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Project Star Catcher: A Novel Immersive Virtual Reality Experience for Upper Limb Rehabilitation

AVIV ELOR, MIRCEA TEODORESCU, and SRI KURNIAWAN, University of California, Santa Cruz, USA

Modern immersive virtual reality experiences have the unique potential to motivate patients undergoing physical therapy for performing intensive repetitive task-based treatment and can be utilized to collect real-time user data to track adherence and compliance rates. This article reports the design and evaluation of an immersive virtual reality game using the HTC Vive for upper limb rehabilitation, titled "Project Star Catcher" (PSC), aimed at users with hemiparesis. The game mechanics were adapted from modified Constraint Induced Therapy (mCIT), an established therapy method where users are asked to use the weaker arm by physically binding the stronger arm. Our adaptation changes the physical to psychological binding by providing various types of immersive stimulation to influence the use of the weaker arm. PSC was evaluated by users with combined developmental and physical impairments as well as stroke survivors. The results suggest that we were successful in providing a motivating experience for performing mCIT as well as a cost-effective solution for real-time data capture during therapy. We conclude the article with a set of considerations for immersive virtual reality therapy game design.

CCS Concepts: • **Human-centered computing → Accessibility design and evaluation methods**; **User studies**;

Additional Key Words and Phrases: Virtual reality, serious games, therapy, rehabilitation, stroke, constraint-induced therapy, disability, HTC Vive

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1 INTRODUCTION

Long-term intensive and expensive physical therapy is often necessary for patients with orthopedic, neuromuscular, cardiovascular, pediatric, oncological, and other conditions. There is significant need for cost-effective yet efficacious treatments to address such conditions (Carter and Rizzo 2007). In 2014, Medicare spent $7 billions on inpatient rehabilitation therapy (which includes

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physical therapy) for 339,000 patients. Currently, Medicare caps outpatient spending at only $1900 per person per year, which can be spent on physical therapy as well as speech and language pathology payments. This does not cover the needs of all patients; 19% of beneficiaries with complex impairments exceed Medicare's cap, spending on average $3,013 out of pocket (for Medicare and Services 2016). Such costs can be reduced by moving inpatient treatment to outpatient programs, which include exercises performed independently by patients outside of the therapy office.

The main issue with relying on patient-initiated exercises outside of the therapy office, however, is that a patient's progress is often dependent on their ability to adhere and comply with such exercise program. The compliance rate for such programs can be quite low, due to perceived barriers to exercise, lack of positive feedback, and degree of helplessness (Campbell et al. 2001; Jack et al. 2010). Patients who set goals collaboratively with their physical therapist have higher compliance rates (Chan et al. 2009). For the purpose of our study, the operational definitions for adherence is a patient's ability to perform exercises as prescribed to them, and compliance is the ability for a patient to continue exercising for the frequency and duration of their prescribed rehabilitation program.

While home regimens traditionally involve a physical therapist's verbal instructions and printed pictures, higher-tech initiatives associated with telemedicine, virtual reality, and robotic programs have been shown to be more effective in promoting compliance than traditional paper-based and verbal instructions (Byl et al. 2013; Deutsch et al. 2007; Mellecker and McManus 2014). These higher-tech exercise programs often use sensors, either to passively monitor a patient's status, provide feedback so an action can be modified, or use actuators to assist the patient in completing a motion (Bamberg et al. 2008; Lindeman et al. 2006). The sensors can include accelerometers, gyroscopes, microphones, bio-chemical sensors, motion detectors, GPS, and EMG. Several Kinect-based systems were proposed for rehabilitation, using avatars to portray the correct motion, or using therapy-based games, e.g., Roy et al. (2013). The feedback provided by these systems included auditory, such as music or beeps; tactile, such as vibrational cues; and visual, with a screen showing correct position or pressure color indicators. While these systems are sophisticated, our literature review suggests that they are not optimal for rehabilitation, because they were designed for entertainment instead of specifically targeting patients performing prescribed health intervention practices.

The system reported in this article is an exercise game for upper limb rehabilitation, which can be set up inside or outside the therapy office by a caregiver or family member, with the following characteristics:

(1) It employs an immersive Virtual Reality (VR) game as a motivation-inducing medium.
(2) It provides immediate feedback to users about their exercise performance through real-time motion tracking.
(3) Its exercise program is adapted from an established physical therapy protocol called "modified Constraint Induced Therapy" (mCIT) (Mark and Taub 2004).

Through our literature search, we believe we are one of the first to leverage the HTC Vive, a recently available commercial VR system, as a single system to integrate high resolution real-time data tracking and collection with a therapist interface in the specific application of upper limb rehabilitation for hemiparesis (weakness in one arm). We are also one of the first to use immersive Virtual Reality to provide psychological motivation to increase compliance in an established method of mCIT with a relatively large sample of users (for example, the closest work that uses Virtual Reality for CIT had participation from only four stroke survivors (Ji and Lee 2016), whereas the study discussed in this article includes participation from nine stroke survivors as well as six users with developmental disabilities with upper-limb impairments). The therapeutic intent of our study is to offer a version of mCIT that is more engaging, accessible, and uses recorded real time

tracking, which could result in improved user experience and increased efficacy in rehabilitation improvements for a given time.

2 WHY VIRTUAL REALITY?

The term "Virtual Reality" was coined long before the advent of recent immersive virtual reality (iVR) systems, which brought differences in opinions of the definitions of the terms "immersion" and "virtual reality." For this study, immersion reflects how well the user is connected to the virtual environment that is dependent on the number of motor channels and range of inputs provided to achieve a high-enough fidelity of sensory stimulation (Bohil et al. 2011). VR systems that provide a head mounted display (HMD) with a binocular omni-orientation monitor along with appropriate three-dimensional spatialized sound were categorized as iVR systems.

Studies comparing VR and non-VR systems for rehabilitation had largely shown that the VR version outperforms the non-VR comparable. A study of upper limb rehabilitation in patients with hemiparesis had shown that the VR group displayed significantly improved performance in paretic arm speed (da Silva Cameirão et al. 2011). In another study of using two-dimensional (2D) video-capture virtual reality (VR) training environment to improve upper limb motor ability in stroke patients compared to those performed in conventional therapy, more patients in the VR group improved upper limb clinical impairment and activity scores and the improvements also occurred earlier (Levin et al. 2012).

Therapeutic VR applications using iVR, non-immersive virtual reality (niVR), and augmented (mixed) reality (AR). niVR systems, or desktop systems, utilize a monitor and allow interaction of the user through conventional means such as keyboards, mice, or controllers (Costello 1997). AR systems employ virtual feedback by allowing the user to see themselves and their surroundings projected virtually onto a screen, usually in a mirror like fashion (Assis et al. 2016). These systems are similar in how they present movement-based tasks with supplementary visual and auditory feedback but differ in their interaction methods (Levac et al. 2016).

There has been a large number of publications and studies focusing on VR technologies and the applications in psychotherapy, physiotherapy, and telerehabilitation within the past two decades. In prior literature, VR has been defined as a computer user-interface that uses real-time simulations to invoke user interaction (Lohse et al. 2014). Modern VR technology is commonly known for its impact on enhancing the video gaming paradigm through involving more dedicated user interaction (Baldominos et al. 2015). The increased physical demands of these video gaming platforms has garnered interest for their potential in therapy through repetitive and quantifiable motor learning protocols (Salem et al. 2012). The use of VR systems has been shown to be effective for emotional, psychological, and physical therapy (Kandalaft et al. 2013; Straudi et al. 2017). Environments can be tailored to cue specific movements in real-time through sensory feedback via the vestibular system and mirror imagery to exemplify desired ranges of motion (Iruthayarajah et al. 2017).

2.1 Virtual Reality Applications for Psychological Therapy

Psychological research has seen an increasing use of VR due to its ability to simulate realistic and complex situations critical to laboratory-based human behavior investigations (Diemer et al. 2015).

