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Emotive, Cognitive and Motor Rehabilitation Post Severe Traumatic Brain Injury–

A New Convergent Approach

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Abstract—**Standard of care treats emotive, cognitive and motor rehabilitation needs post severe traumatic brain injury separately. This paper proposes an alternative in the form of *convergent rehabilitation*, which uses virtual environments to treat the three domains simultaneously. Two clients chronic post severe TBI participated in a feasibility study in which they practiced their affected upper extremity playing custom video games on the Rutgers Arm II. The ABAA protocol consisted of neuro-psychological and motor evaluation pre-, 18 training sessions, then motor and neuro-psychological evaluations post- and at 6 weeks follow up. Training sessions were gradated in duration, difficulty, included dual-tasks, and rewards for good performance. Participants improved in depression, focusing, executive function, shoulder strength and one was faster on the Jebsen test of hand function. Most gains were maintained at follow-up and resulted in improved independence in activities of daily living. Participants liked the technology, giving it a subjective rating of 4.45 out of 5.**

Keywords- traumatic brian injury; virtual reality; dual-task; depression; upper extremity; motor retraining; memory; executive function; focusing; shoulder strength.

I. INTRODUCTION

Health statistics show that 1.7 million Americans suffer a traumatic brain injury (TBI) each year [1]. These clients present with diminished executive function, difficulty focusing, affected short term memory) [2], emotive difficulties [3] and may also require motor relearning (active range of motion, motor control, and strength) [4].

Close to one third of all patients post-mild-to-moderate TBI suffer from severe depression [5]. Since depression has a strong influence on cognitive dysfunction, antidepressant therapy is prescribed as adjuvant to rehabilitation. Considering that many patients post-severe TBI also undergo motor retraining, the inter-relation between cognitive impairments and physical/occupational therapy outcomes needs to be studied. Functional outcomes post-neural infarct benefit from performance feedback, considered the second most important element of the intervention after the necessary amount of practice [6]. Motor retraining outcomes in such populations are negatively affected by cognitive deficits that impact the processing of performance feedback [7]. The reduction in cognitive processing resources in patients with severe TBI was found to lead to longer reaction time and subjective mental fatigue when patients were faced with simultaneous tasks. Dual-task rehabilitation has been applied primarily to aging populations with cognitive decline [8], but more recently it was recommended for veterans post TBI [9].

A substantial number of patients post TBI need emotive, cognitive, and motor interventions, done currently through separate clinical paths. Therapy cost could in theory be reduced if these separate paths were to occur simultaneously, as long as clinical efficacy is not compromised. This needs a rehabilitation system that is flexible enough to provide cognitive and motor retraining exercises, preferably simultaneously, and make them automatically adaptable to each patient. It also needs to be motivating and engaging to help patient's focus, and mediate multiple dual-task interventions without substantially increasing subjective cognitive load. Virtual reality [10] is a flexible environment which easily adapts to the user and intrinsically stimulates multi-modal, multi-task, real-time interactions. It has been investigated for cognitive assessments and rehabilitation [11-12], dual-task balance retraining [13] and upper-extremity motor retraining post TBI [14].

Several computerized systems for virtual rehabilitation are commercially available. In the cognitive domain virtual environment-based therapies are provided by companies such as Virtually Better (Atlanta GA), Lumosity Labs's (San Francisco, CA) and Nintendo DS *Brain Age* series. Game consoles are also currently being used in motor rehabilitation, with the Wii being the most popular game console adopted clinically. Cognitive games for the Wii train language (vocabulary) skills (*My Word Coach*) or memory and logic (*Big Brain Academy*) [15]. The Wii game console is not appropriate for individuals challenged by arm gravity loading or with severe shoulder, elbow or finger spasticity. Patients post-TBI would further be at a disadvantage using the Wii in timed cognitive tasks. Moreover, overuse-induced tendonitis (called "Wiiitis") has been reported [16].

Virtual rehabilitation offers the possibility of merging the cognitive and motor therapies into a single simultaneous

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intervention which we call *convergent therapy*. This paper presents the first feasibility study of convergent emotive, cognitive and motor rehabilitation post severe TBI.

II. PARTICIPANTS DESCRIPTION

The study participants were chronic post TBI which had occurred approximately five years prior. They were recruited from the brain injury support group at JFK Rehabilitation Institute (Edison, NJ) and received medical clearance from their attending physicians. Subsequently the participants signed a consent/assent form approved by Rutgers Institutional Review Board and trained at the university's Tele-Rehabilitation Institute (Piscataway, NJ) in summer 2010.

