Concurrent Virtual Rehabilitation of Service Members Post-Acquired Brain Injury – A Randomized Clinical Study

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ABSTRACT

The study objective was to determine the feasibility of concurrent training with the BrightBrainer Rehabilitation System while providing improved clinical efficiency and patient access to care in a military clinical setting. The participants trained 6 weeks on a number of custom, adaptable, therapeutic games. An occupational therapist supervised the one-on-one and concurrent (one-on-two) treatment interventions. Training consisted of using a uni-manual play in the first week, followed by bimanual interaction (involving higher cognitive load), and the addition of wrist weights in weeks 2-6. Initial study findings demonstrated that with continued practice, participants were able to increase the intensity of play (repetitions/minute), and improve their performance on a subset of memory and attention games. Furthermore, proof of concept was established to demonstrate concurrent training in nearly half of the training sessions recorded. There was no reduction in training intensity or game performance when training concurrently.

1. INTRODUCTION

Concurrent therapy in rehabilitation is a term used in billing services for situations when one therapist trains two patients at the same time (Center for Medicare Services, 2017). Concurrent *virtual* rehabilitation describes a scenario when the two patients are immersed in virtual environments of a therapeutic nature. Concurrent training represents a newer area of virtual rehabilitation, currently under investigation.

It is intuitive that concurrent virtual rehabilitation, if successful, presents clear advantages that supplement those of virtual rehabilitation itself (Burdea, 2003). One of these additional benefits stems from increased access to care in instances where the available therapists cannot meet caseload demand. Another is a reduction in care costs (mainly personnel). Finally, increased socialization through games is facilitated when both patients share the same virtual environment.

On the flip side, management needs to ensure that quality of care is not diminished when two (side-by-side) patients are overseen by a single therapist. The patients' compatibility and level of assistance needed are important elements when determining who can be trained concurrently. Just as important is the willingness of the independent therapist to have a higher physical and cognitive demand when training two patients at the same time.

In a scenario when two individuals (whether patient and therapist, patient and healthy relative, or patient and patient) interact simultaneously with a therapeutic virtual environment, three possible settings occur: a) competitive play (the two patients play against each other); b) cooperative play (the two patients help each other); and c) individual play (each of two collocated patients plays individually against their computer). A recent study compared the intensity and motivation of competitive vs. cooperative games used in arm rehabilitation (Goršič et al., 2017). Researchers found that both types of game play were motivating, however the intensity of play was (as expected) higher in competitive play.

The present paper details aspects of a recently completed randomized clinical study on integrative virtual rehabilitation conducted at a large military medical center in the US. The study targeted service members post traumatic brain injury (TBI) and/or acquired brain injury (ABI)/stroke. The participants received training on the BrightBrainer Virtual Rehabilitation System (Burdea et. al., 2015), in which a portion of the therapy was completed concurrently. The particular form of concurrent training was individual interaction with similar virtual environments rendered on systems placed side-by-side. The software used had been designed for input from a single user, thus competitive or collaborative concurrent training was not feasible. This paper focuses on computer game performance, training intensity (which are non-standardised outcomes), as well as therapist's impressions. This is part of a larger study which measured clinical outcomes based on standardised evaluations, with results presented elsewhere (Buccellato et al., 2018b).

2. METHODS

2.1 The BrightBrainer Rehabilitation System

The BrightBrainer Rehabilitation System is an integrative training platform, in which both cognitive and motor impairments of a patient are trained simultaneously using therapeutic games.

Participants' interaction with the therapeutic games was mediated by a pair of game controllers with the magnetic base station placed in front of the computer (Figure 1). Two systems were placed on a non-metallic table to minimize tracking interference caused by Eddy currents occurring in nearby metallic objects. Each participant used digital wireless headphones to prevent game sounds from being masked by ambient clinic noise. A partition board was placed between the two BrightBrainer systems, so to help focusing during concurrent face-to-face, but individual play. The system used in this study is the precursor to BrightBrainer BBX, a class I medical device currently marketed by Bright Cloud International (www.BrightBrainer.com).