Some of these investigations include the success in reducing pain through the use of stimuli in VR that is equivalent to effects of an analgesic (Gromala et al. 2015; Hoffman et al. 2011). With the immersive capabilities of modern headsets such as the HTC Vive and Oculus Rift, there has been an increase of success for VR exposure therapies such as for post traumatic stress disorder (Morina et al. 2015; Rothbaum et al. 2014), borderline personality disorder (Nararro-Haro et al. 2016), phobias (Diemer et al. 2015; Grillon et al. 2006; Shiban et al. 2015), and schizophrenia (Rus-Calafell et al. 2014) as well as many other psychological therapies.

The acceleration of VR use in psychological therapy can be attributed to the relationship between increased presence and emotion (Morina et al. 2015). Increasing the amount of stimuli using iVR is a key factor to influencing user behavior and experience (Baños et al. 2004), and, with the price of computing devices and hardware decreasing, VR headsets are becoming more popular and immersive (Corp 2013; Follow 2016). Thus increasing immersion through VR leads to more emotional influence of the user and can incite desired physiological responses through crafting a stimulating and engaging virtual environment (Chittaro et al. 2017).

2.2 Virtual Reality Applications for Physical Therapy

Traditional forms of physical therapy and rehabilitation are based on therapist observation and judgment, coincidentally this process can be inaccurate, expensive, and non-timely (Mousavi Hondori and Khademi 2014). There is evidence that VR can be an effective tool in improving outcomes compared to conventional physical therapy (Lohse et al. 2014). With the emergence of new immersible multimedia, VR experiences with sight, sound, and touch can be augmented in rehabilitation. As a result, VR has been shown to be effective in improving a variety of motor impairments, such as hemiparesis, caused by Parkinson's disease, multiple sclerosis, cerebral palsy, and stroke (Iruthayarajah et al. 2017).

High repetition of task oriented exercises are critical for locomotive recovery, and user adherence to therapy protocol is imperative. VR-based physical rehabilitation can induce adherence to therapy protocol as well as and sometimes better than human-supervised protocol due to the capabilities of multi-sensory real time feedback (Corbetta et al. 2015). The multi-sensory, auditory and visual, feedback can further persuade users to exercise harder through increased stimuli (Corbetta et al. 2015).

VR-based physical rehabilitation also allows for increased quantitative feedback for both the user and the therapist. With modern iVR systems implementing three dimensional motion tracking, VR serves as an effective way to monitor progress during rehabilitation (Baldominos et al. 2015).

2.3 Teletherapy Virtual Reality Applications

Telerehabilitation can result in decreased treatment cost, increased access for patients, and increased quantifiable data for therapists (Lum et al. 2006). There have been various studies confirming the technical feasibility and efficiency of in-home telerehabilitation with VR (Kairy et al. 2013). Users generally achieve better results in rehabilitation due to the increased feedback from the telerehabilitation VR (Piron et al. 2009). Telerehabilitation VR increases the usability and motivation of the user compared to traditional in-home therapy systems, while reducing work for physical therapists and reducing costs for patients (Lloréns et al. 2015).

2.4 Virtual Reality and Motor Stroke Rehabilitation

Our literature review concludes that VR is largely effective for motor stroke rehabilitation (Cameirão et al. 2008; Mousavi Hondori and Khademi 2014; Saposnik et al. 2011), with many of these studies supporting that the use of VR had resulted in significant improvements when compared to traditional forms of motor stroke therapy (Corbetta et al. 2015; Iruthayarajah et al. 2017). These studies used Kinect, Nintendo Wii, IREX: Immersive Rehabilitation Exercise, Playstation EyeToy, Cave Automated Virtual Environment, as well as custom designed systems. For a given treatment time, video game-based rehabilitation is more effective than standard rehabilitation (Corbetta et al. 2015; Iruthayarajah et al. 2017; Lohse et al. 2014). The physical rehabilitation communities have been enthusiastic with the potential to use gaming to motivate post-stroke individuals to perform intensive repetitive task-based therapy, with some combining motion capture as a way to track therapy adherence and progress. However, older studies commented

that technology at the time needed to improve, such as in motion tracking accuracy, to become more effective, reliable, and accessible (Crosbie et al. 2007; Mousavi Hondori and Khademi 2014). Additionally, more studies are needed to continue gaining a deeper understanding of the efficacy of VR in rehabilitation (Cameirão et al. 2008; Dascal et al. 2017).

Interactive video games and VR games were applied in stroke rehabilitation as early as the era of the Sony PlayStation II gaming console, with the EyeToy Camera for motion capture (Flynn et al. 2007) and the Nintendo Wii (Saposnik et al. 2010). The combination of games and motion capture technology was used successfully in home and clinical settings, demonstrating the feasibility and potential of such technology. Since then, a variety of games employing robots, tangible surfaces, and VR systems have been proposed for stroke rehabilitation. Specific applications include a robotic-assisted game for motor and cognitive post-stroke rehabilitation (Heins et al. 2017), a multi-user VR game for upper extremity rehabilitation (Tsoupikova et al. 2016), and a tangible gaming board for the training of upper limb gross and fine motor skills (Wang et al. 2017).

However, applying consoles and games, which were designed for entertainment applications, to stroke rehabilitation has several challenges. The first challenge is the design of the controller, which might not work for individuals who have insufficient hand and grip strength or arm control. The second challenge is understanding how the controller works to tailor the game mechanics appropriately for a particular therapy goal. For example, the Wii remote responds to acceleration more than position changes, so faster movements will garner more points than wide sweeping but slower movements (Pasch et al. 2008). This mechanic might not translate well for stroke rehabilitation that encourages users to extend their arms as much as they can as they are not rewarded for having wider ranges of motion. The third challenge is for the game itself to strike many balances, including its:

(1) Levels of difficulty: The game should be adjustable for different ability levels that can vary depending on the severity of hemiparesis.
(2) Rules/mechanics: The game should not assume any prior knowledge of rules and should be understandable by those who might be cognitively impaired, which is a common symptom of stroke affected persons.
(3) Design: The game's theme, reward, and design elements such as background and soundtrack should not be perceived as too childish, boring, or meaningless by users of varying ages and backgrounds.
(4) Data interpretation: Data should be leveraged to measure progress towards therapy goals and be used for treatment planning.

Past motor rehabilitation studies have been far and apart due to costly and sluggish VR systems existing in the past (Costello 1997). These issues are being resolved, leading to high performance VR headsets costing only a fraction of the price; with new headsets such as the Oculus Rift, PlayStation VR, HTC Vive, Google Cardboard, and Microsoft Hololens (Follow 2016).

3 WHY CONSTRAINT-INDUCED MOVEMENT THERAPY?

As mentioned above, the purpose of the game we develop is to act as a motivating exercise program for upper limb rehabilitation. To inform the game mechanics, we leverage an established therapy technique commonly used for upper limb rehabilitation: Constraint-induced movement therapy.

Constraint-induced movement therapy (CIMT) involves massed and intensive practice with the weaker affected upper extremity and includes two components: The use of the unaffected upper extremity is restrained during 90% of waking hours, and at the same time, the more affected upper extremity receives repeated and intensive training for more than 6 hours per day (Mark and Taub 2004). CIMT has been widely used and studied compared to traditional rehabilitation techniques and "could improve functional performance and increase the usage of the more affected upper

extremity" (Mark and Taub 2004). Although research shows benefits from CIMT, in a survey of stroke survivors, 68% of respondents said they were unlikely to comply with the therapy protocol due to either logistical aspects (length and duration of therapy) or aspects of the therapy itself (wearing a physical constraint for a long period) (Page et al. 2002).

Modified constraint-induced therapy (mCIT) is a form of CIMT that requires less engagement and compliance from the patient. Researchers have designed a modified CIMT that has a shorter intensive training period as well as shortening of the period that the unaffected upper extremity is constrained (Shi et al. 2011). For example, a patient may visit a therapist several times per week and in each 30-minute session the patient practices focused exercises using their weak arm. This therapy has been demonstrated to increase the mobility and use of the patient's arm only if they have some mobility remaining in their wrist and fingers (Shi et al. 2011). The program our system was designed for follows mCIT instead of CIMT, with a slight modification. Instead of a physical constraint, we utilize the game mechanics to provide a psychological constraint. Specifically, we provide more reward if the participant uses their weak arm and considerably less reward if the participant uses their strong arm during game play.

