Feasibility study of a new game-based bimanual integrative therapy

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***Abstract*—Therapeutic games motivate patients and intrinsically generate a large number of movement repetitions that is key to inducing brain plasticity and facilitating recovery. While virtual rehabilitation has gained clinical acceptance, bimanual therapy is less developed at this time. The novel RABBIT system combines physical and cognitive training via integrative game-play sessions. Using the Razer Hydra game interface, patients play a series of custom games designed to improve attention, decision making (executive function), short-term and long-term memory. These games progress in difficulty over 6 weeks of therapy. The system and its first feasibility study on patients who were chronic post-stroke are presented here.**

Keywords*—*therapeutic games; integrative therapy; bimanual rehabilitation; cognitive function; stroke.

I. INTRODUCTION

Post-stroke, traditional physical rehabilitation of the paretic arm involves passive movement, compensatory training on the other arm, electrical stimulation, and recently constraint induced therapy to combat learned non-use of the hemiplegic hand [1]. These are uni-manual training approaches which do not take into account the prevalence of activities of daily living (ADLs) which involve both arms.

Another drawback of uni-manual training is diminished neural cross talk to mirror motor areas associated with bimanual activities. A meta analysis of 48 stroke studies to determine the cumulative effect of bilateral arm training on motor capabilities post-stroke [2] found a significant effect post training involving bimanual repeated reach movements timed to auditory cues. Another argument in favour of bilateral training was provided by a randomised controlled study of stroke patients at the end of their outpatient therapy [3]. Researchers found, for the first time, that training the healthy arm (in a peg-board filling task) resulted in a 23% functional improvement in the *non-trained* paretic arm. Researchers also observed improvement in bilateral tasks performance in the experimental group.

There are indications that bimanual training induces higher functional improvements compared to uni-manual training. A randomized controlled study [4] was performed on patients chronic post-stroke, half doing bimanual training and the controls doing training of the affected arm, with some coping mechanism (assistance) from the other arm. While both groups had the same training duration and intensity, those doing bimanual training had a clinically-significant 9 points larger improvement in motor function (as measured by their Fugl Meyer Assessment [5] scores vs. controls. These studies point to untapped advantages of bimanual training and motivate the development of the system presented here.

Repetition, while necessary to induce recovery through brain plasticity, can lead to lack of engagement (attendance to task). Second only to the amount of practice, feedback on performance is a key element in motor training and a way to engage the patient. Knowledge of performance feedback can be provided by the therapist (present next to the patient), or through graphics in a virtual rehabilitation setting [6], where the therapist may be remote. Virtual rehabilitation benefits attention, motivation, and provides the intensive training beneficial for patients post-stroke (for a review see [7]). Recently VR was used in a randomized study of 36 nursing home residents to try to lessen cognitive decline and improve memory function [8]. The experimental group showed significant improvements in long-term recall and in several other aspects of cognition, while controls showed progressive decline.

Stroke survivors, as well as other patient populations present with both motor and cognitive deficits [9]. Typically their short term and long term memory are affected, as are decision making (executive function), and the ability to focus. A significant number of stroke patients also go on to develop depression [10]. Under the current fractionated care system, such patients are attended by therapists, as well as psychologists or psychiatrists, in separate sessions. This method is costly and does not exploit fully the mind-body continuum. The elderly form the majority of stroke survivors, and their situation worsens due to age-related cognitive decline [11].

One age-related cognitive deficit is the diminished ability for complex attention (or dual-tasking). These patients need a system designed from the start for integrative cognitive and motor therapy, in order to minimize costs and maximize outcomes. Such a system would use therapeutic games that pose both cognitive and whole arm motor demands. Furthermore, the system should train grasping in dual tasks and needs to automatically adapt to the patient's functioning

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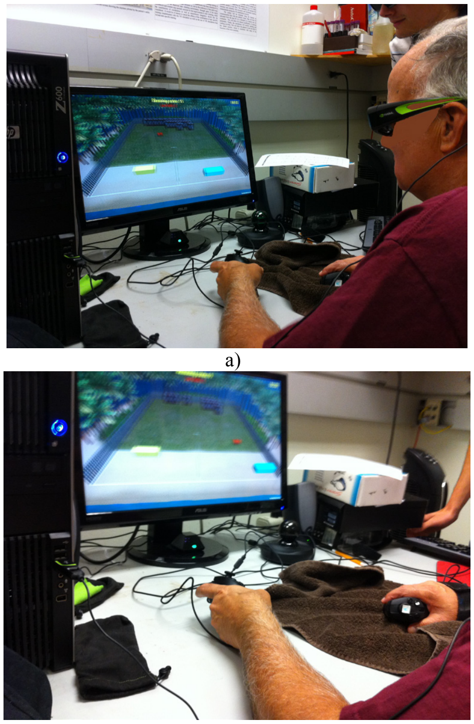
level. This adaptation makes games winnable so to improve morale (reduce depression). The above findings motivated the development of the Repetitive Bimanual Integrative Therapy (RABBIT) system described here.