A library of 11 custom therapeutic games created by Bright Cloud International in Unity 3D (Unity Technologies, 2017) was used to interactively train the participants. Upper extremity training was first done uni-manually, then both arms were used for higher level of exercise. These games were *Breakout 3D*, *Card Island*, *Kite*, *Tower of Hanoi*, *Pick & Place*, *Treasure Hunt*, *Submarine Rescue*, *Arm Slalom*, *Xylophone*, *Avalanche* and *Musical Drums*.

Each game involved manipulation of avatars in 3D, as well as index finger flexion/extension, when performing certain tasks. Avatar manipulation was done through arm movements in 3D space, while index flexion/extension was used to pick up virtual objects or to activate avatar properties (as detailed below). Games targeted both the cognitive

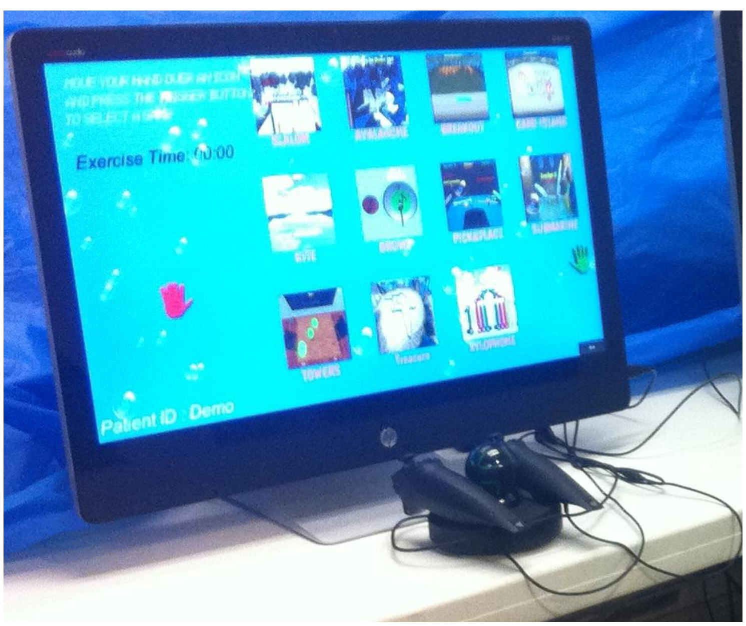

Figure 1. *The BrightBrainer Rehabilitation System in a Military Outpatient Occupational Therapy Clinic. © Bright Cloud International. Reprinted by permission.*

(short term memory, focusing, executive functions, reading comprehension) and motor (control, endurance, and strength of the arms, shoulders, core and finger flexion) domains. Each game adapted to the participant at every session, though a process of arm reach and index finger range baselines. Furthermore, games had settings to accommodate participants who could not use their index to press the controller button so to grasp virtual objects or to trigger avatar properties. In those instances object selection was based on a 2-second hover time above that object. For example, in the *Card Island* game, once a hand avatar had hovered 2 seconds above a card, it would flip face up to reveal its image. Furthermore, each game had between 10 and 16 levels of difficulty, ensuring good variability so to combat boredom and keep participants challenged. The resulting participants' motivation was evidenced by their subjective evaluation of the system, desire to continue playing at the completion of the 6-week training protocol, as well as therapist's observations. Games induced a large number of movement repetitions and contributed to shoulder and core strengthening when wrist weights were added.

The use of bimanual interaction increased cognitive load as well as blood flow to the upper body. Cognitive training (which was the primary goal for the study population) was enhanced through task sequencing (arms taking turns doing a task), and dual tasking (attention was split between a purely motor task and a simultaneous more cognitively demanding task (McIsaac and Benjapalakorn, 2015). Bimanual interaction was also important to increase focus and concentration which are problematic areas for individuals post-TBI. For example, in the *Breakout 3D* game (Burdea et al. 2013) (Figure 2*a*) participants were asked to bounce a ball between paddle avatars and an array of crates placed on an island. The goal was to destroy all the crates and win the game. The difficulty of this game related to ball speed (progressively faster), paddle size (progressively shorter) and number of crates to destroy (progressively more). Tasks sequencing meant each arm took turns bouncing the ball, while dual-tasking (used at higher levels of difficulty) meant that the participant had to remember to press the controller trigger precisely at the moment of bounce, lest the ball passed right though the paddle and became lost.