A. Participant 1

Participant 1 was a 33-year-old right handed, Caucasian male, 57 months post severe TBI due to a motor vehicle accident. He suffered occipital subdural hematoma and bilateral frontal cerebral hemorrhage with midline shift and had an initial Glasgow Coma Scale score of 3 [17]. At 2 months post-injury he was lethargic, disoriented and confused and presented with severe impairments in the verbal, visual, and processing speed domains. Subsequent to 6 months of inpatient rehabilitation he continued to experience cognitive dysfunction (impaired attention, memory, executive function, visual-spatial ability, and verbal fluency) and seemed unaware of his disability. During the years since his brain injury Participant 1 underwent inpatient and outpatient occupational therapy, as well as psychological and psychiatric counseling. At the time of the study, he reported major loss of touch and of hearing subsequent to ear surgery, as well as visual deficits.

At the start of this study he was taking anti-depression medication, was seeing a psychologist weekly and a psychiatrist once a month. His performance on the pre-study neuropsychological evaluation was notable for mild depression. His attention was variable with moderately impaired simple auditory attention, but average simple auditory working memory and simple visual attention. The participant's visual working memory was mild-to-severely impaired. Psychomotor processing speed was severely impaired when increasing demands for sustained attention were introduced. Both his verbal and visual memory were impaired secondary to a retrieval disturbance. Executive functioning generation was mildly impaired (see Table I). Pre-training he ambulated independently and had normal gait. The occupational therapy evaluation showed his left shoulder was weaker by 15% compared to his right shoulder (measured with calibrated weights placed at the wrist). The participant had minimal impairment of his left upper extremity with a Fugl-Meyer Score of 63 [18]. He reported having some degree of difficulty in 7 tasks on the standardized list of 20 activities of daily living [19] (see Table II).

B. Participant 2

Participant 2 was a 23-year-old, right handed Hispanic female, 55 months post severe TBI due to a motor vehicle accident. She suffered diffuse axonal injury (Grade II), subarachnoid hemorrhage of the right Sylvian Fissure, right basal ganglia hemorrhage, and bifrontal hemorrhagic contusions. An EEG two weeks later found diffuse bilateral slowing. While neurocognitively she was in a vegetative state post-accident, she progressed to a minimally conscious state over the next months while in a brain trauma unit. After 3 months of in-home care Participant 2 was admitted to a

TABLE I. CHANGES IN EMOTIVE, COGNITIVE AND MOTOR IMPAIRMENTS IN TWO PARTICIPANTS CHRONIC POST-TRAUMATIC BRAIN INJURY OVER THE 6 WEEKS OF TRAINING AND AT 6-WEEK FOLLOW-UP.

	Participant 1			**Participant 2**		
Outcomes	**PRE**	**POST**	**FOLLOW UP**	**PRE**	**POST**	**FOLLOW UP**
Emotive Outcomes						
Depression Index	Mild (14) On anti-depressant med	Minimal (4) On anti-depressant med	Minimal (1) No anti-depressant med	Minimal (5)	Minimal (5)	Minimal (3)
Cognitive Outcomes						
Verbal Attention (digits forward)	Moderately Impaired T = 30	Low Average T = 41	Average T = 48	Mildly Impaired T = 36	Low Average T = 41	Average T = 52
Visual Attention (Dots)	Average T = 50	Average T = 55	Average T = 55	Severely Impaired T = 23	Low Average T = 41	Moderately Impaired T = 30
Processing speed (TMT-A)	Low Average T = 42	Low Average T = 42	Average T = 51	Severely Impaired T = 25	Severely Impaired T = 17	Severely Impaired T = 17
Upper Extremity Motor Impairment Outcomes						
Shoulder strength anterior	17 lbf	17.5 lbf	20 lbf 18% increase	5 lbf	10 lbf 100% increase	8 lbf 60% increase
Shoulder strength lateral	12 lbf	16 lbf 33% increase	17.5 lbf 46% increase	5 lbf	8 lbf 60% increase	9 lbf 80% increase
Grasp strength	47 lbf	42.6 lbf	45.6 lbf	unable	2 lbf	0.67 lbf
Key Pinch strength	21 lbf	21.33 lbf	21.67 lbf	3 lbf	2.33 lbf	3.33 lbf

comprehensive outpatient brain injury rehabilitation program. She subsequently underwent a combined 4 years of in-patient and outpatient rehabilitation as well as psychological and social coaching.

At the start of this study Participant 2 had minimal levels of depression. Her attention was variable with mildly impaired simple auditory attention, while visual attention and visual working memory were severely impaired, as was her psychomotor processing speed. Executive dysfunction was noted with set-shifting, concept formation, and generation (see Table I pre-training neuropsychological test scores).