4 OUR STUDY

Our study aims to evaluate the use VR for rehabilitation, specifically the use of the HTC Vive for upper limb rehabilitation of users with hemiparesis. To inform our study, several commercial, private, and research-based systems have been methodically tested, including Microsoft Hololens, Microsoft Kinect, Oculus Rift, Playstation VR, and HTC Vive. We came to the conclusion that HTC Vive provides the most high-resolution data capture regarding head and upper limb movements. It also provides the most accurate 6-DOF motion capture capabilities (Staff 2017). More detailed explanation of why HTC Vive was the chosen technology is described in the System Design section.

The aim of our study can be translated into four main questions:

(1) Are participants with hemiparesis able to use the controllers during game play?
(2) Can the game mechanics result in improved adherence and compliance than the adherence of conventional mCIT as reported in the articles?
(3) Is the game understandable and enjoyable by our target population?
(4) What does the data tell us about user game play strategies?

We sought to answer those questions through a series of brainstorming sessions with physical therapists, stroke survivors, their caregivers, and us at Cabrillo College's Stroke and Disability Learning Center (SDLC) and Hope Services, our long-term collaborators. The intent of mCIT is to constrain the stronger limb to encourage the use of a weaker limb. Our approach makes use of a VR game with the same intent. Therapists concluded that the benefits outweigh the risk of using a psychological constraint in VR instead of a physical constraint. While they did not expect a VR game to cause injury to patients, because game play can be done seated and physical interaction with the game is limited to a lightweight headset and controllers, the therapists said there is risk that the VR rehabilitation game potentially will not be effective in encouraging use of the weaker limb and may not be enjoyed by patients, especially if they have never experienced VR before. Because our VR game is dependent on psychologically encouraging the use of a weaker limb, it could be rendered ineffective if the gaming experience does not motivate patients. To mitigate this risk, we considered game themes in unconventional environments that could distract or fascinate the player. The benefits of the VR rehabilitation game is the prospect of using the game at home, which allows patients to maintain treatment even at times when they canot make it to clinic sessions, and that psychological constraint does not feel as invasive to the independence of the patient as a physical one does. Physical constraint, therapists commented, could feel demeaning and makes some patients feel like

they lose independence, so they may resist treatment especially in the beginning before they start to feel the benefits of mCIT. Patients must go to a clinic and are dependent on being strapped into their restraint by a therapist, and the restraint itself could feel claustrophobic or unconformable. The therapists believed that psychological constraint through game rules and an immersive experience would not feel like losing independence; instead, the patients maintain dignity and feel as if they chose to play the game. Patients can even measure their own progress by tracking game scores and session durations. Thus we expected that the use of psychological constraint for a gamified mCIT protocol would be equivalent or more successful than using physical constraints.

We went through the process of choosing the game domain that appeals most patients. We defined the following characteristics for our game:

- The game domain chosen is about stars and galaxies.
- The game provides immediate feedback about users' task performances through data captured using motion tracking sensors,which can allow patients and therapists to see performance in real time.
- The game encourages the use of hemiparesis-affected limbs through adapting the principles of an established physical therapy protocol called "modified Constraint Induced Therapy" (mCIT) described above (Mark and Taub 2004).

We should note that the long-term goal of physical therapy is to gain back the ranges of motion and strength of the weak arm (NINDS 2014) while the scope of this study is to encourage users to use their weak arms while capturing movement data that can be used by therapist. The Hope Services and SDLC therapists reviewed and approved our proposed game play mechanics and worked with us to develop the user evaluation protocol.

5 SYSTEM DESIGN

Our designed game is named, for simplicity, Project Star Catcher (PSC). PSC incentivizes game participants to use their hemiparesis-affected arm through catching falling stars in a cosmic VR environment while collecting real-time user data. The game was developed leveraging the HTC Vive system that includes of a headset, wireless controllers, and lighthouses.

On reviewing multiple commercial VR and motion capture systems such as the Oculus Rift, Playstation Morpheus, IREX, and Optitrack, we decided to use the HTC Vive as the medium to create a upper limb rehabilitative experience. The HTC Vive differs from other modern systems in its localization system and affordability. The HTC Vive, developed by the Valve Corporation and HTC, is a VR head mounted display (HMD) that implements room scale 4×4 m tracking technology by utilizing a "lighthouse" system of lasers that enables user interaction and accurate 3D motion capture (+/− 1.2mm worst case) for an affordable price of 600 USD (Kreylos 2016). Its adjustable headset allows for users who wear glasses, which might be the case of many of our target population (Marshall 2016). Complementary to the HTC Vive are two hand held controllers that feature dynamic haptic feedback that enhance spatial orientation (Savov and Vlad 2015). The HMD provides a 110^{o} field of view and 90Hz refresh rate, and the system itself has a significantly low latency of 22ms, which is known to reduce motion sickness (Soffel et al. 2016). Motion capture is tracked at 120Hz using infrared laser sweeping and photo-diodes that enable for recovery of position and orientation (Savov and Vlad 2015). The HTC Vive also features a safety guidance system preventing users from potential injury in the real-world environment (Niehorster et al. 2017; Soffel et al. 2016). While the HTC Vive is known to produce inaccurate data and reset when the user exits the tracking area (Niehorster et al. 2017), the risk of this affecting our therapy game is minimal. Because our target participants are persons with motor impairments that need upper-limb exercises, we can prescribe VR interactions to be in a seating position and contained within the tracking area.

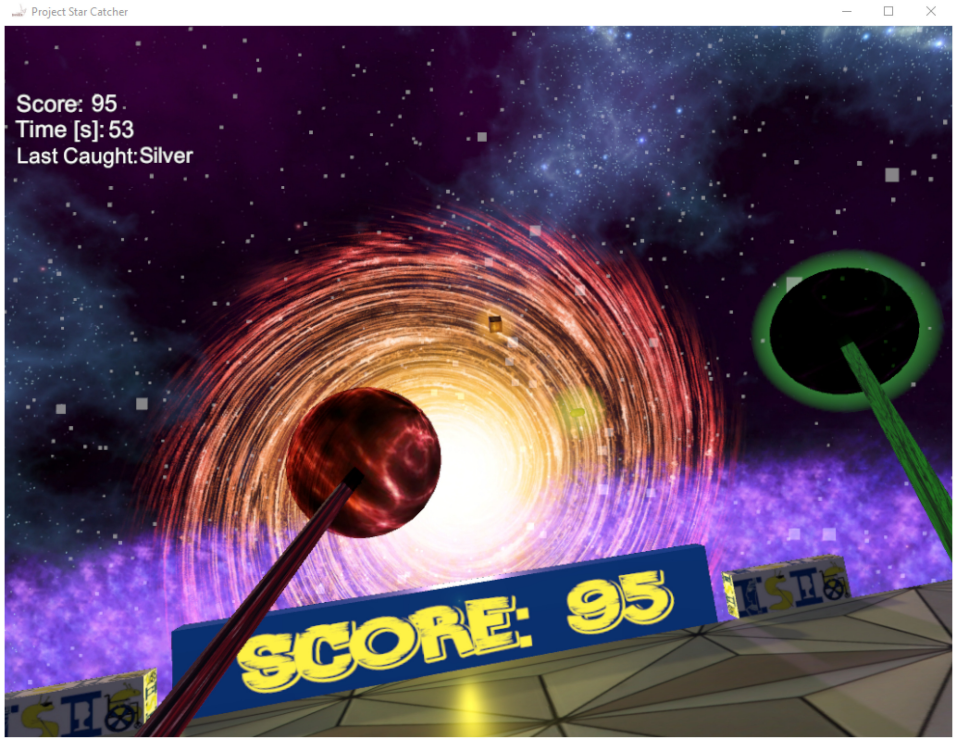

Fig. 1. Player gazes into the cosmic galaxy showing ted and green star catchers as arms lift to catch stars.

In PSC game play, the HTC Vive controllers are visualized in the player's hands as "Star Catchers" that are colored either red (for the strong arm) or green (for the weak arm), seen in Figure 1. The Star Catcher colors were chosen to help remind users that their goal is to catch with the weak arm. Before the player is an ethereal, cosmic galaxy that the stars fall from. Stars are caught when the player touches them with a Star Catcher, resulting in haptic feedback as the controller vibrates, figuratively feeling the stars being caught, and an attached speaker plays sounds effects. This design supports an immersive experience of sight, sounds, and touch that could be exciting enough to motivate users.