Submarine Rescue (Figure 2*b*) (Burdea et al., 2015) was a game that primarily trained executive function, namely arithmetic problem solving. The scene depicted the inside of a damaged submarine with water gushing in and an array of numbered crates. The participant needed to lighten the submarine, by removing crates one-at-a-time and placing them in an exit port for flushing. The current and next shallower depths were displayed, and the correct crate to remove was the solution of a subtraction equation between the two depths. Thus the participant needed to perform the subtraction sequence until the submarine surfaced. At higher levels of difficulty the volume of water gushing in was so large as to cover the numbered crates. In that scenario the participant had to use the other arm to pump water out, something that trained split attention. A video showing some of these games being played can be found online.

a) b)

Figure 2. *Therapeutic games used in BrightBrainer training in a military OT clinic: a) Breakout 3D (Burdea et al., 2013); b) Submarine rescue (Burdea et al., 2015). © Bright Cloud International. Reprinted by permission.*

An automatic session report was developed so to capture participant ID code, level of supervision required by the OT (one-on-one or two at once), playing modality (uni-manual or bimanual), wrist weights size (when used), games played, their difficulty levels and scores. Additionally, the session report provided counts of arm repetitions and finger flexion for each arm, total session time, total exercise time and total training time for each cognitive domain. Other variables reported were game scores, training intensity (number of repetitions/minute), error rates, blood pressure and pulse, as well as therapist notes. The session report provided graphing to store arm and finger range baselines, as well as compare multiple sessions to objectively gauge participant's progress.

2.2 Training Protocol

The study had two arms, with an experimental group receiving customary care plus six weeks of BrightBrainer training. The wait-list control group had three weeks of customary care before start of the experimental therapy (Murphy et. al. 2017). Each week of experimental training had three sessions of virtual rehabilitation (Figure 3).

Over the 6 weeks of experimental training the play duration was to increase from 30 minutes/session in week 1, to 40 minutes of actual play in every session of the last 4 weeks of training. The protocol stipulated that concurrent sessions provide a total of 480 minutes of actual training for each of two participants, while being supervised by one clinical or research staff. Two sessions were considered concurrent if there were at least 10 minutes of overlap out of the total session duration.

In order to determine if concurrent virtual rehabilitation was possible with the BrightBrainer system, participants were to be paired based on scheduling availability, as well as functional levels. No two severely impaired participants were to be paired for concurrent training. The participants were to be assisted by an occupational therapist one-on-one during the first two weeks (a total of 6 sessions). Subsequently, two collocated participants, were to train independently on two BrightBrainer systems under the supervision of a single therapist for four weeks (12 sessions).

Session game composition similarly were to increase, from 6 different games in the first week to 11 games in the last week of therapy. In other words every week introduced a new game, so to maintain participant interest and engagement. The game difficulty was also to progress from "easy" to "demanding," such that no two weeks of training were the same. Additionally, wrist weights were to be used for core, shoulder and arm strengthening, incrementally increasing, from 0.5 lb in week 2, to 3 lb in weeks 5 and 6.

2.3 Subject Characteristics

The study inclusion criteria were: military health care beneficiaries 18-67 years of age, presence of TBI or ABI/stroke that occurred at least six weeks prior to participation, good or corrected vision and hearing, ability to comprehend the consenting process, to understand instructions and the English language. Due to the adaptable and integrative nature of BrightBrainer therapy, upper extremity dysfunction (limited or decreased coordination, increased tone, decreased strength, or decreased sensation) did not constitute reasons for exclusion.