Pre-training she ambulated independently, but gait was uneven and slow. Her left hand had an abnormal posture, and she had a left visual field cut and diminished stereopsis. Occupational therapist evaluation showed a left shoulder 66% weaker than her right one and she hand an inability to exert force in grasping or in pinching with her left hand. Participant 2 UE function level was moderately impaired, with a Fugl-Meyer test score of 40. She reported having some difficulty in 19 of the 20 activities of the ADL questionnaire, of which she was unable to perform 9 tasks. The only task she could do with no difficulty was sleeping, and she rarely used her left arm.

C. Data collection instruments

We used an ABAA protocol, with data collected at pre-(A), post-(A), and 6-week follow-up (A) evaluation sessions and during each training session (B). Evaluation sessions primarily involved collection of clinical cognitive, emotive (by a neuropsychologist), UE motor impairment and functional measures (by a senior OT). Both clinicians were blinded as to the therapy methodology and scope. The neuropsychologist subsequently became a co-author of this study (JH).

The standardized measures used in the emotive/cognitive evaluations were the Beck Depression Inventory [20]; the Brief Visuo-spatial Memory Test, Revised [21]; the Hopkins Verbal Learning Test, Revised [22]; the Neuropsychological Assessment Battery Attention Module and the Categories and Generation subtests of the Executive Functioning Module [23]; and the Trail Making Test A and B [24]. Alternate test forms were used whenever possible to minimize test-taking practice effect. Subsequently a reliable change score (RC) was calculated to determine if meaningful changes had occurred.

For the motor retraining part of the study the impairment measures were the affected UE shoulder strength (measured with calibrated weights placed at the wrist), grasp strength measured with a mechanical Jamar dynamometer (repeatability of 2.6 and 3.1 pounds force [25]) and finger pinch strength measured with a mechanical pinch gauge. The motor retraining functional measures were the Jebsen test of hand function [26], the UE subset of the Fugl-Meyer (FM) test, and changes in activities of daily living (ADLs) self-reported on a standardized questionnaire. The reported reliability for Fugl-Meyer and Jebsen tests is 0.97 [27] and 0.95 [28], respectively. To improve ADL self-report accuracy, Participant 2 filled the form with her mother's assistance.

D. Computerized system

Participants sat against a custom square table with one corner cut out and low-friction top surface, and rested their affected forearm and hand on a custom low-friction support. The support had embedded electronics which allowed tracking of the arm movement on the table top, as well as grasp strength measurement. Grasp data was transmitted wirelessly to a PC running custom rehabilitation games rendered on a large monoscopic display. An overhead infrared (IR) camera imaged IR markers at the table corners and on the forearm

TABLE II. CHANGES IN UPPER EXTREMITY FUNCTION AND INDEPENDENCE IN ACTIVITIES OF DAILY LIVING OVER THE 6 WEEKS OF TRAINING AND AT 6-WEEK FOLLOW-UP.

	Participant 1			Participant 2		
Outcomes	**PRE**	**POST**	**FOLLOW UP**	**PRE**	**POST**	**FOLLOW UP**
Jebsen Test of Hand Function (seconds – less is better)						
Writing	44	32	58	180 (unable)	173	117
Simulated page turning	8	8	5	97	71	77
Lift small common objects	7	7	8	171	99	160
Simulated feeding	12	9	9	39	180 (unable)	180 (unable)
Stacking checkers	2	2	3	20	60	147
Lifting large, light objects	5	4	3	28	24	41
Lifting large, heavy objects	47	38	4	25	26	45
Total Time	125	100	90	380	453	587
Average task time	17.8	14.3	12.8	54.3	64.7	83.8
Percentage change	-	-25%	-28%	-	19%	54%
Fugl Meyer Test Score (66 is maximum)						
Upper extremity subset score	63	63	64	40	38	43
Activities of Daily Living (out of 20 standardized tasks)						
Unable to perform	1	0	0	9	6	1
Some difficulty	6	0	0	10	10	12
No difficulty	14	20	20	1	4	7

support. This determined arm position and orientation on the table, which allowed participants to play the games with their arm and hand. Gravity loading on the affected UE was controlled through the table tilt (see [29] for more details on the Rutgers Arm II system hardware).

At the start of every session the participants were baselined for affected arm reach and hand grasp strength. The arm reach depended on the angle the table was tilted that session. These data were used to adapt the games to each participant, such that, for example, a game momentary grasp condition was set to 25% of the measured grasp strength that day, and sustained grasp condition at 10%. These values were chosen to prevent arm pain and discomfort observed in earlier trials [30]. Sessions consisted of five custom games written in Java3D [31] of which *Pick-and-place*, *Breakout 3D* and. *Treasure Hunt* were previously described [30].