PSC has several levels of difficulties in terms of the speed of the falling stars, the rate of the falling stars, and the angles the stars fall from. For a personalized experience, the difficulty of the game can be adjusted by the evaluator or user based on the data collected in an introductory round, the user's past rehabilitation history, or the recommendation of a therapist. The stars are colored bronze, silver and gold to indicate different speeds of falling and score values. The base speed is adapted to each individual player's reaction time. Bronze star falls at 75% of the base speed, silver at 100%, and gold at 125%. The score is calculated based on the user's performance, with the weak arm (green Star Catcher) providing the most weight, and it is mainly used as a motivational landmark for the user to see progress and beat high scores. Stars spawn from various locations to make sure that users will perform rehabilitative arm movements to catch them. These movements were designed in consultation with a physical therapists from the SDLC and Hope Services.

PSC was developed in Unity v5.5.0f3 with the SteamVR plugin v1.2.0, which connects HTC Vive hardware to Unity. SteamVR is open source and both have documentation for C# and Javascript. Using the Unity physics engine, the Rigidbody class was used to model stars and the HTC Vive

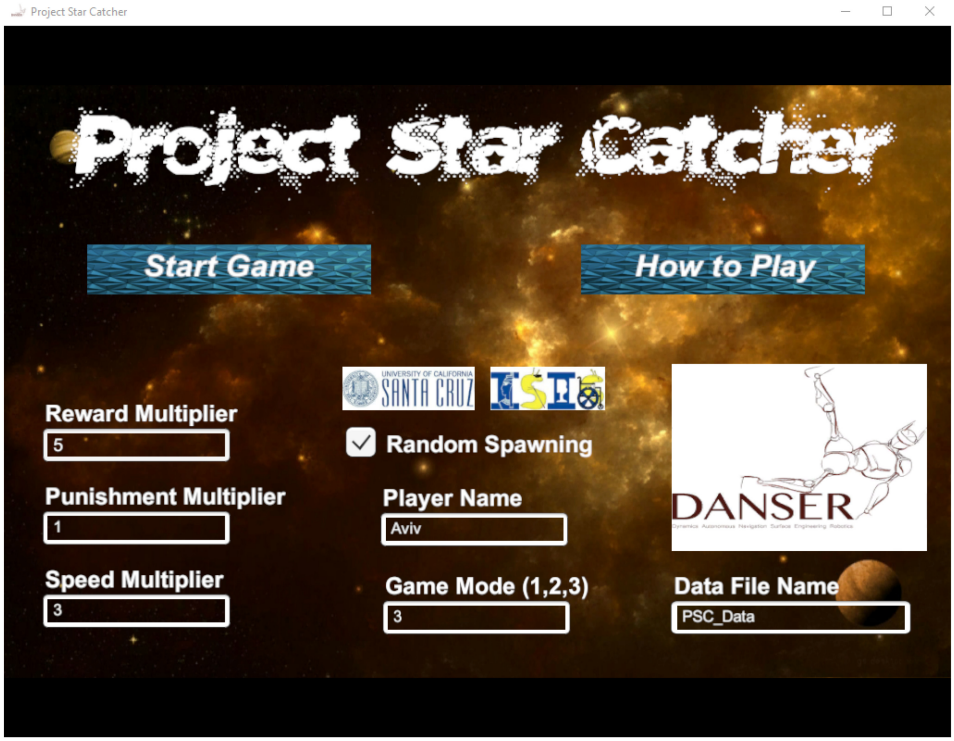

Fig. 2. Project Star Catcher Evaluator Interface (note that the "How to Play" module contains explanation about what the game settings are and how to adjust them).

controllers were modeled as Capsule Colliders that detected contact with stars. Stars randomly spawn at different locations along a half circle in front of the player in three game modes—stars fall from 0^o (directly above the user) in Mode 1, 45^o in Mode 2, 90^o (directly in front of the user) in Mode 3—to vary motions and body posture when catching stars. All game play was set to a time-dependent state, allowing for a customizable and time-dependent assignment of the moving stars. Data communication was achieved through utilizing C# and Microsoft .NET Framework allowing for successful data exportation of 90Hz (and greater depending on the machine).

The evaluator user interface, shown in Figure 2 has the following inputs: Reward Multiplier, Punishment Multiplier, Speed Multiplier, Game Mode, Player Name, and Data File Name. Reward and Punishment Multipliers allow a therapist to customize the amount of score points earned for the green and red Star Catchers, respectively. Game Mode allows selecting Mode 1, Mode 2, or Mode 3. Player Name allows PSC to provide identifying information to data collected during game play.

These mechanics were implemented so that the user could perform therapy without a therapist and occasionally meet a therapist virtually so that they could be re-evaluated, effectively enabling low-cost telerehabilitation through readily available online collaboration platforms.

6 PILOT STUDY

To investigate the evaluation protocol and ensure that our study and game design can answer the four questions we set out, we evaluated PSC with six participants with developmental disabilities who have upper limb impairment. The participants consisted of four men and two women, with ages ranging from 23 to 31 as seen in Table 1. We received IRB approval from our university for our game play testing.

Table 1. Summary of Participant Demographics
Pilot Study

ID	Age	Gender	Disability
Co	23	M	Cerebral Palsy
Ty	31	M	Autism
Pp	25	M	Inverted X Syndrome
Cn	24	M	Autism
Cs	26	M	Mild Intellectual Disability
Fa	30	F	Down Syndrome

Participants were recruited through Hope Services, a local non-profit organization that promotes independence for people with a variety of developmental disabilities, including Autistic Spectrum Disorder, Down Syndrome, and cerebral palsy. By providing jobs and other activities, Hope Services intends to change attitudes about the abilities of these persons in the workforce and in the community. The session started with the participants filling in a consent form as well as a video and audio release form. A professional caregiver was present to help explain in a way that is understandable to the participants and make sure that the participants did not get overstimulated or did any movements that might cause upper limb strain. There were always two to three researchers present in the sessions. The researchers and caregiver helped the participants don the head-mounted display and place the Star Catchers in their hands if requested. However, most participants were able to don the head-mounted display by themselves.

After getting an explanation of game, the players were introduced to Modes 1, 2, and 3 for about 1 minute each. The players then selected their preferred mode and played for 5 minutes, a duration recommended by therapists at SDLC and Hope Services. During the 1-minute introductory modes, the participants' reaction times were calculated and a base speed for the falling stars were customized to each user for their 5-minute trial so that the stars were not too slow or too fast.

The play session was videotaped. After the session, the participants were interviewed using a retrospective testing method, in which the researcher and the participant reviewed the video together, and the reviewer stopped the video at multiple points and asked the participant directly to explain certain behaviors when deemed necessary.

7 RESULTS AND DISCUSSION FROM THE PILOT STUDY

The pilot study aims at investigating whether our game design and study protocol can answer four main questions:

(1) Are participants with hemiparesis able to use the controllers during game play?
(2) Can the game mechanics result in improved adherence and compliance than that of conventional mCIT?
(3) Is the game understandable and enjoyable by our target population?
(4) What does the data tell us about user game play strategies?

To answer these questions, we analyzed the collected performance and behavior data.

7.1 Are Participants with Hemiparesis Able to Use the Controllers During Game Play?

Our concern in this study was that whether the participants could hold or manipulate the controllers.

Direct observation of the sessions revealed that the six participants were able to hold or manipulate the controllers enough to play PSC. Depending on their disability, they developed user-specific

Fig. 3. An example of a participant's initial strategy in holding the controllers.

strategies to hold the controllers better. Figure 3 shows one participant with cerebral palsy that has weakness and hypertonicity in his right hand, who held the right controller by resting his hypertonic pointing finger inside the ring.

There was one occasion when the controller slipped from a participants' hand and fell to the ground, because this participant with wheelchair was very excited and made an exaggerated movement that caused the controller to fly. We found that wrist straps prevented this incidence and hence, since that point, we ensured that participants had wrist straps put on before starting the game play.

We also deduced that arm sleeves can also help the controllers stay on their hands (arm sleeves covered from midway between their elbows and hands all the way to their palms, with the controllers' sticks encased inside those sleeves).