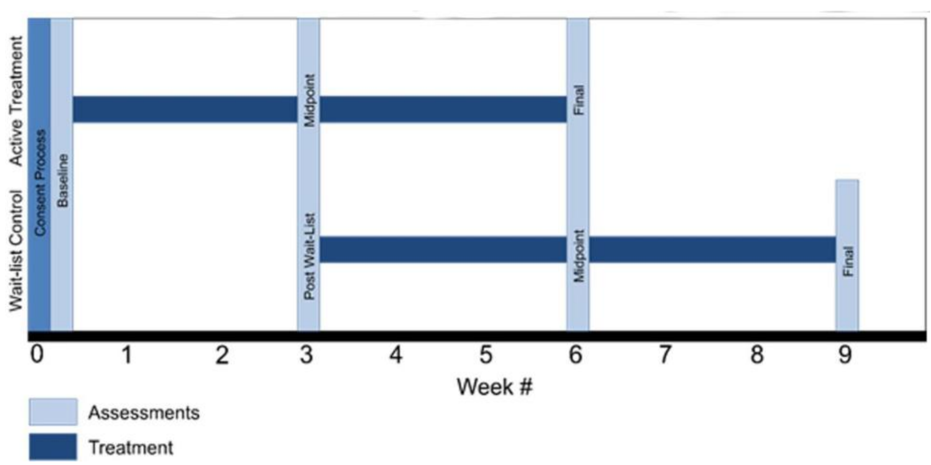

Figure 3. *Therapeutic protocol of the randomized controlled study (Murphy et al. 2017).*

Participants who were younger than 18 or older than 67, or were blind or deaf were excluded. Inability to comprehend the consent procedure, active psychosis, suicidal or homicidal thoughts, violence, drug addiction, alcoholism or inability to minimally operate the game controllers constituted reasons for exclusion.

Subsequent to approval from the Walter Reed National Military Medical Center IRB, 26 participants were consented. Of these 21 completed the study and one subject withdrew from the study due to scheduled surgery. Two subjects were unable to fit three sessions a week into their schedule, and thus dropped out. One subject was lost to follow up after not attending scheduled sessions. One other subject started training, but left the study early due to sensitivity to light and migraines after treatment sessions. Their incomplete data were not used in the outcome analysis.

Of the 21 (active treatment [AT]=11, waitlist control [WLC]=10) participants who completed the study, 13 were post TBI (AT=7, WLC=6), 4 were post ABI/stroke (AT=2, WLC=2) and 4 had both TBI and ABI/stroke (AT=2, WLC=2). The gender distribution was 15 males and 6 females, with an average age of 41 years (STD=12.31 years). The 21 subjects averaged 15.5 years (SD=2.2 school years) of formal education.

2.4 Data Collection Instruments

Participant and therapist acceptance of the technology was measured with the USE standardized questionnaire (Lund, 2001), as well as custom subjective assessment questionnaires. These custom questionnaires consisted of 10 questions, each rated on a 7-point Likert scale (Joshi et al., 2015).

Non-standardized measures were sampled transparently by the BrightBrainer system. These data included counts of arm repetitions and index finger flexion/extension for each arm and hand, total session time, total exercise time (session time minus rest periods and set up time) and total training time for each targeted cognitive domain. Other variables measured were game scores, training intensity (number of repetitions/minute), game performance, game composition, game difficulty levels and how many times each game was played in a given session.

3. RESULTS

The first participant started training in June 2016, and the last one completed the BrightBrainer therapy in December 2017. Over the 6 weeks of integrative virtual rehabilitation participants played on average a total of 382 games, lasting an average total of 349 minutes. The average length of most games was under 1 minute, except for *Kites* which lasted on average 2 minutes and *Breakout 3D* which lasted 2-5 minutes, depending on participant's skill and game difficulty level.