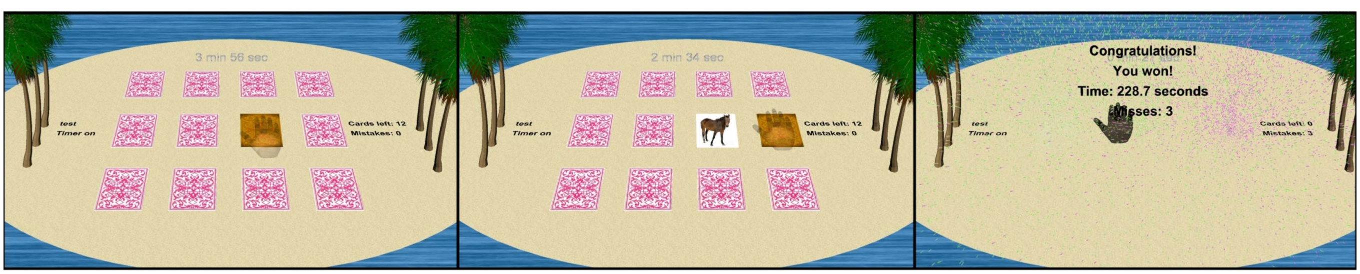
The *Card Island* game (Fig 1*a*) was aimed at training short term memory and visual memory as well as grasp coordination and shoulder strengthening. The game scene was a tropical island showing an array of playing cards arranged face down on the sand. The cards were positioned inside the area that corresponded to the arm reach baseline, such that the participant could turn cards face up by overlapping them with the hand avatar. In order to turn a virtual card face up and reveal its image the participant had to momentarily grasp on the forearm support deformable element. The cards were customized for each participant with images of pets, relatives, or other scenes of interest, so as to increase motivation. If two subsequent selections show the same image, the matched cards disappeared from the island, otherwise they turned face down again. Game difficulty was increased by adding more cards, which required more motor and grasp repetitions and increased cognitive effort for matching.

Tower of Hanoi is a classic logic and executive function game that asks players to stack disks of different diameters on one of 3 poles. The disks are initially on one pole, stacked in increasing size from top to bottom and the player has to re-stack the disks on another pole in the same order of sizes, while using the third pole as a way point. During the game the disks are selected and moved with a mouse on 2D screen, and acceptable moves are dictated by the condition that a smaller disk is never to be placed under a larger one. *Tower of Hanoi 3D* (Fig 1*b*) is our version of the well-known game just described. It presents a 3-D scene showing 3-D disks, 3-D poles and a hand avatar controlled by the participant's arm movement and grasping. The poles are placed inside the participant's arm reach area, and participants had to overlap a disk with the hand avatar, and then grasp to pick it up and subsequently place it precisely on a desired pole. The continuous grasp condition was set when training dual-tasking. In such setting the participant had to maintain gasp strength above a threshold, else the disk fell en route and had to be picked up again. Game difficulty was increased by adding more disks, which corresponded with a larger sequence of moves needed to restack the disks. Thus *Tower of Hanoi 3D* trained not only logic and executive function but also motor control, shoulder/grasp strengthening and dual-tasking.

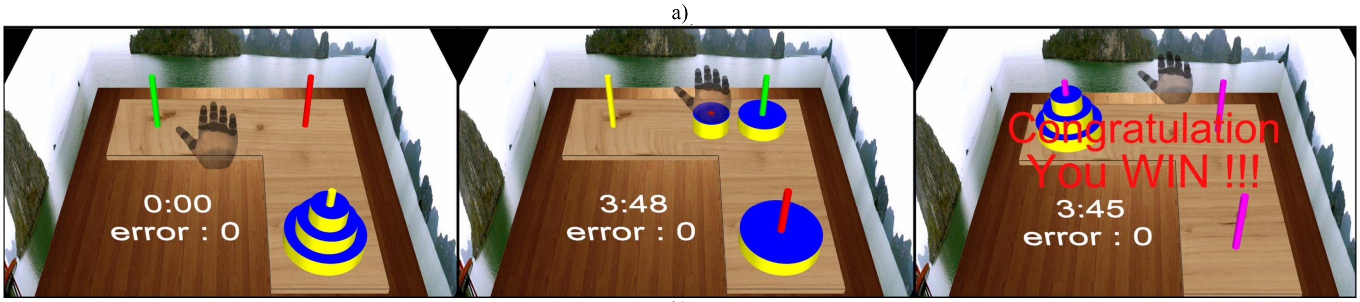
Each of the 5 games presented summative feedback, with variables dependent on the particular game. For *Card Island* and *Tower of Hanoi 3D* summative feedback was the number of errors the participant made, as well as the time taken to complete the game. Another form of performance feedback was rewards (fireworks and applause) at the completion of each game in which the participants did well. These rewards provided positive reinforcement and were designed to improve the participant's morale. The frequency of rewards was high since the games adapted to each participant's level of function, with a high probability of success in the game.