II. THE RABBIT SYSTEM

A. System Hardware

The bimanual therapy system consists of off-the shelf gaming hardware and a library of custom therapeutic games written in Unity 3D Pro [12]. The games are rendered on an HP Z600 graphics workstation with an nVidia Quadro 2000 graphics accelerator. The graphics are in 3D, so to facilitate immersion and help the patients in their manual tasks. Therefore the workstation is connected to an Asus VG236H 3D monitor, and the patients wear nVidia “3D Vision” active stereo (3D) glasses.

The interaction with the games is mediated by the Razer Hydra bimanual interface [13] shown in Fig. 1. It consists of two hand-held pendants, each with a number of buttons and a trigger, and a stationary source connected to the workstation over an USB port. The source generates a magnetic field which allows the workstation to track the 3D position and orientation of each hand as relative movements. Of the many buttons on the pendants, the RABBIT system uses analog triggers so to detect the degree of flexion/extension of the patient’s index on each hand. The pressing of these analog triggers controls the closing/opening of hand avatars, while the position/orientation of the hand avatars is determined by the position/orientation of the corresponding Hydra pendants. The Hydra is calibrated at the start of each session by placing the two pendants next to the source. Its work envelope is sufficient to detect hand position for a patient exercising in sitting.


a)

b)

Figure. 1 The experimental system: a) System view; b) bimanual game interface detail.© Rutgers Tele-Rehabilitation Institute and Bright Cloud International Corp. Reprinted by permission.

Stroke patients in the acute stage (just after the cerebral infarct) have weak arms. Similarly, patients who are in the chronic phase may have low gravity bearing capability. Some of them also have spasticity (difficulty flexing/extending elbows or fingers). Thus using the Hydra with this population is different from use in normal play by healthy individuals. The adaptation in the present study was to place the weak arm on a table, and use a small towel under the forearm, so to minimize friction and facilitate arm movement. Furthermore, for spastic patients who may have difficulty holding the pendant in their spastic hand, the solution was to use Velcro strips to position the index finger properly over the pendant analog trigger.

B. Therapeutic Games

Several games were developed to be played either uni-manually or bimanually. This gives flexibility when the therapy focus is motor re-training (using uni-manual mode) or integrative motor and cognitive retraining (using bimanual mode). The requirement for developing a multi-game therapy stems from the need to address several cognitive areas (by targeted games), as well as to minimize boredom by alternating games.

1) Baselines. Each patient is different, each day. It is therefore necessary to establish baselines to determine the patient’s motor capabilities, and adapt the games accordingly. The system uses three baselines, two for arm range, and one for the index. As seen in Fig. 2*a*, the horizontal baseline asks thepatient to draw a circle on a table covered by a large sheet of paper. The software then fits a rectangle to the “circle” and this range is used to map the limited arm horizontal range to the full horizontal space of the game scene. The vertical baseline (Fig. 2*b*) is similar, except now the patient is asked to draw a circle on a virtual blackboard.

During bimanual play sessions each arm performs the baseline in sequence, and each arm has different gains to the virtual scene. Thus the movement of their respective hand avatars appears equal (and normal) in the virtual world, something designed to motivate the patient. A further reason to present exaggerated movement of the paretic arm when mapped to VR is the positive role image therapy has traditionally played. In other words, the patient is looking at the display, not at her hand, and believes what she sees.

The third baseline measures the range of movement of the index of each hand. Unlike the arm range baselines, done in sequence, the index baseline is done simultaneously for both hands. As seen in Fig. 2*c*, the patient sees two spheres that move vertically between target blocks, in proportion with the index movement on each pendant trigger. First the patient is instructed to flex, and the two balls move up a certain percentage of full range. Subsequently the patient is asked to

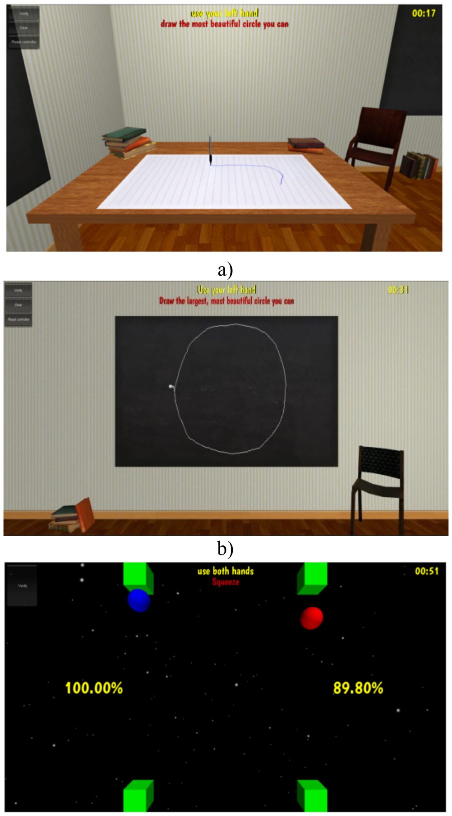


Figure. 2 Game baselines: a) horizontal reach; b) vertical reach; c) index flexing/extending. © Rutgers Tele-Rehabilitation Institute and Bright Cloud International Corp. Reprinted by permission.

extend the index of each hand and the balls move down, again a certain percentage of full range. For spastic patients the paretic index will have little difficulty flexing, but substantial difficulty extending. The resulting limited range for the paretic index, and full range of the non-paretic one are then mapped to the hand avatars. The two hand avatars will thus show full flexing and full extension during the games.