3.1 Game-induced repetitions

The participants exerted an average total of 27,551 arm repetitions (summing both arms), with session averages progressing over the 6 weeks of therapy based in part on session duration (Fig. 4*a*). Game characteristics as well as how many times a game was played in a session also played a role. For example repetitions induced by *Card Island* game were less than half those for *Breakout 3D* (Fig. 4*b,c*) which lasted longer and had two versions. Participants had an average total of 10,072 index finger flexion/extensions across the study. This finger repetition average number was adjusted based on 19 subjects, since two participants' motor impairment prevented them from using their index in game play.

Since participants were to train concurrently 12 sessions (3 sessions/week for 4 weeks) and there were 10 pairs of participants, there were to be 120 instances of concurrent training. Post-hoc database analysis compared game time stamps for the two systems in order to determine overlap. Concurrent sessions were considered those with time overlap of at least 10 minutes (out of 40 minutes of play), under the supervision of a single therapist. This analysis revealed that only 57 such concurrent sessions occurred.

3.1 Training Intensity progression

Game play "intensity" was computed as the frequency of arm or index finger use - that is, intensity was the number of repetitions divided by the corresponding session duration (in minutes). The session-average intensity was computed in terms of the median and interquartile interval (IQI) of each session among all of the participants. Each session's point estimate and IQI correspond to the distribution of intensity for that session, irrespective of whether any game was played in solo or concurrent sessions. The increase in session intensity in terms of arm repetitions is seen in the left panel of Figure 5, with the linear ordinary least squares (OLS) estimate of longitudinal improvement of 1.2 points per session ($p<0.001$), represented by the dashed line. A similar progression for index finger flexion/extension