E. Experimental Protocol

The 18 therapy sessions progressed in duration from 40 minutes of actual play per session (week 1), to 50 minutes (week 2), to 1 hour (weeks 3 to 6). Motor retraining intensity was also increased by progressively higher table tilt, from 0° (horizontal table) in weeks 1-2, to 10° (week 3) and 20° (weeks 4 to 6). Each session consisted of a sequence of *Pick-*



a)



b)

Figure 1. Screen images: a) Card Island game relaxes the patient, trains short term visual memory, as well as shoulder abduction/adduction, shoulder flexion/extension and grasp strength; d) Tower of Hanoi 3D game trains executive function, as well as shoulder abduction/adduction, shoulder flexion/extension, motor control and grasp strength.

and-Place, then *Breakout 3D*, followed by *Treasure Hunt, Card Island* and *Tower of Hanoi 3D*. Depending on the session duration, the sequence was repeated as needed. Each exercise difficulty was progressed from easier games in weeks 1 to most difficult ones in week 6. Game difficulty depended not only on the table tilt and the grasp condition (no grasp required in week 1, momentary grasp required in weeks 2-4 and sustained grasp in weeks 5-6) but also on other game parameters. Difficulty was increased further by increasing the number of cards to be matched in *Card Island* and by adding more disks to be stacked in *Tower of Hanoi 3D* (2 disks – easy, 3 disks – medium, 4 disks – difficult).

III. OUTCOMES

The changes in the participants' emotive, cognitive and motor impairments following the experimental convergent virtual training are summarized in Table I. Table II shows the participants' upper extremity motor function and the degree of independence in activities of daily living following the therapy. The progression in subjective evaluation scores the participants gave the system over the 6 weeks of convergent therapy (3 subjective evaluation forms) is seen in Table III.

A. Participant 1

Pre-intervention Participant 1 had mild depression, with a Beck Depression Inventory (BDI – II) raw score of 14 and was on antidepressant medication. Post-training his BDI-II raw score dropped to 4, indicative of minimal depression. At that point Participant 1 made the decision to stop taking the anti-depressant medication, but without informing the researchers. At six weeks follow-up he did not have symptom reoccurrence, and his BDI-II raw score continued to improve to a 1. Participant 1 reported at follow-up that he had less frequent headaches. Neuro-cognitive evaluation showed remarkable gains in ability to focus, such that Participant 1's simple auditory attention improved from the moderately impaired range (NAB Digits Forward Form1, T = 30) pre-training to the low average range at post- (Form 2, T = 41) and average at follow-up (Form1, T = 48). After controlling for test-retest practice effects the above change is significant (2.0 Z score, $p > .05$). Participant 1 simple auditory working memory remained average, but he did have improved raw scores from pre-training (NAB Digits Backwards subtest, Form1, raw score = 4) to post-training (Form 2, raw score 6) and six week follow-up (Form 1, raw score = 6). His simple visual working memory (NAB Attention Module Letters and Numbers subtest Part B, Part C, and Part D efficiency) showed variable improvement. Most notably on Part D, which is a dual attention task, pre-treatment score was mildly impaired (Form1, T = 36), and improved to the low average range post- (Form 2, T = 41), and then to the average range at follow-up (Form1, T = 46). This was a positive change, although not significant (.92 Z-score improvement). While Participant 1's speed on a sustained attention task (NAB Attention Module, Letters and Numbers Part A [Speed]) remained severely impaired, his raw scores trended in the positive direction (Form1 pre- raw score = 421 seconds; post- Form 2 raw score = 374 seconds; follow-up Form1 raw score = 354 seconds). Participant 1's processing speed on the Trail Making Test A was low average pre- (raw score = 26 seconds, T = 42), improved to the average range post- (raw score = 25 seconds, T = 51) and remained average at follow-up (raw score = 20 seconds, T = 51). His visual memory improved from severely impaired pre-training (BVMT Form 1, Trials 1-3 = 15, T = 25) to average post- (Form 2, Trials 1-3 = 27, T = 51) and remained in the average range at follow-up (Form 3, Trials 1-3 = 26, T = 49). His performance on the Trail Making Test part B, began in the low average range pre-training (raw score = 73 seconds, T = 41), remained there at discharge (raw score = 64 seconds, T = 41) and declined to the mildly impaired range at six week follow-up (raw score = 96, T = 32). This decline in performance is in contrast to other executive functioning measures, which showed improvement. His word generation was mildly impaired pre-training on the NAB Generation subtest (Form1, raw score = 5, T = 35), but improved to low average post- (Form 2, raw score = 11, T = 43) and remained there at follow-up (Form1, raw score = 7, T = 40).