2) Games to train attention (focusing). Two games were developed to train patient's ability to focus. The *Kites* game presents two kites flying over water, while the sound of wind is heard (Fig. 3*a*). One kite is green, one red, and they have to be piloted through like-colored target circles. The circles alternate randomly in their color and their position on the screen, and the difficulty of the game is modulated by the speed of the circles, the duration of the game, the visibility (a foggy sky gives less time to react) and the presence of air turbulence (acting as a disturbance). The game calculates the percentage of targets entered vs. those available, and displays it at the end of the game as summative feedback on performance.

Scoring in the *Kites* game is as follows:

$$\text{Success }\% * s_{kite} * f_r * \left(\frac{100}{100-d_f}\right) * (1.2 \text{ if bimanual}) \qquad (1)$$

In this game, the success rate, given by the percentage of rings caught, is multiplied by the predefined parameters, kite speed (s_{kite}) and ring frequency (f_r = number of rings per unit time), as each parameter works to increase the difficulty of the game. The term in parentheses considers the fog density (d_f), applying a higher multiplier for denser fog. Since all parameters other than success rate are predefined at the start of the game, the final score is directly proportional to the number of rings hit. Finally, a 20% bonus is granted for bimanual mode so to account for increased difficulty that introduces new sources of error (hitting the ring with the wrong kite).

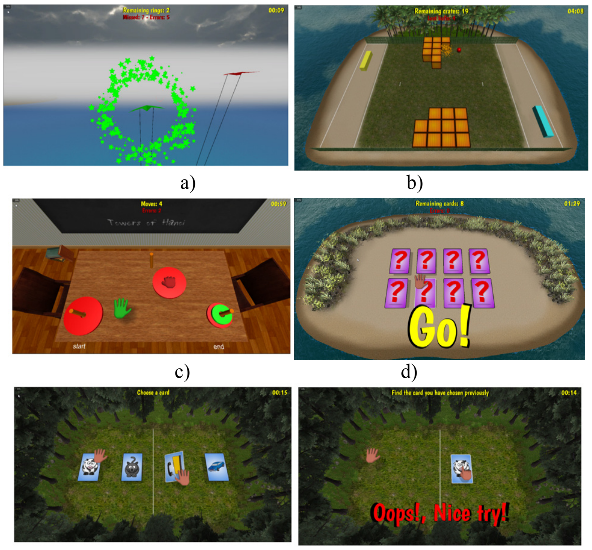


Figure. 3 Training to focus: a) *Kites* game; b) *Breakout 3D* bimanual game Training memory: c) *Towers of Hanoi 3D* bimanual game; d) *Card Island* game; e) and f) *Remember that Card* game. © Rutgers Tele-Rehabilitation Institute and Bright Cloud International Corp. Reprinted by permission.

The *Breakout 3D* game (Fig. 3*b*) is a bimanual adaptation of the game developed earlier by this group for uni-manual training on the Rutgers Arm II system [14]. The scene depicts an island with an array of crates placed in a forest clearing. Two paddle avatars of different color, each controlled by one of the patient's hands are located on each side of the crates. The patient needs to bounce a ball with either paddle, so to keep it in play, and attempt to destroy all the crates. The sound of waves is added to help the patient relax. The difficulty of the game is modulated by the speed of the ball, the size of the paddles, and the number of crates to be destroyed in the allowed time. The score for *Breakout 3D* is given by:

$$\text{crates hit} * \left(\frac{v_{ball}}{l_{paddle}}\right) * \left(\frac{1}{\log(\text{lost balls}+2)}\right) \qquad (2)$$

The number of points awarded for each destroyed crate is dependent not only on the preset parameters Ball_speed (v_{ball}) and Paddle_length (l_{paddle}), but also on the number of lost balls. Since the logarithm is an increasing function, there is always a penalty for losing balls. Yet, as more balls are lost, the penalty increases at a progressively slower rate, enabling players of lesser skill to achieve better scores. The number 2 is added to prevent divide-by-zero issues (in case no balls are lost).

3) Game to train executive function. The *Towers of Hanoi 3D* games (Fig. 3*c*) is similar to the version of the game being played with a mouse online. The patient has to restack a pile of disks of different diameters, from one pole to another, using a third pole as way-point. The game trains problem solving by setting the condition that no disk can be placed on top of a smaller diameter one. This condition in turn establishes an ideal sequece which minimizes the number of moves needed to restack all disks.

In the version of the game for bimanual therapy, the scene shows two hand avatars, one green and one red, as well as red and green disks. Each hand avatar is allowed to manipulate only disks of like color. The game chooses randomly the green or the red color for the smallest disk and allocates the other color to the other disks. In this configuration, both hands are doing approximately the same number of moves. The difficulty of the game depends on the number of disks to be stacked (2- easy, 3- medium, 4- difficult). The number of moves is counted and compared to the ideal (smallest) number of moves to complete the task. The score is:

$$\frac{150 * disks * (1.2 \text{ if } bimanual)}{\log\left(moves - pow(2, disks) + 3\right) * \log(Playtime)} \tag{3}$$

If a participant was unable to complete the game, we assigned a flat score of 100, so to maintain patient motivation. In this game, each disk is worth 150 points, with 20% increase in bimanual play mode to account for the increased difficulty and newly introduced sources of error. This number is countered by a product of logarithms (for leniency): the first compares the number of moves made by the participant against the optimal solution, and the second factors in the time taken to solve the puzzle.