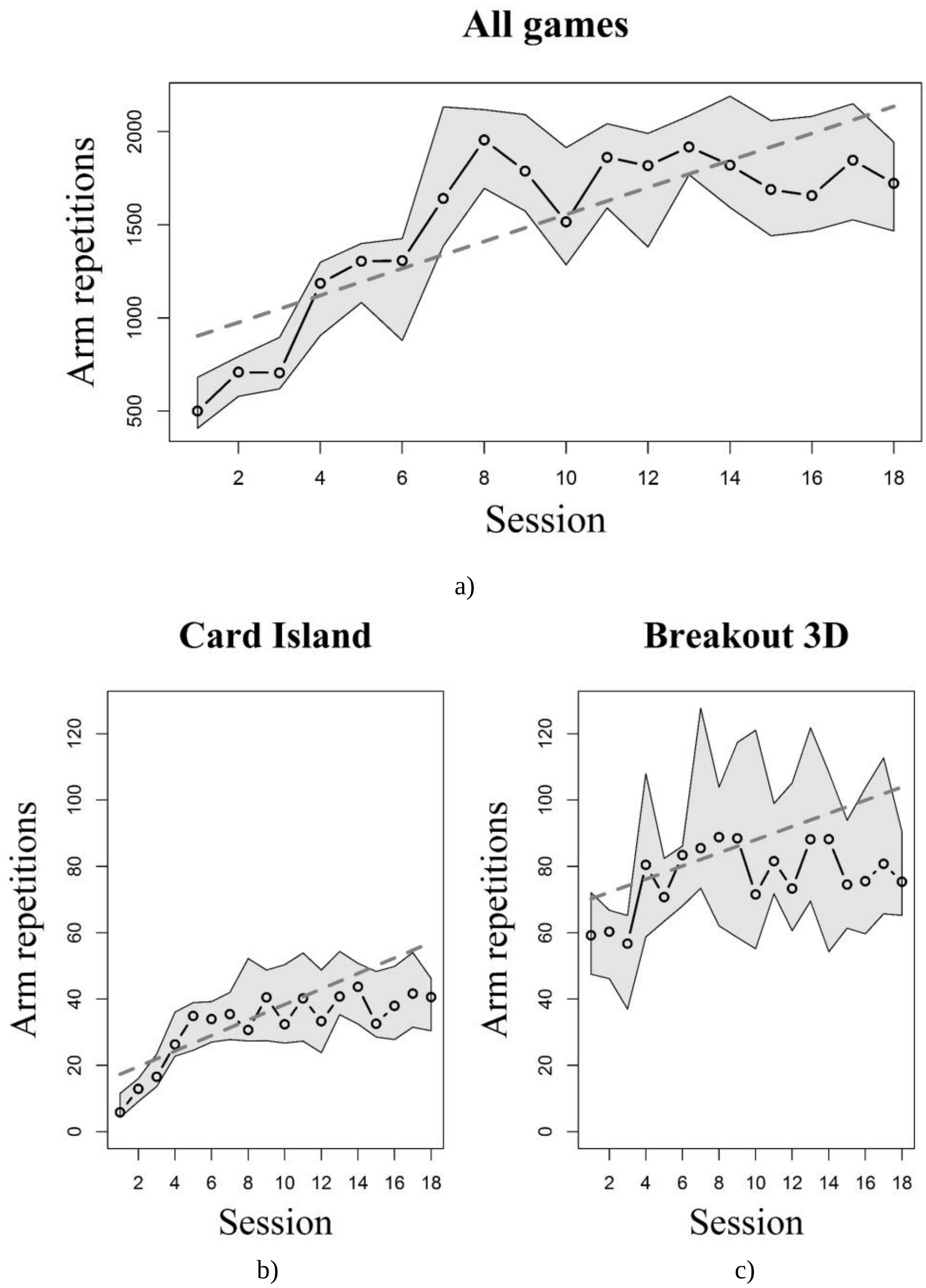

Figure 4. *Combined groups average arm repetitions over 6 week intervention: a) arm repetitions for all games in a session; b)* Card Island *group average arm repetitions; c) group average arm repetitions when playing* Breakout 3D. *© Bright Cloud International. Reprinted by permission.*

repetitions is featured in the right panel of Figure 5, with the linear OLS estimate of longitudinal improvement of 0.73 points per session ($p<0.001$). There was an increase in variance of intensity scores across sessions for the arm, as well as for the index finger: Breusch-Pagan test of heteroskedasticity p-values of 0.008 and < 0.001, respectively. This is indicative of the participants varying skills as well as less uniformity in their ability to sustain intensive play at higher levels of game difficulty.

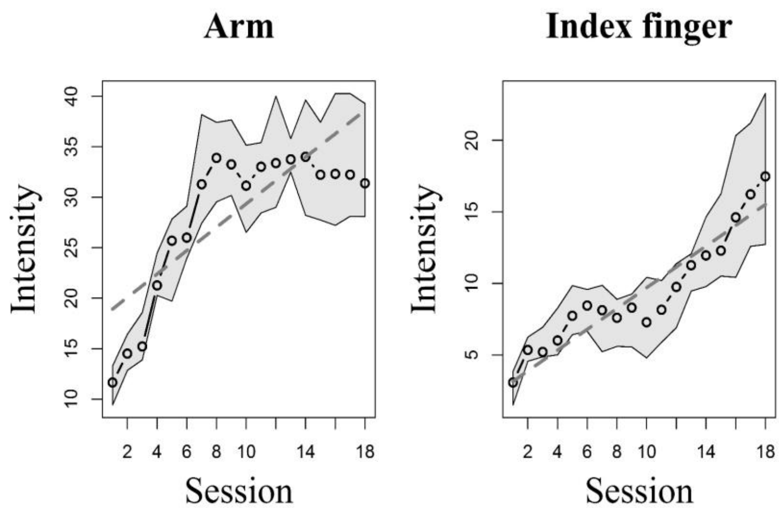

Figure 5. *Longitudinal change in intensity of therapeutic games of BrightBrainer training; the session-average median efficiency score is represented by the connected dots, and the shaded region represents the corresponding interquartile intervals; the dashed line represents the linear ordinary least squares estimate of the longitudinal change. © Bright Cloud International. Reprinted by permission.*

3.2 Game performance progression

Game play performance was computed as the average of game scores for all games played in a given session. As stated in the Methods section, the number of different games available for play increased steadily from 6 in week 1 to 11 in week 6. In order to have consistency in game performance analysis, it was necessary to select games played on all sessions. This means that selection was obtained from the 6 games introduced in week 1.