In the motor impairments domain Participant 1 showed statistically significant improvements as well. His affected shoulder strength anterior movement (flexion/extension) progressed from lifting 17 pounds at the wrist pre- to lifting 20 pounds at follow-up (18% gain). Lifting his affected arm laterally showed an increase in strength from 12 pounds force pre- to 16 pounds force post- (33% gain). His strength continued to improve to 17.5 pounds at follow up (a 46% gain from pre-training). His grasp strength went from 47 pounds pre- to 42.6 pounds post- (9% decline) and 45.5 pounds at follow up. The difference between post-training and follow-up grasp strengths may be due to test-retest artifacts of the Jamar dynamometer [25]. Participant 1 experienced slight increases of 1.5% and 3.5%, respectively between his pre-, post- and follow-up in key pinch strength (21, 21.33, to 21.67 pounds, respectively), but these are not clinically significant changes [32].

With respect to UE function, Participant 1 started with an almost normal Fugl-Meyer test score (63 out of 66). He maintained this score post- (63 points) and had a small increase at follow-up (64 points). Fugl-Meyer test has high reliability (0.97), but is has been reported that test-retest score differences of ±2 points could occur by chance [33]. Furthermore, statistical significance at 0.05 means that Fugl-Meyer score differences should be more than 3 points to be statistically significant. Thus Participant 1's increase from 63 to 64 out at the follow up evaluation is not statistically significant and could have been also due to test-retest artifacts. His main increase in function was determined by the timed Jebsen test of hand function (see Table II). For the writing, simulated page turning, lifting small common objects, simulated feeding, stacking checkers, lifting large light objects and lifting large heavy objects sub-tasks comprising the Jebsen test, Participant 1 was 25% faster overall post-training. At follow-up evaluation he showed further improvement in hand speed, being 28% faster overall, compared to pre-training. Participant 1 improved shoulder strength and hand function had benefitted his degree of independence in activities of daily living. On the standardized subjective questionnaire he reported pre-training having some degree of difficulty in 7 out of the 20 ADL activities. However, at post- and follow-up he reported having no difficulty with any of the 20 ADL tasks.

B. Participant 2

This participant had minimal/normal levels of depression pre-therapy (BDI-II = 5) and remained so at post- (BDI-II = 5) and six week follow-up (BDI-II = 3). Following the convergent therapy, her simple auditory attention improved from mildly impaired pre- (NAB Digits Forward Form 1, T = 36) to low average range post- (Form 2, T = 41) and then to the average range at follow-up (Form 1, T = 52). The change between pre- and follow up is significant (1.95 Z, $p > .10$). Her simple visual attention was severely impaired pre- (NAB Dots subset Form1, T = 23), improved to low average post- (Form 2, T = 41), but declined to moderately impaired at follow-up (Form1, T = 30). Her simple visual working memory (NAB Attention Module Letters and Numbers subtest Part B, Part C, and Part D) and visual attention (Driving Scene subtest of the NAB) were impaired from pre-training to follow-up. Participant 2's verbal and visual memory were severely impaired at the three testing intervals and marked by an encoding disturbance. Concept formation improved from mildly impaired pre- (NAB Categories subtest Form 1, T = 36), the average range post- (Form 2, T = 46) and remained there at six week follow-up (Form 1, T = 46).

In the motor impairment domain Participant 2 greatly benefitted in the strength of her affected upper extremity. She had a 100% increase in her shoulder flexion/extension anterior strength between pre-training (5 lb at the wrist) and post- (10 lb). At follow-up she lost some of these gains, but was still able to lift 8 lb at the wrist (60% gain compared to pre-training). When lifting her affected arm laterally, shoulder strength increased from 5 lb to 8 lb (60% gain) between pre- and post-training and continued to increase to 9 lb at follow-up (80% gain from pre-). Prior to therapy Participant 2 was unable to complete the grasp strength test, but she was able to apply 2 pounds of force on the dynamometer post-training (a clinically significant gain of 200%). She lost some of this gain at follow-up, when she was able to exert only 0.7 pounds force. Her key pinch strength gain from 3 lb pre- to 3.33 at follow-up (10% gain) was not clinically significant. Participant 2 did have a clinically significant increase of approximately 43% in her key pinch strength from 2.33 lbf post - to 3.33 lbf at follow-up.