7.2 Can the Game Mechanics Result in Improved Adherence and Compliance than Those of Conventional mCIT Reported in the Papers?

PSC was designed to improve adherence and compliance rate in a psychological constraint-induced therapy by using game mechanics to provide reward if the participants use their weak arms to catch falling stars of varying speeds. It was apparent that we could easily gauge adherence rate through analyzing performance data that the motion capture system that came with HTC Vive collected. As for compliance, a post-testing survey showed that 84% of participants believed they were "very likely to comply" with using a VR game like PSC as a long term rehabilitation tool.

To do a proper comparison of the adherence rate, we normalized the number of the stars caught by each participant into percentages for a specific star color. So, for example, if a participant caught

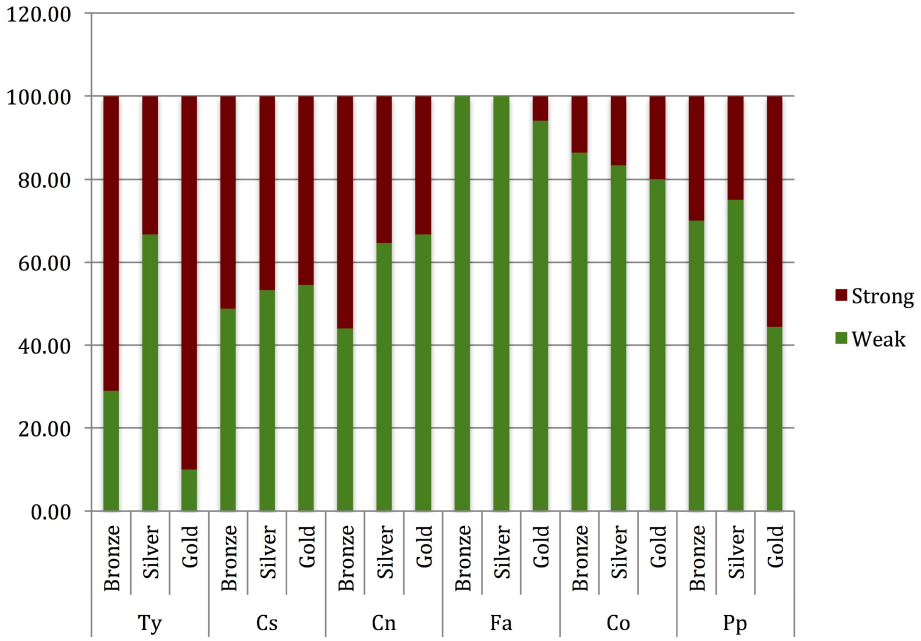

Fig. 4. The percentages of stars caught by each participant in pilot study.

20 bronze stars with the weak arm and 20 with the strong arm in the five-minute session, then it is calculated as 50–50.

Figure 4 shows the percentages of the stars caught by the six participants, each using the weak (green) and strong (red) arms while playing the first iteration of PSC. In general, we can see that the participants are mostly adherent to the game rules. Specifically, they tried to use the weak arms as much as they can. The exception is Participant Ty, who slipped into using mostly the strong arm for the gold stars (that are the fastest of the star types). Participant Fa almost had the perfect compliance, having only one gold star caught with the strong arm, and Participant Co was also highly compliant, although again, just like Participant Ty, slipped into using the strong arm in gold star condition.

Figure 5 shows the median of the percentages of these six participants by star color while playing PSC. This figure overall shows that participants are adherent to using their weak arms, averaging 60%. This percentage is considerably higher than the reported adherence rate of conventional mCIT, where 32% of patients were likely to use traditional therapy protocol (Page et al. 2002).

7.3 Is the Game Understandable and Enjoyable by Our Target Population?

To answer this question, we relied on qualitative data. The qualitative data reported in this study consists of a combination of (i) themes extracted from the interviews and (ii) observations obtained from the researchers during the play sessions. The interviews were transcribed and analyzed by two researchers using content analysis, more specifically open coding, to extract themes. The researchers did the open coding in a line-by-line fashion. The researchers came into the data with no preset theme or bias. The observations were extracted by two researchers watching the videos together but coded the behaviors independently. The two video coders then compared the behaviors and resolved differences in coding through discussing the cause of the difference to come up with unified themes.

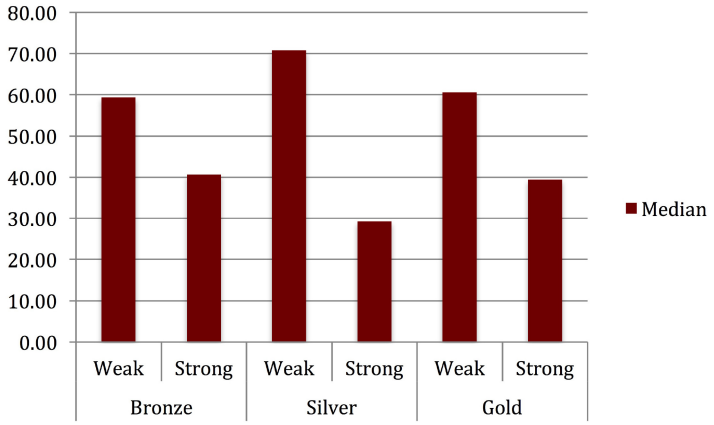

Fig. 5. Median percentages of the stars caught in pilot study.

During game play, we noted that the HTC Vive did not cause noticeable tracking jitter and participants confirmed that they did not feel motion sickness. Participants thought PSC was fun and enjoyable, and did not request significant changes or improvements to PSC other than "happier music." They did request "more games" with different themes, because it would be "more interesting." When asked what they thought of the sound effects and haptic feedback on the controller, most participants stated they did not even notice the music or vibration. Similarly, when asked whether they felt that the star colors were visible, most did not notice that there were three different stars, although they noticed that some stars fell faster than other stars. Finally, when asked whether they preferred the game or the physical therapy exercises that they currently do, everyone unanimously preferred PSC, which they concluded was more fun and entertaining than their usual exercises.

7.4 What Do the Data Tell Us about User Game Play Strategies?

To answer whether the participants understood the game mechanics, we relied on observations from game play that was recorded and analyzed post-session. We captured game play data automatically by counting the number of stars caught with weak and strong arms. Our video data was analyzed to derive strategies and performance. Video coding a 5-minute session video took two coders an average of 20 minutes. Transcribing and analyzing the interviews took another 20 minutes average per participant per coder. Through game play data video content analysis, we extracted several themes about these strategies. The observations yielded a rich set of results that indicated that not only participants understood the game mechanics, they developed strategies to more effectively catch the stars in spite of their upper limb weaknesses.

Through video content analysis, we extracted several themes about these strategies:

(1) Number of strategies employed = [1, 2-3, 3+]. Some participants were consistent in their strategy in catching the stars while others changed strategies multiple times in the span of 2 minutes. For example, one participant changed strategies more than 10 times.
(2) Arm ranges of motions = [only lower arms (resting the elbows somewhere), the whole arms]. Essentially, some participants rested the elbows on their wheelchairs or chair arms, only moving the lower arms to catch the stars, while others swung freely their whole arms.
(3) Arm movement patterns = [vertical swipe, horizontal swipe, extension swipe, flexion swipe, serendipitous catch]. The basic motions are illustrated in Figure 6.

