, larger sample sizes are also a requirement of future studies, particularly as a way of exploring other correlates like severity of TBI and the time since injury.

Conclusions

The findings presented here support those of previous case studies (e.g. [2, 44]), demonstrating that, as an adjunct to conventional physical therapy, the Elements VR system can improve upper-limb motor control in TBI. Currently, upper-limb training is often secondary to mobility training in rehabilitation centres. In addition, the type of training that does exist is often based on repetitive and labor-intensive treatments. Given that the VR-based approach we evaluated here is relatively low cost, fully automated, and has engaging and motivating workspaces, it may prove to be a useful addition to the tools used by physical therapists. Adoption of the system in the future will depend on its validation using a randomised controlled trial. Finally, we noted improvements in participants' overall neurobehavioral functioning, especially memory and attention, following the VR training. These findings, if replicated, are significant because the effects of training during therapy often do not generalise to other aspects of patients' lives.

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