4) Games to train short term memory and delayed recall. The first memory game is *Card Island* (Fig. 3*d*), again a bimanual version of the game previously used in uni-manual training on the Rutgers Arm II system. The patients are presented with an island and an array of cards placed face down on the sand. The array is divided symmetrically by a central barrier, such that each hand avatar has to stay on its half of the island. When a hand avatar overlaps a card, the patient can turn it face up by squeezing the trigger. The task is to find matching pairs. Since non-matching cards turn face down again, the patient has to remember where a given card was seen before, training short term visual memory. The game difficulty is proportional with the number of cards in the array, and the allowed completion time. *Card Island* is scored by:

$$\left(Correct\ matches - \frac{Errors}{2}\right) * \left(\frac{Deck\ Size}{\log(Playtime)}\right) \tag{4}$$

An incorrect match deducts points equal to half of a correctly matched pair. This allows players a second chance to correct their mistake. If the mistake is repeated a second time, the score for eventually hitting the correct match is nullified, and deducted from the total score. Lenience is granted towards slower players as exhibited by the logarithm of their playtime measured in seconds. At the same time, this leniency is also depending on the starting deck size. Lastly, no performance bonus is given for bimanual play mode, as the difficulty of this game lies in the participant's short-term memory abilities.

Remember that card (Fig.3*e,f*) game trains long-term visual and auditory memory. It consists of two parts, separated by a number of other games. In the first part the patient is presented with a number of cards placed face down. Each card needs to be turned face up, at which time a sound in played. This sound is associated with the image on the card (example is the card depicts a phone booth, then a ring tone will be played). After all cards have been explored, the patient selects one, by flexing the hand avatar over that card, and is prompted with "Remember that card" text. After a number of other games are played, the second game scene appears, with the cards previously explored, this time face up. The patient is asked to choose the card she had selected before. If the attempt is unsuccessful, the "Ops, nice try!" text appears, otherwise the patient is congratulated for remembering the card correctly. The difficulty of the game is modulated by number of available choices and number of other games interposed between the two parts of the game. The score is:

$$\frac{50 * Number\ of\ Cards}{\log(Recall\ time + 2)} \tag{5}$$

Being our simplest game, we scale the score linearly with the number of cards while being more lenient on the time taken to recall and choose the correct card. The recall time is the time taken by the patient to pick their previously selected card among those shown, measured in seconds. For any given number of cards in this formula, a player who takes less time to choose the correct card will always receive a higher score than a slower player. However, the slower player will not see a larger gap in scores, regardless of how long they take to remember the original card. Again, we add 2 (measured in seconds) to the recall time in order to prevent divide-by-zero errors.

III. FEASIBILITY EVALUATION

A pilot feasibility evaluation was undertaken in order to ascertain RABBIT ease of use and acceptance, as well as its utility for clinical benefits in the cognitive and emotive domains. The study was approved by Rutgers University Institutional Review Board and took place in Summer/Fall 2012 in the Tele-Rehabilitation Institute.

A. Participants

Participants were recruited from among the members of the stroke support group at the JFK-Johnson Rehabilitation Institute and at the Institute for Adults Living with Communication Disabilities at Kean University. Three participants were consented and started the study. However one participant was subsequently removed from the study due to hospitalization. The other two participants completed the training.

1) Participant 1 was a 64 years old male stroke survivor with right side hemi-paresis. He had sustained a left side ischemic stroke 45 months prior and had limited use of his affected arm due to spasticity. The participant had expressive aphasia, and was familiar with virtual reality as he participated in an earlier trial on the Rutgers Arm II system [15]. He was wheelchair bound and was assisted by his spouse.

2) Participant 2 was a 55 years old female stroke survivor with left side hemi-paresis. She had sustained a right side ischemic stroke 67 months prior and a subsequent aneurism. Participant 2 had very limited use of her left arm due to spasticity, and ambulated with a cane. She had a left sided hemianopsia (visual field loss), which was partially corrected with prism glasses. Participant 2 speech was not affected by her stroke.

B. Data Collection Instruments

The study 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 involved collection of clinical cognitive and emotive measures, and were performed by a neuropsychologist who was blinded to the therapy methodology. He subsequently became a co-author of this study (JH). No measures were taken for motor involvement and function due to the focus of this first feasibility study on the cognitive and emotive domains.

The standardized measures used were the Beck Depression Inventory (BDI) [16]; the Brief Visuospatial Memory Test, Revised (BVMT-R) [17]; the Hopkins Verbal Learning Test, Revised (HVLT-R) [18]; the Neuropsychological Assessment Battery (NAB)[19] Attention Module and the Categories and Generation subtests of the Executive Functioning Module; and the Trail Making Test A and B (TMT-A & TMT-B) [20]. Alternate test forms were used whenever possible to minimize test-taking practice effect.

Technology acceptance was evaluated based on non-standardized subjective evaluation questionnaires which participants had to fill at the end of every other therapy week (three data points per participant). Participant 1 filled the subjective evaluation form with his spouse's assistance.