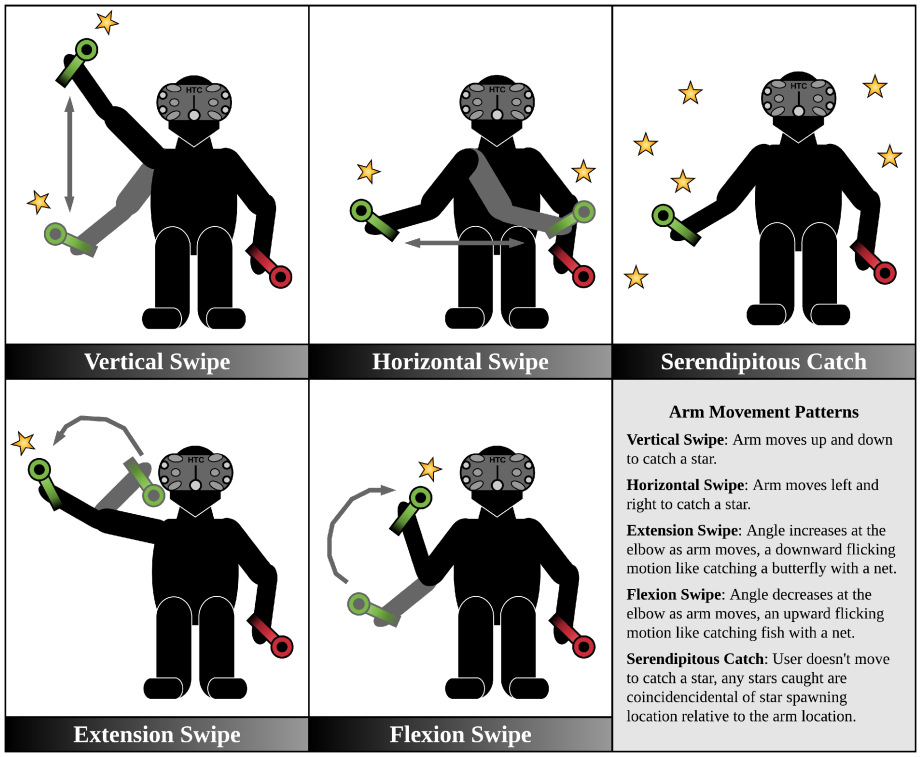

Fig. 6. Identified basic arm movement patterns during user studies.

(4) Arm movement speeds = [fast, slow]. We noticed that participants either waited by resting their arms and then extended one arm very fast to catch the star [fast] or slowly extended one arm anticipating the location the star would hit the Catcher [slow].
(5) Head movements = [vertical rotations (e.g., nodding), horizontal rotations (e.g., shaking heads), looking only at a certain angle (e.g., either up, down, or straight ahead)]. For example, one participant in wheelchair rested his head on his wheelchair and kept it there for the whole session, always looking up. However, with the exception of this particular participant, we noticed that the participants were having problems with stars falling from above or at 45° angle, because the angles the participants needed to tilt their heads caused head and neck strains.

In summary, through video content analysis of the interviews and observations, we could argue that our game design choices were understandable and enjoyable for people with developmental disabilities, although some design elements were not noticeable by the participants, indicating the needs to revise those elements to make them more salient.

After the pilot study, we automated the video coding process by leveraging the real-time data generated during PSC game play. Through coding the data automatically, we can analyze the data in a more efficient and quantifiable way.

8 REVISED SYSTEM

The pilot study helped us tremendously in understanding how to best address many challenges in using games for rehabilitation. Another round of brainstorming sessions were performed at

SDLC and Hope Services to agree on modifications to PSC with consideration of the pilot study. Additionally, we decided to automate behavioral capture to save time video coding, so that future testing could be scalable. A second iteration of the system design for PSC was done based on the lessons learned from the pilot study.

The modifications include:

(1) Speed weighting of stars were increased by 25%. The speed weighting became 50%, 100%, and 150% of user's comfortable speed for bronze, silver, and gold difficulties, respectively, to increase the varying reaction times for the user to catch stars as some users caught most of the stars. These changes were made to increase the exaggeration of difficulty between stars.
(2) Haptic feedback was adjusted to emit stronger and longer pulses and a dull sound effect with the use of the strong arm. A dull bell sound is emitted whenever the user catches a star with their strong arm, in contrast to the exciting strum sound emitted when the user catches with their weaker arm. These changes were made to increase contrast between the arms.
(3) The falling stars were changed to have varying sizes and shapes for the user to identify the differences between each star type. The stars were changed to bronze octahedrals, silver diamonds, and gold stars. Shade of colors was adjusted as well. These changes were made to increase contrast between star types, and were implemented due to the feedback of not noticing different star types of the users in the pilot study.
(4) Data sampling rate was made customizable, which is recommended 90Hz or greater depending on computer performance, during game play and saved in a file in the following format for each datum:
    - Time [s]
    - Score
    - Last Caught [star type]
    - Weak Catches [count]
    - Weak Arm Position (x,y,z) [m]
    - Weak Arm Rotation (x,y,z) [°]
    - Strong Catches [count]
    - Strong Arm Position (x,y,z) [m]
    - Strong Arm Rotation (x,y,z) [°]
    - Headset Position (x,y,z) [m]
    - Headset Rotation (x,y,z) [°]

    The data is stored in comma-separated values format, which can be imported into MATLAB, Microsoft Excel, or other tools for analysis. Analysis can illuminate user strategy, performance, and adherence to using their weaker arm. We also created scripts to automatically calculate the trajectory and speed of each head and arm movement, the total number of stars caught with the weak arm and strong arm, and the total number of stars missed.
(5) Various changes to the evaluator interface were made as well:
    - An adjustable spawn rate input was added to allow further customization for how many repetitions of movement were required of the user for the given spawn time.
    - An updated "How to Play" menu was added with instruction text that recommended and explained input fields to teach therapists how to properly set up values in PSC and adjust the user to the virtual environment.
    - A pause menu, which is triggered by the evaluator or user, was implemented for the player view to include written instruction of PSC mechanics. This was added to ensure uniformity between researcher in how to explain the game to a participant.

The Star Catcher size and the trajectory of the stars (or rather the movement required to catch the stars) remained unchanged in the revised system. In summary, the changes described in the items above were a result of the observations made in the pilot study. With the approval and recommendation of therapists from SDLC and Hope Services, we then updated PSC and moved on to a new user evaluation with post-stroke participants.

9 USER EVALUATION

We evaluated PSC with eleven stroke survivors at Cabrillo College's Stroke and Disability Learning Center. Since 1974, the SDLC has provided an interdisciplinary educational program for adults who have survived a stroke or are living with disabling conditions. The SDLC is a unique program that starts where medical rehabilitation leaves off. Patients become students and enroll in specialized classes to develop strategies and gain skills in a supportive learning community. For the sessions at SDLC, PSC was run on a laptop in their physical exercise room. Participants were accompanied by physical therapists and caregivers.

Two participants were excluded from data analysis for reasons discussed in the next section. The remaining nine post-stroke participants consisted of five men and four women, aged 36 to 87 years old, and had been recovering from stroke for at least three years (the longest was nine years after stroke). Three participants were in wheelchairs, four used canes, and two had personal assistants to help them walk by holding their arms. Due to HIPPA privacy rule, we were not informed about their specific disabilities.

Each user was verbally instructed on the mechanics of the game, then re-read the objectives through PSC's start menu. The users were instructed to identify all logos in the environment by physically looking around in the 360° environment before initial game play, which was done to acclimatize the user to the VR experience. All users participated in an introductory round of 90s of game play with Game Mode 3 (stars approaching the user from the forward view), a spawn rate of five seconds per spawn, and a base speed of three meters per second. Base speeds were then adjusted appropriately for each participant based on their physical ability and time since stroke. Next, the users were asked to try to surpass their introductory score while data was collected as an actual trial of about 5 minutes of game play. As with the pilot study, participants were interviewed after the play session. Because of the situation we observed with the pilot study, where the participants seemed to be having neck and head strains with stars that were falling from above or at a 45° angle, we only ran studies with stars approaching the users from a forward view (Game Mode 3).

10 RESULTS AND DISCUSSION FROM USER STUDY

A lesson we learned from our pilot study is that if we could record performance, strategies, and adherence in a more quantitative way, then we could analyze in a more quantifiable, automated method compared to human video coding.

10.1 Are Participants with Hemiparesis Able to Use the Controllers During Game Play?

Similar to our pilot study, the answer to this question was readily accessible through direct observation by researchers in the play sessions. Wrist straps and arm sleeves were useful for 9 of 11 participants.