In the UE function domain Participant 2 had a 3 point improvement in the Fugl-Meyer upper extremity score (from 40 pre- to 43 at follow up). As previously mentioned, the score difference of 2 on this test could occur by chance, but the 3 point increase between the pre-training and follow-up assessments is statistically significant. The Jebsen timed test results were mixed, with overall performance being slower by 19% at post- and slower still by 54% compared to pre- at follow-up. This is in contrast with the gains Participant 2 had in some of the sub-tasks. She had been unable to write with her affected hand pre-training, but was able to do so post-, and had improved her writing speed by 30% at follow-up. Page turning speed improved by 27% post-training, and was largely maintained at follow-up (21% faster than pre-training). In lifting small common objects Participant 2 had improved her speed substantially, being 70% faster post-. This gain had largely extinguished by follow-up when her lifting of small common objects was only 6% faster than pre-training. Overall Participant 2's motor gains benefitted her degree of independence in ADLs. As seen in Table II, while pre-training Participant 2 reported being unable to perform 9 tasks out of 20 listed on the standardized form, post- training she was not able to perform 6 tasks and at follow-up she was unable to perform only one task (driving). Pre-training the only task she had no difficulty performing was sleeping, post- she reported having no difficulty grooming her hair, dressing, sleeping and laundering clothes. At follow-up she reported continued improvement, having no difficulty lifting a bag of groceries at wrist level, grooming her hair, dressing, opening doors, cleaning and carrying a small suitcase.

IV. DISCUSSION

A. Training Results

The 2 participants started with different degrees of emotive, cognitive and motor impairments. They were however able to play the games with their affected UE, due to the experimental system ability to customize the intervention to each participant. This study results showed that it was feasible to play games even by the more impaired Case 2, and indeed proved beneficial for both participants to train on the Rutgers Arm II convergent therapy system. At follow-up 6 weeks after the end of therapy, both participants maintained their large gains in verbal attention, and one maintained large visual attention gains. This may be explained by the game interaction which involved fast graphics, something that trained primarily the visual cortex. The fact that Participant 2 had less gain in the visual attention, and lost it at follow-up may be explained by her left eye field cut and loss of stereopsis which may have diminished the amount of visual information she processed. Participant 1 had substantial gains in processing speed (from a low-average pre- to average follow-up), while Participant 2, who was cognitively more impaired, had no such gains. Both Participants had no gains in verbal memory, which may be explained by the training which emphasized visual, rather than auditory (verbal) memory. In fact Participant 1 substantially increased his visual learning and memory ability, progressing from severely impaired (<1 percentile pre-) to average (54 percentile post-), and maintained this gain at follow-up. Concept formation improved in both participants, with Participant 2 having the largest gains (from mildly impaired pre- to average post-training, and at follow-up). Other commonalities were observed on simple attention, which was significantly improved for both ($p > .05$ for Participant 1 and $p > .10$ for Participant 2). Participant 1 made remarkable improvement in free recall of visual information. Overall, there was a positive trend to improved neuro-cognitive functioning among the two chronic severe TBI patients, which warrants further investigation.

Both participants benefitted in their shoulder strength from convergent therapy, the gains being larger for Participant 2 who had a more impaired UE. She had been unable to grasp at pre-, but was able to do so post-therapy, a resultant of the grasp training provided by the games she played. She also had a clinically significant increase in key pinch strength between the end of therapy and the follow-up measure. Since there was no training on the experimental system during the 6 weeks following therapy, we hypothesize that the increased key pinch strength was due to more use of the affected hand in ADLs. Functional changes were observed in the time it took participants to complete the Jebsen test. Both participants had improved in some sub-tasks, with Participant 1 showing uniformly faster hand movement, and Participant 2 being faster in some tasks and slower in others. Since the therapy did not train finger dexterity, we hypothesize that the reduction in the time needed to perform the Jebsen test was due to a faster arm pre-positioning.

At the end of training sessions in weeks 5 and 6 Participant 2 was asked to briefly practice functional tasks, such as carrying a small suitcase, and to open the laboratory door with her affected arm. At the completion of the protocol she was encouraged to use her affected arm in ADLs, so not to lose gains she made during the experimental intervention. The self-reports on the standardized ADL questionnaire show that the six weeks of training were associated with improvements in ADLs independence for both participants. Participant 1 had been unable to throw a ball with his affected arm pre-training, when he also reported having moderate difficulty buttoning clothes and carrying a small suitcase, and having a little bit of difficulty in household tasks, using tools, opening a jar, or sleeping. Post-rehabilitation Participant 1 reported having no difficulty in any of these tasks. At follow-up he volunteered that he was now more confident holding the leash in his affected arm when walking his dog.