C. Intervention

The experimental protocol consisted of six weeks of training, three times per week, with sessions progressing in duration from 30 minutes (week 1), to 40 minutes (week 2), to 50 minutes (week 3), to 1 hour (weeks 4 to 6).

Apart from the increased duration, there was a qualitative change between the first two weeks where patients played with the non-affected arm only, and the subsequent month were they had to use both arms. The initial uni-manual play sessions were aimed at familiarizing the patient to the game requirements, the Hydra interface (tracking and buttons) and viewing the scene in 3D (stereo). During the following 4 weeks, one Hydra pendant was attached to the affected arm with Velcro strips and participants were allowed to support their spastic arm on the table on top of a small towel. This way the movement of the affected arm was not affected by gravity and the patients could better focus on the therapeutic games. No occupational therapist was present to assist, however technical staff set the game sequencing and occasional rest periods.

Each session consisted of a sequence of games, depending of the week of training. In week 1, after baseline, participants played *Kites*, then *Breakout 3D*, followed by *Card Island, Remember That Card (part 1), Tower of Hanoi 3D, Remember that Card (part 2), Card Island* and *Breakout 3D*. In subsequent weeks more games were repeated to provide the necessary duration of training, and their difficulty increased, For example *Kites* became faster, and turbulence and fog were added. In *Breakout 3D* the balls became faster and the paddles shorter, in *Card Island* there were more cards to pair and in *Towers of Hanoi 3D* more disks to stack. Finally for the *Remember That Card* game, the number of card choices gradually increased, as was the time interval before the participant needed to recall the initial choice.

Dual-tasking is problematic with older populations (whether stroke survivors or not). Thus some of the games had embedded dual-tasking features, notably *Breakout 3D*. When the dual-tasking parameter is set, the paddle avatar characteristics depend on whether the trigger is squeezed or not. When a momentary squeeze is required, the patient has to squeeze the trigger at the moment of bounce, lest the ball passes through the paddle. When a sustained squeezing is required, the movement of the paddle is decoupled from that of the pendant if the trigger is not pressed. Thus the patient has to remember to keep squeezing to move the paddle to bounce the ball. Recognizing that sustained squeezing may be fatiguing and induce discomfort for some patients, the game sets a threshold as a % of range when classifying an index flexion as a squeeze.

D. Outcomes

Outcomes reported here refer to the cognitive and emotive domains, game performance progression (in terms of scores) and technology acceptance (in terms of subjective evaluation scores).

1) Cognitive and emotive outcomes. The feasibility study cognitive and emotive outcomes are summarized in Table I below.

<u>Participant 1</u> pre-intervention had mild depression, as indicated by the Beck Depression Inventory, Second Edition (BDI-II raw score = 17). Post-training his depressive symptoms dropped into the minimal/normal range (raw score = 7). A little while after the end of therapy he had had some family discord resulting in significant depressive symptom emerging at six week follow-up (raw score = 39). The participant's simple auditory attention as measured by the NAB Digits Forward subtest was severely impaired pre-intervention (T-score = 19, < 1st percentile) and remained so at the end of therapy (T-score = 19) and at six week follow-up (T-score = 19). His simple auditory working memory, as

measured by the NAB Digits Backwards subtest, remained severely impaired at pre, post, and six week follow-up testing (T-score = 19). Of note, auditory attention was verbally mediated and his low score likely reflected his expressive aphasia. The participant's visual attention/working memory as measured by the NAB Dots subtest showed a notable improvement (1.7 standard deviation improvement) from low average at pre-treatment (T-score = 41) to high average at six week follow-up (T-score = 58). At the end of therapy his performance was largely consistent with pre-intervention (T-score = 44). His psychomotor processing speed was severely impaired at pre-intervention (T-score = 12), but improved notably (1.9 standard deviations) and into the mildly impaired at the end of therapy (T-score = 31). His overall performance improved a total of 3.2 standard deviations, into the average range, at six week follow-up (T-score = 44). Participant's verbal learning and memory, as measured by the Hopkins Verbal Learning Test-Revised (HVLT-R), remained consistently impaired secondary encoding disturbances at pre-intervention, end of therapy and at six week follow-up (T-score < 20th percentile). Visual learning and memory on the Brief Visuospatial Memory Test-Revised (BVMT-R) was similarly impaired at all three testing intervals secondary to retrieval disturbances. His performance on the Trail Making Test part B, a measure of set-shifting, began in the severely impaired range at pre-treatment (TMT-B, T-score = 8), but improved significantly (2 standard deviations) at the end of therapy, even though his qualitative score was still in the severely impaired range (T-score = 28). However, at six week follow-up his performance again returned to pre-intervention levels (T-score = 10). Participant's verbal fluency as measured by the Word Generation subtest of the NAB Executive Functioning Module was severely impaired at pre-intervention (T-score = 23), severely impaired at discharge (T-score = 19), and mildly impaired at six week follow-up (T-score = 31). His concept formation as measured by the Categories subtest of the NAB Executive Functioning Module was severely impaired pre-intervention (T-score = 27), moderately impaired post-intervention (T-score = 30), and mildly impaired at six week follow-up (T = 35).