During testing, we did not have resources to reasonably accommodate two players, because they were early in their recovery and unable to use their stroke-affected arm to hold the game controller even with the strap and arm sleeves. Both players tried out Project Star Catcher using only their strong arm and both requested to participate in a follow-up study with accommodations to hold

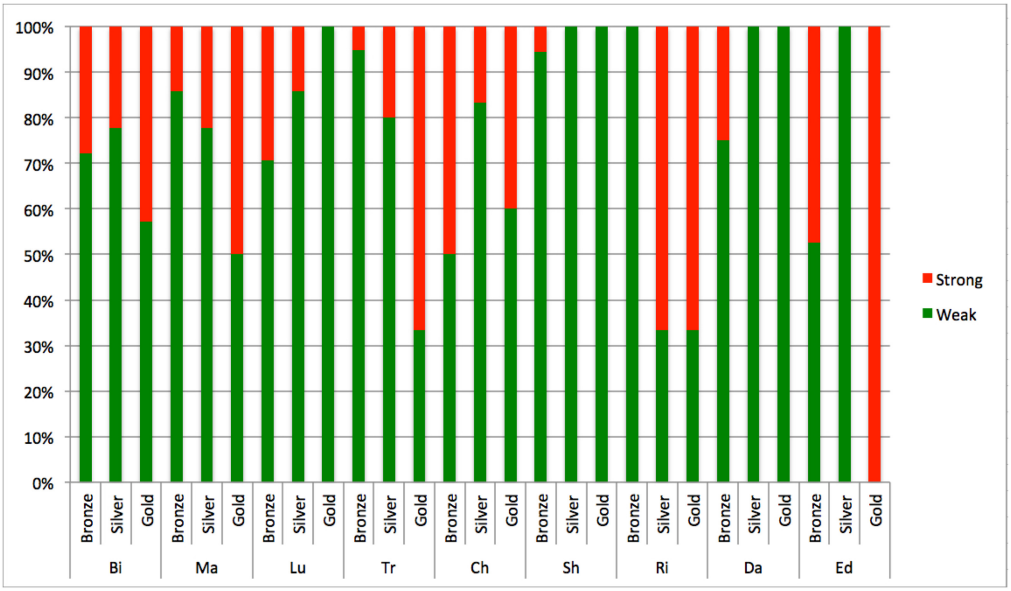

Fig. 7. The percentages of stars caught by each post-stroke participant.

the controller with their weak arms. Data collected from these two players were skewed, because they only used their strong arm to play, therefore they were excluded from analysis. Future work will include accommodation for participants who cannot grasp the controllers, our next iteration will leverage Vive Trackers to perform full body motion capture to potentially eliminate the need for a controller.

10.2 Can the Game Mechanics Result in Improved Adherence and Compliance than That of Conventional mCIT?

Figure 7 shows the percentages of stars caught by arms with and without hemiparesis for each participant. As observed in the pilot study, with very few exceptions, participants are adherent in using their weak arms, although adherence rate went down for faster stars. Across all participants, the adherence rates for using their weak arms were 77.26%, 81.99%, and 59.31% for the bronze, silver, and gold stars, respectively. This rate is higher than that of conventional mCIT (NINDS 2014). The average adherence rate of 73% was also higher than our pilot study that had 65%, which may suggest that our changes to PSC had a positive effect.

10.3 Is the Game Understandable and Enjoyable by Our Target Population?

To answer whether the game was enjoyable, we relied on interview data that were coded in a similar manner to the pilot study. The participants thought the game was fun and also noted that the experience was more fun than their regular exercise regime. Furthermore, the participants did notice that the stars were different colors, shapes, and speeds. The users did not appear to have increased difficulty with varying sizes or shapes based on observation. They also noticed the differences in vibrations and sound effects when the stars were caught with the weak versus the strong arms. Additionally, some participants clearly stated that they wished they could play longer, indicating that they really enjoyed the game.

Reactions to PSC ranged from curiosity, where they wanted to know more about future iterations of the game and new games, to enthusiasm to quickly adopt PSC for routine physical therapy.

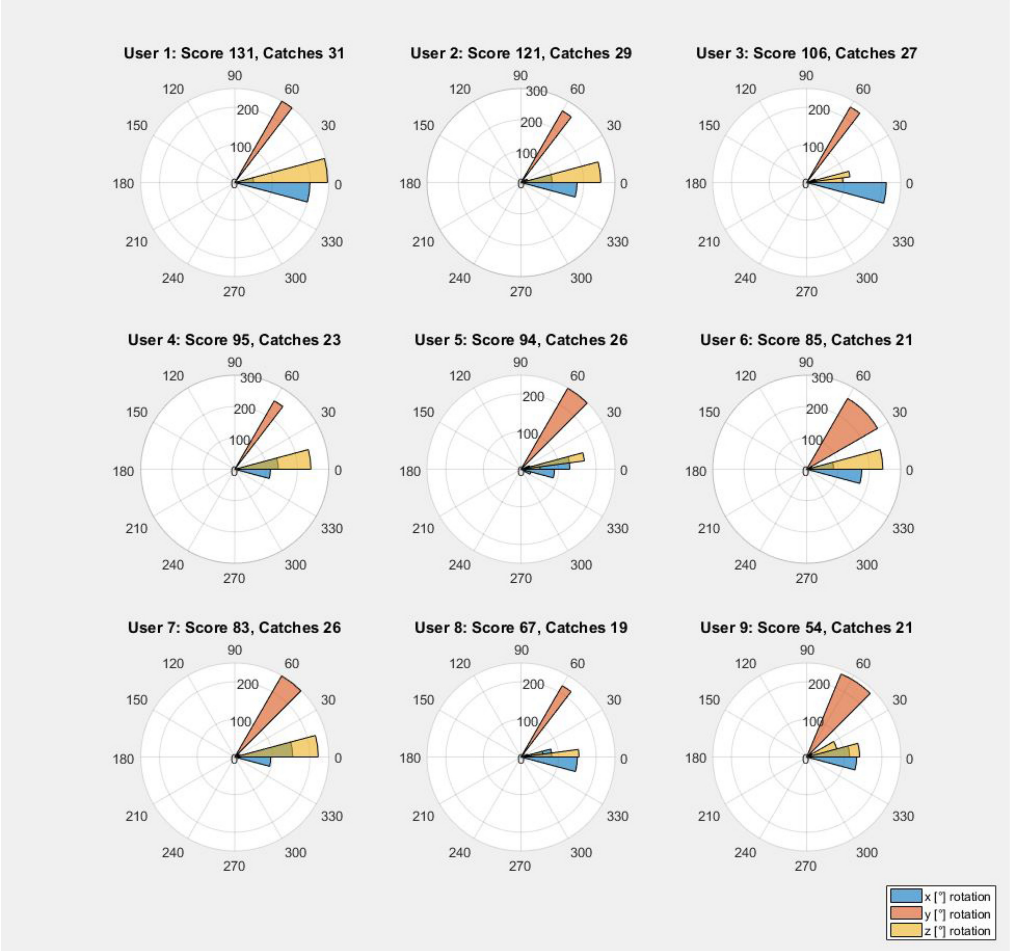

Fig. 8. Histogram of head rotations of stroke survivors from HTC Vive.

Some therapists and stroke survivors expressed interest in using PSC as a part of physical therapy routines, because it is a Virtual Reality game that addresses the movements needed for rehabilitation. One therapist commented, "For me, the most interesting thing and the biggest benefit for patients is the fact that the game requires the sitting balance, because they have to reach and lean and come back to the center." One stroke survivor showed their excitement for VR when they explained, "When you have a stroke you want to escape into another reality, and this helps you do that. I think that's a good thing, because if you are not mobile in reality, you can escape into a world where you are mobile, and that would feel like a positive thing."

It was apparent from direct observation and video observation post-session, that the participants understood the game rules and developed unique strategies to garner points and catch more stars. However, instead of analyzing the video using human coders, this time we automatically captured the strategies using our data files and scripts. It seems to us that the automatic capture was quite successful in providing us with similar data to that of human coders.