A further constraint for game analysis related to the patient population being enrolled in the study. Patients post mild, or moderate TBI are affected primarily in the cognitive domains of focusing and memory (Key at al., 1993). As such. From among the games that started in week 1, this paper considers *Card Island* (training short term visual and auditory memory) and *Breakout 3D* (training focusing). Their longitudinal change in game performance over six weeks of therapy is shown in Figure 6.

The session-average game performance was computed in terms of the median and interquartile interval (IQI) of each session among all of the participants. The linear ordinary least squares (OLS) estimate of longitudinal improvement in performance for *Card Island* was 1.3 points per session ($p<0.001$), while that of *Breakout 3D* was 13.3 points per session ($p<0.001$). Moreover, we observed an increase in variance of performance scores across sessions for the *Breakout 3D* game (Breusch-Pagan test of heteroskedasticity p-value < 0.001), but not for *Card Island* (Breusch-Pagan test of heteroskedasticity p-value of 0.971). This may be due to the difference between game characteristics (with *Breakout 3D* emphasizing speed of response, while the emphasis in *Card Island* was short-term visual/auditory memory). The frequency of change in game difficulty was lower for *Card Island*, which may also reflect the flattening of the performance curve in later sessions.

3.3 Therapist impression of BrightBrainer concurrent sessions

The OT who trained the majority of participants (a co-author of this paper) believed that the games used in the training sessions were both classic and intuitive in nature. It was easy to complete the activities unless there was a metal object or an active Blue Tooth emitter anywhere near the game controllers (a known issue with Hydra controllers). Learning to recognize common errors based on how the avatar moved on the screen took time. The therapist's confidence to problem solve technical challenges, while simultaneously engaging the participant in a positive and productive treatment sessions independently, also improved over time. There were very few treatment sessions which required rescheduling due to technical challenges.

When performing concurrent sessions it was critical to utilize a 10 to 15 minute staggered participant schedule. This time allowed for daily baseline, configuration of the controllers (required approximately 5 minutes),

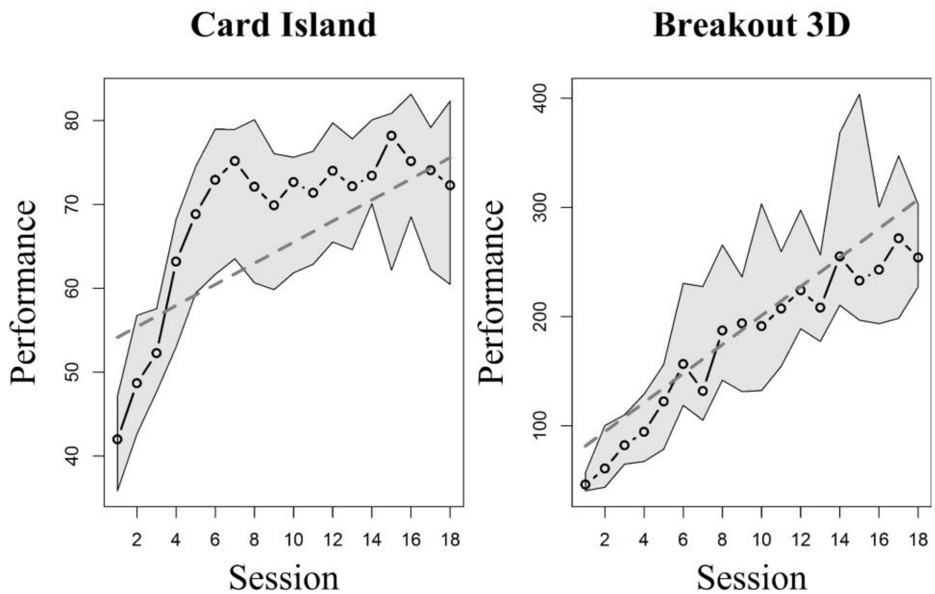

Figure 6. *Longitudinal change in performance of therapeutic games during BrightBrainer training; the session-average median game performance is represented by the connected dots, and the shaded region represents the corresponding interquartile intervals; the dashed line represents the linear ordinary least squares estimate of longitudinal change. © Bright Cloud International. Reprinted by permission.*