Participant 2 endorsed moderate depression on the Beck Depression Scale, Second Edition (BDI-II = 24) pre-intervention and remained within the same range at the end of treatment (BDI-II = 25) and at six week follow-up (BDI-II = 24). The participant's simple auditory attention as measured by the NAB Digits Forward subtest was average pre-intervention (T-score = 44), high average at the end of therapy (T-score = 58), and back to average at six week follow-up. From pre-intervention to end of therapy her performance improved 1.4 standard deviations, which trends towards clinical significance. The participant's visual attention/working memory, as measured by the NAB Dots subtest, was average at pre-intervention (T-score = 45), declined into the moderately impaired range at the end of therapy (T-score = 29) and improved into the low average range at six week follow-up (T-score = 40). Participant's psychomotor processing speed was mildly impaired at pre-intervention (T-score = 36), but improved into the low average range at the end of therapy (T-score = 41), and remained so at six week follow-up (T-score = 41). Her verbal learning and memory, as measured by the Hopkins Verbal Learning Test-Revised (HVLT-R), was average at pre-intervention (HVLT-R: Trials 1-3 = 29, T-score = 54), average at the end of therapy (HVLT-R: Trials 1-3 = 26, T-score = 46), and again average at six week follow-up (HVLT-R: Trials, 1-3 = 30, T-score = 56). Her performance generally remained consistent across all three testing intervals.

TABLE I. CHANGES IN EMOTIVE, AND COGNITIVE IMPAIRMENTS IN TWO PARTICIPANTS CHRONIC POST-STROKE OVER THE 6 WEEKS OF TRAINING AND AT 6-WEEK FOLLOW-UP.© RUTGERS TELE-REHABILITATION INSTITUTE AND BRIGHT CLOUD INTERNATIONAL CORP. REPRINTED BY PERMISSION.

Outcomes	**Participant 1**			**Participant 2**		
	PRE	***POST***	***FOLLOW UP***	***PRE***	***POST***	***FOLLOW UP***
Emotive Outcomes						
Depression Index	Mild (17)	Minimal (7)	Severe (39)	Moderate (24)	Moderate (25)	Moderate (24)
Cognitive Outcomes						
Verbal Attention (digits forward)	Severely Impaired T=19	Severely Impaired T=19	Severely Impaired T=19	Average T=44	High Average T=58	Average T=48
Visual Attention (Dots)	Low Average T=41	Average T=44	High Average T=58	Average T=45	Moderately Impaired T=29	Low Average T=40
Visuospatial Memory (Trials 1-3)	Severely Impaired T<20	Severely Impaired T<20	Severely Impaired T<20	Average T=54	Average T=46	Average T=56
Delayed Recall (BVMT)	Moderately Impaired T=30	Moderately Impaired T=30	Severely Impaired T=25	Mildly Impaired T=32	Low Average T=37	Low Average T=41
Set shifting (Trial Marking Test-B)	Severely impaired T=8 >300s	Severely impaired T=28 104 s	Severely impaired T=10 >300s	Mildly Impaired T=34 128s	Average T=47 87s	Average T=47 83s
Concept Formation (NAB Categories)	Severely Impaired T=27	Moderately Impaired T=30	Mildly Impaired T=35	Average T=47	Average T=55	Average T=46

Visual learning and memory, as measured by the Brief Visuospatial Memory Test-Revised (BVMT-R), was mild/moderately impaired at pre-intervention, at the end of therapy, and at six week follow-up (BVMT-R: Trials 1-3 = 13, T-score = 31). Of note, her delayed recall improved from moderately impaired at pre-intervention (T-score = 30) to mildly impaired at the end of therapy (T-score = 32) and eventually low average at six week follow-up (T-score = 41). She showed a total of 1.1 standard deviation improvement across testing intervals. Participant's performance on the Trail Making Test part B was mildly impaired at pre-intervention (T-score = 34), average at the end of therapy (T-score = 47), and average at six week follow-up (T-score = 47). She showed an overall 1.3 standard deviation improvement across testing intervals. Her verbal fluency was average pre-intervention (T-score = 47), average post- therapy (T-score = 50), and average at six week follow-up (T-score = 46). Her concept formation as measured by the Categories subtest of the NAB Executive Functioning Module was average pre-intervention (T-score = 47), average post- therapy (T-score = 55), and average at follow-up (T-score = 47).

2) Game performance outcomes. Performance was gauged in terms of game scores, as a global variable encompassing the various conditions that were changed from week to week. Participants gradually exhibited improvement in game play (Fig. 4). In fact in *Breakout 3D* Participant 2 played a perfect game in her last session, despite having a severe field cut interfering with clear view of the highly interactive scene.

In *Card Island*, during session 11, Participant 2 completed the game unusually quickly (2x faster than normal), despite having to pair the highest number of cards (16). Similarly, in the *Kites* game, Participant 2 performed extremely well on Session 12, missing only two rings in a high-speed, dense-fog game.