The larger gains in ADL independence were made by Participant 2. Based on her ADL questionnaire, pre-training she had quite a bit of difficulty lifting a bag of groceries at waist level and was unable to groom her hair, prepare food, tying laces on her shoes, or opening a jar. Post-training she was able to do these tasks, albeit with quite a bit of difficulty. At follow-up, however, she reported having no difficulty lifting a bag at waist level, and having only moderate difficulty preparing food. While pre-therapy she reported moderate difficulty dressing, post- she had no difficulty with this ADL, something maintained at follow-up. It is possible that while training on real tasks in her last 2 weeks of therapy Participant 2 became aware that she could do these tasks and had the confidence to continue using her arm after therapy ended.

B. Participants Acceptance of the Technology

Participants complied with the protocol and attended all 18 training sessions and the 3 evaluation sessions. They practiced the required amount of time (up to one hour of actual exercise/session) without complaining, or leaving the room. At the end of weeks 2, 4, and 6 participants filled a subjective rating questionnaire, with results summarized in Table III. Overall they gave the convergent therapy system a score of 4.45 out of 5, which is a good indication of acceptance. In 4 out of the 9 questions participants gave a maximum score, which was repeated at each rating interval. Participant 1, who was an avid computer game player, and had high motor function, regularly finished the therapy session ahead of time. Rather than leaving, he requested to play more, and was given additional games, within the prescribed session time. This participant was able to train in his last 1 hour-session with a 1 pound weight attached to his wrist and against a 20° table tilt for the full duration. This was a test to see if shoulder strength can be increased for high functioning patients by incorporating wrist weight training while playing games.

C. Changes in Participant's Well Being and Morale

Both participants had an improvement in their depression index, with Participant 1 having the largest gains. At follow-up this participant asked if the therapy was specifically targeted at combating depression. Interestingly, he had never discussed the subject of his depression until then. Despite not being on his anti-depression medication for six weeks,

TABLE III. SUBJECTIVE EVALUATION SCORES COMPLETED BY THE PARTICIPANTS OVER SIX WEEKS OF CONVERGENT REHABILITATION (1 IS THE LEAST DESIRABLE OUTCOME, AND 5 THE MOST DESIRABLE OUTCOME). THE LAST COLUMN REPRESENTS THE AVERAGE OF SCORES FOR A GIVEN QUESTION FOR BOTH PARTICIPANTS. © RUTGERS TELE-REHABILITATION INSTITUTE. REPRINTED BY PERMISSION.

Number	Questions	Participant 1			Participant 2			Question Avg. Score
		Week 2	Week 4	Week 6	Week 2	Week 4	Week 6	
1	The system was easy to use	3	5	5	3	3	3	3.67
2	The games were interesting	5	5	5	3	5	5	4.67
3	I had no muscle pain or discomfort	1	5	5	5	1	2	3.17
4	The instructions given to me were useful	5	5	5	5	5	5	5
5	I was not bored while exercising	1	4	5	4	5	5	4
6	The length of exercising in a day was appropriate	5	5	5	5	5	5	5
7	There were few technical problems	5	3	3	5	4	5	4.17
8	I would encourage another patient to use it	5	5	5	5	5	5	5
9	I liked the system overall	5	5	5	5	5	5	5
	Average score per participant	4.52			4.37			
	Average score for all participants	4.45						

Participant 1 depression index continued to improve, dropping from a 4 post-therapy to a 1 at follow-up. A phone interview with Participant 1's mother, conducted post-study, revealed that she thought her son seemed happy, more focused, more socially outgoing, and that he had told her the training had benefitted him. Participant 1's clinical psychologist, in a phone interview post-study, confirmed his client told him he believed the training had benefitted him and that his patient seemed happy with the results of the experimental training.

Participant 2 told the team at her follow-up examination that "I feel normal again!" and thanked us for the therapy provided. In a post-study phone interview Participant 2's mother stated she observed an improved focus in her daughter following the training on the experimental system.

V. CONCLUSIONS

The present paper introduced the concept of convergent emotive/cognitive/motor virtual reality therapy and tested its feasibility in two participants chronic post-severe TBI. The study contributes to the body of knowledge on the benefits of virtual reality to cognitive and motor re-training for those who are chronic post-TBI. Furthermore, the unitary method of delivery proposed here has implications for cost and therapist availability, and points to a new direction in integrative medicine based on unified computer training. The results of this feasibility study need to be replicated in a larger clinical study to gauge effectiveness of convergent therapy compared to standard of care for patients post-TBI. Furthermore, we plan on testing the convergent therapy described here on cognitively impaired patients who are chronic post-stroke.

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