education on new games (2 minutes) and the opportunity for the participant to demonstrate understanding of a new game (2 minutes). This gap also ensured time to answer any questions, problem solve any technical issues (with the computer or therapeutic games), and created a time cushion for participants who were possibly running late.

If both participants were high functioning (physically and cognitively) there was very little for the therapist to do and running a concurrent session was feasible. When the participant required continuous redirection, cues, physical assists or modifications to reduce glare, the ability to provide quality care for more than one participant at a time became very challenging. However, having an assistant available to manage the technical challenges ensured the sessions were successful.

Recruitment, patient schedules, and medical issues were a continuous challenge when attempting to book two participants concurrently. A few of the participants barely tolerated a 30 minute session due to light and screen sensitivity. Even though they performed the entire session, the training session likely did not count as concurrent because they did not spend 10 minutes or more in the active play mode simultaneously with another participant for that training session. This is one reason why the number of sessions considered to satisfy concurrency was smaller than the theoretical number based on protocol.

The participants' and therapist's evaluation of the technology usability and perceived clinical benefit as evidenced by their subjective evaluations was very favourable (72-85%). (Buccellato et al., 2018a).

4. DISCUSSION

Looking at the graphs in Figure 5 it seems that concurrent training did not affect the game play intensity. While available study data is limited (in part due to the relatively small number of participants) as well as occasional technology issues, the intensity of play seemed to continue increasing during concurrent sessions. More studies, and more accurate tracking data will (in the future) allow for more definite analysis of concurrent virtual rehabilitation.

Another aspect that warrants discussion is the influence of the number of difficulty levels on the game performance graphs. Looking at Figure 6, the reader observes that group game performance when playing *Card Island* seemed to plateau about mid-way through the therapy. By contrast, group performance in the *Breakout 3D* had a steady increase over the length on training. There were more levels of difficulty in *Breakout 3D* game (due - for example, to progressively faster speeds the ball traveled, progressively smaller paddles, and dual tasking condition of remembering to squeeze the game controller trigger before ball bounce at higher levels of difficulty). This compared to the levels of difficulty for *Card Island* which depended on number of cards to be paired (2 pairs, 4 pairs, 6 pairs, and 8 pairs) as well as the progressive removal of cognitive cues (such as different color of the question mark on the back of cards already seen). If participants achieved the highest level of difficulty early in their training, it was only through making fewer errors and having shorter game completion times that they could achieve higher game performance.

This study examined the benefits of VR training on the BrightBrainer system, as well as ability to integrate the system in a military outpatient clinic settings. It is likely that some neural rewiring occurred owing to the large number of arm repetitions needed for game play, and the bimanual nature of play. Figure 4a graph shows an average 900 repetitions for each arm (about 1,800 total) in the last 3 weeks of the virtual rehabilitation. This is *28 times more* than the 32 repetitions observed in customary UE rehabilitation for stroke populations (Lang et al., 2009). However, in the absence of brain imaging it is not possible to confirm the authors' hypothesis that there were neural paths changes in the present study participants.

Some of the challenges mentioned by the training OT stem from the limitations of magnetic tracking used by the Hydra game controllers. In the two years that passed since the study had started, the tracking technology has evolved substantially. The modern BrightBrainer BBX system uses the HTC VIVE game controllers (HTC 2016). The VIVE does not use magnetic fields, thus it is impervious to interference from metal objects in the vicinity, or to the presence of other magnetic field sources nearby. Other advantages of the new tracking technology are much more precise tracking and wireless tracking. The elimination of the cables used by the Hydra controllers means that today a more natural and unencumbered arm movement is possible.

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