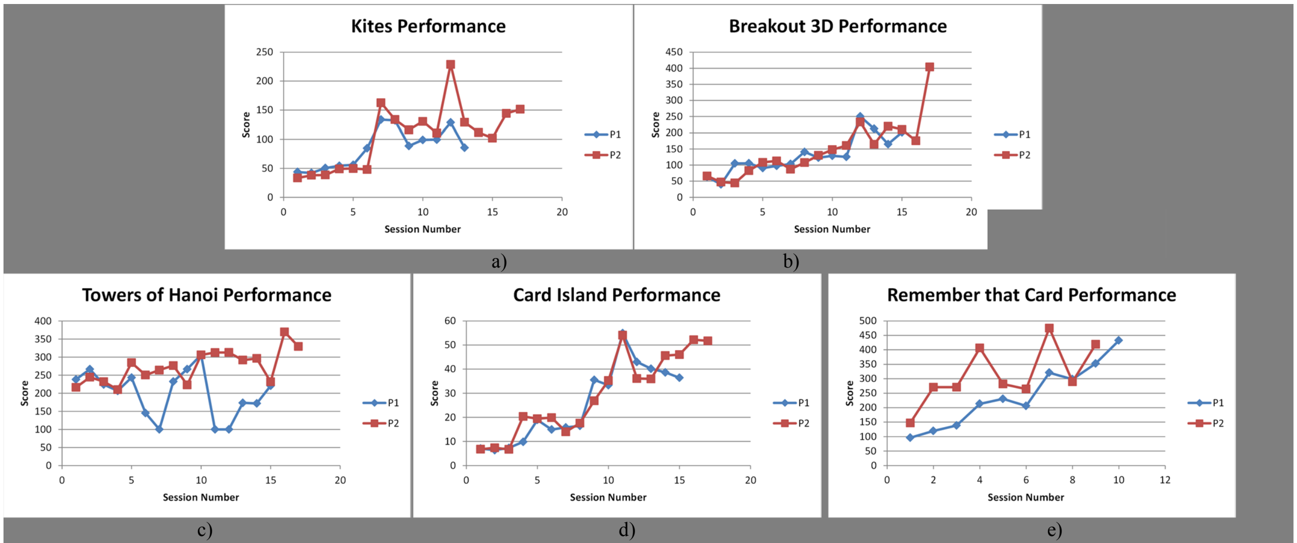
However, there where sessions where performance did not follow the general positive trend. For *Delayed Recall*, session 8, Participant 2 took an unusually long time to recall the card (from a usual 1-2 seconds to 9 seconds). In *Towers of Hanoi 3D*, Participant 1 had a number of sessions where he was unable to solve the puzzle (in particular, session 7 and session 11). These are the times when the number of disks switched from 2 to 3 and from 3 to 4. Subsequently, however, his performance increased, which explains the up-down-up shape of his performance curve in that game.

3) Technology acceptance. Participants provided their subjective evaluation of the system by answering nine questions: 1) *The bimanual system was easy to use*; 2) *The games were interesting*; 3) *I had no headaches*; 4) *Playing with both hands was easy*; 5) *I was not bored while exercising*; 6) *3D (stereo) graphics was useful when playing the games*; 7) *There were few technical problems*; 8) *I would encourage another patient to use it*; 9) *I liked the system overall*. Each question was scored on a 5-point Likert scale, with 1 the least desirable outcome and 5 the most desirable one. Overall the participants rated the system with a 4.36 score, with the highest score (4.83) given to question 8, *I would encourage another patient to use it*. The lowest score (4) was in answer to question 3, *I had no headaches.*

IV. DISCUSSION

The particular neuropsychological measures used in this study were selected based on their respective ability to elicit functioning of a given domain (i.e., Digit Span for auditory attention, Dots for visual working memory, etc.). These measures are routinely employed in neuropsychological practice for formal evaluations to aid in diagnostic clarity, as well as for treatment planning. The aim of the present study was to compare established domain specific measures (e.g., attention, memory, executive functioning, etc.) with the RABBIT system to determine functional outcome following the treatment protocol.

The results of neuropsychological testing of attention,



a) b)

c) d) e)

Figure. 4. Participants game scores: a) *Kites* game (trains atention); b) *Breakout 3D* game (trains dual-tasking); c) *Towers of Hanoi 3D* game (trains executive function); d) *Card Island* game (trains short term memory); e) *Remember That Card* game (trains delayed recall). © Rutgers Tele-Rehabilitation Institute and Bright Cloud International Corp. Reprinted by permission.

processing speed, memory and executive functioning suggest some trends towards functional improvement of different neurocognitive domains following completion of the RABBIT therapy. In general, trends for improved set-shifting are observed across the two participants. Individually, there seem to be improvement for distinct neurocognitive domains that could represent additional trends that may become more apparent following a large scale implementation of the RABBIT system. Of note, Participant 1, who had a left hemispheric stroke, had significant improvement in processing speed from pre-intervention to the end of therapy (1.9 standard deviations), which continued to improve at six week follow-up (total of 3.2 standard deviations). He also had a 1.7 standard deviation improvement in visual attention/working memory at six week follow-up. Participant 2, who had a right hemispheric stroke, had a 1.4 standard deviation improvement in simple auditory attention from pre-intervention to end of therapy, as well as a 0.9 standard deviation improvement in delayed recall of visual memory from pre-intervention to six week follow-up. Overall, the improvement trends suggest greater efficiency within the frontal lobe structures, which are known to contribute to attention, information processing speed, memory retrieval, set-shifting and concept formation, and were the primary targets of the RABBIT system. These improvements occurred on participants who had initial cerebral injury on opposite hemispheres. These findings are consistent with evidence based research [21, 22] supporting neuro-rehabilitation of stroke and traumatic brain injury patients to improve attention, executive functioning and problem solving.

Practical limitations of the current study are rooted in its extremely small sample size. While trends towards improvement are seen for both individuals it is difficult to extrapolate their true meaning until similar interventions are applied to a larger cohort. Future research should aim to enroll a larger participant sample as well as establish a control condition to determine real change following treatment. Furthermore, in the future we will analyze the transferences of the benefits achieved with the training to performance of activities of daily living.

REFERENCES

[1] C.Y. Wu, L.L. Chuang, K.C. Lin, H.C. Chen and P.K. Tsay, Randomized trial of distributed constraint-induced therapy versus bilateral arm training for the rehabilitation of upper-limb motor control and function after stroke. Neurorehab Neural Re, Vol 25, 2, pp. 130–139, 2011.

[2] J.H. Cauraugh, N. Lodha, S.K. Naik and J.J. Summers, Bilateral movement training and stroke motor recovery progress: a structured review and meta-analysis. Hum Movement Sci, Vol 29, 5, pp. 853–870, 2010.

[3] C. Ausenda and M. Carnovali, Transfer of motor skill learning from the healthy hand to the paretic hand in stroke patients: a randomized controlled trial. Eur J Phys Rehabil Med.,Vol. 47, 3, pp. 417–425, 2011.

[4] K. Lin, Y. Chen, C. Chen, C.Y. Wu and Y.F. Chang, The effects of bilateral arm training on motor control and functional performance in chronic stroke: arandomized controlled study, NeurorehabNeural Re,Vol 24; pp. 42-51, 2010.

[5] P.W. Duncan, M. Probst, and S.G. Nelson, Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident. Phys Ther, Vol 63, pp. 1606–1610, 1983.

[6] G. Burdea, Virtual rehabilitation-benefits and challenges. J Meth Inform Med,pp. 519–523, 2003.

[7] K. Laver, S. George, S. Thomas, J.E. Deutsch, M. Crotty, Cochrane review: virtual reality for stroke rehabilitation. Eur J Phys Rehabil Med, Vol. 48, 3, pp. 523-530, 2012.

[8] G. Optale, C. Urgesi, V. Busato, S. Marin, L. Piron et al., Controlling memory impairment in elderly adults using virtual reality memory training: a randomized controlled pilot study. Neurorehab Neural Re, Vol 24, 4, pp. 348–357, 2010.

[9] C. Brooks, B. Gabella, R. Hoffman, D. Sosin, and G. Whiteneck, Traumatic brain injury: designing and implementing a population-based follow-up system. Arch Phys Med Rehab, 78, pp. S26–S30, 1997.

[10] F. Göthe, D. Enache, L.O. Wahlund, B. Winblad, M. Crisby et al., Cerebrovascular diseases and depression: epidemiology, mechanisms and treatment. Panminerva Med, Vol 54, 3, pp.161–170, 2012.

[11] M. Wang, N.J. Gamo, Y. Yang, L.E. Jin, X.J. Wang, et al., Neuronal basis of age-related working memory decline, Nature, Vol 476, pp. 210-213, July, 2011.

[12] Unity Technologies, Reference Manual. San Francisco, CA., 2010.

[13] Sixense Entertainment, Razer Hydra Master Guide, 11 pp., 2011.

[14] G. Burdea, D. Cioi, J. Martin, D. Fensterheim and M. Holenski,The Rutgers Arm II rehabilitation system – a feasibility study, IEEE Trans Neural Sys Rehab Eng, Vol 18, 5, pp. 505–514, 2010.

[15] G. Burdea, D.Cioi, J. Martin, B. Rabin, A. Kale, et al., Motor retraining in virtual reality: afeasibility study for upper-extremity rehabilitation in individuals with chronic stroke, J. Phys Ther Educ.,Vol 25, 1, pp. 20–29, 2011.

[16] A.T. Beck, R.A. Steer, and G.K. Brown, Manual for Beck Depression Inventory II.TX: Psychology Corp., 1996.

[17] R.H.B. Benedict, Brief Visuospatial Memory Test—Revised. Psychological Assessment Resources, 1997.

[18] J. Brandt and R.H.B. Benedict, Hopkins Verbal Learning Test—Revised. Professional manual. Lutz, FL: Psychological Assessment Resources, Inc., 2001.

[19] R.A. Stern and T. White,Neuropsychological Assessment Battery. Lutz, FL: Psychological Assessment Resources, Inc., 2003.

[20] R.M. Reitan, Validity of the Trail Making test as an indicator of organic brain damage. Percept Motor Skill, Vol 8, pp. 271–276, 1958.

[21] K.D. Cicerone, C. Dahlberg, K. Kalmar, D.M. Langenbahn, J.F., Malec, et al., Evidence-based cognitive rehabilitation: Recommendations for clinical practice. Arch Phys Med Rehab, Vol. 81(12), pp. 1596-1615, 2000.

[22] K.D. Cicerone, D.M. Langenbahn, C. Braden, J.F. Malec, K. Kalmar, et al., Evidence-based cognitive rehabilitation: Updated review of the literature from 2003 through 2008. Arch Phys Med Rehab, 91(4), pp. 519-530, 2005.