Figure 8 is a histogram of the head rotations of stroke survivor during game play. The X, Y, Z rotations indicated the roll, pitch, and yaw movements of the heads. In this figure, we can clearly

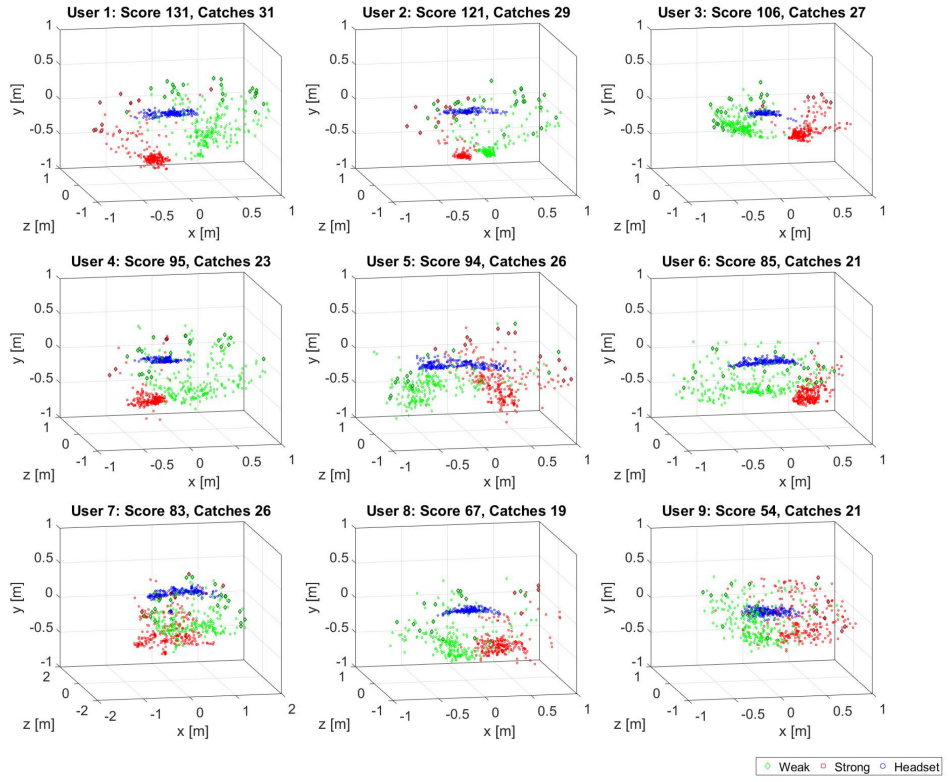

Fig. 9. Motion capture of hand and head positions. Green = weak arm, red = strong arm, blue = head.

see which participants rotated their heads up and down, left and right, or remained more constant than others throughout the session. The hand and head positions are shown in Figure 9. We organized the participants in descending scores.

Through analyzing these figures, we could deduce that the stroke survivors were very motivated to use their weak arms, although some users (e.g., Users 3, 5, and 9) also used their strong arms extensively. In our observation, this was due to fatigue and weaknesses affecting their ability to continue using solely their weak arms, instead of attitudinal non-adherence.

10.4 What Do the Data Tell Us About User Game Play Strategies?

Figure 9 told us many things about stroke survivors' performance, strategies, and adherence. Just by comparing participants with higher and lower scores, we could see which strategies led to better scores. For example, we found the following patterns from those diagrams:

(1) Those who caught more stars with their weak arms scored higher.
(2) Head movements were not related to scores. Essentially, it does not make a noticeable difference in the game whether a participant moved their head a lot or not in terms of the success of catching stars.
(3) Larger ranges of motions led to higher scores.
(4) Strong arm movements affect the scores very little (i.e., those who moved the strong arms more did not necessarily gain higher scores).

10.5 Discussion

This article reports on how we address the challenges of designing and evaluating a VR game that adapts an established physical therapy program through its game mechanics. The game was one of the first to leverage the HTC Vive for an immersive therapy experience that was evaluated by its intended users, participants with hemiparesis that need upper limb rehabilitation, as well as their therapists and caregivers. Our pilot study involved hemiparesis-affected participants with developmental disabilities. We gained useful insights on the need for simplifying the game instructions, mechanics, and reward structure, while still maintaining the idea of constraint-induced therapy. Therapists from Hope Services and SDLC provided input to assure that our translation of mCIT into VR was relevant and applicable. The stroke survivors who played our revised VR experience helped verify that our updated mechanics and game design made sense.

The scoring system and VR experience of Project Star Catcher encouraged players to actively perform upper limb rehabilitative motions in an engaging and stimulating environment. User evaluations provided us with some considerations for rehabilitation games that we will share with other researchers working with similar populations or developing similar systems. The data shows that the adherence rate of the user goes down when the stars are harder to catch. This can be seen in Figures 4 and 7; there is a noticeable trend that the users ended up using their strong arm to catch the gold stars whereas the strong arm catching rate is less for silver and bronze stars. Improvement for future iterations of PSC can be to spawn more high reward stars closer to the green Star Catcher to encourage players to use their weak arm. The immersive experience made the game exciting to play, but adding different types of games will make it more interesting according to participants. Because participants developed strategies to randomly catch stars by randomly waving their arms in a swiping motion, other game types can focus on emphasizing precision and patterns in their motion.

Gathering quantitative and qualitative data enabled us to relate the performance data with the qualitative explanation of why the performance data shows a certain pattern. One lesson learned is that, at least with people with disabilities that worked with us, observation data were more meaningful than interview data. Users do not always know what they need or can express it completely, so observing them with the game gave more meaningful conclusions. This could be because the disability renders their verbal responses to be less elaborate or that they were too polite to critique our design. However, our observation data did reveal that participants enjoyed the game, either because they stated it or through our video analysis of their behaviors. Some of them also stated that they would like to play more when their session were over, which indicated that the game was not boring. We also found out that data capture and automated analysis allowed us to cut down on the time required by human coders to extract themes related to behaviors and strategies. This is helpful for scaling sample size in future user evaluations.

On the design side, a lesson learned was to keep the game simple but to design different stimuli to be more salient in their differences. For example, in our pilot study we only used colors to differentiate star speeds. This color difference was not noticed at all. However, in the second iteration when we used more than one design feature to differentiate speeds, including colors, sizes, and shapes. These were noticed by the participants in the debrief interviews.

On the strategy for effective constraint-induced therapy, we learned that having larger ranges of motion for the weaker arms and varying movements (strategies) result in better game performance, which may lead to better, more effective exercise. In other words, unsurprisingly, to be more effective in doing constraint-induced therapy, users need to practice a variety of movements and extend their arms as much as they can.

11 CONCLUSION AND FUTURE WORK

Physical therapy can be boring, uncomfortable, and sometimes painful. This experience may result in less consistent participation from patients. We aim to contribute an engaging way of performing physical therapy through a VR game that rewards efforts in exercising hemiparesis-affected arms using the HTC Vive, a relatively new system as of this article. Our game was developed with user-centered design method involving representative stakeholders from Hope Services and Cabrillo College's Stroke and Disability Learning Center.

Project Star Catcher is based on an established therapy method called modified Constraint Induced Therapy. Our study indicated that it is possible to convert physical constraint proposed by mCIT into psychological constraint through game mechanics that are understandable by our target population. Test data suggest that such users were adherent to game rules, although the adherence rate declines when the difficulty level significantly exceeds their comfort level. Our data suggest that iVR in PSC yields noticeably larger adherence rates compared to traditional forms of mCIT.

Our study provided us with design guidelines for other researchers and practitioners in similar areas:

(1) Make sure that the feedback is perceived to be relevant to the goal of the therapy. Some of our users did not even notice audio and haptic feedback to indicate which hand caught the star as they were perceived to not directly relate to their goal of catching the next falling star, while our intention was that the audio and haptic feedback should inform them whether they had used the strong or weak arm so that in the future they were more compliant in using the weak arm.
(2) Make the different stimuli more salient in their differences using more than one design feature. When we differentiated stars with varying difficulties by only using colors, it was not noticed. However, when the stars were differentiated by color, shape, and size, they were noticed.
(3) Always triangulate quantitative and qualitative data, especially when working with people with disabilities that tend to be polite and might not elaborate as much as we expect.
(4) Not all qualitative or quantitative data are equal, so decide which one to follow when there is contradiction—in our study we found that observation was more insightful and truthful than interview data as the participants tend to be too polite to critique our game or not as eloquent in describing their experience. We chose to weight the observation data much higher than that of the interview data in those cases.

Specifically, on physical rehabilitation, our study also provided us with some design guidelines for other researchers and practitioners in these areas:

(1) To maintain adherence, design the game so that it can be set, for each user, to be relatively close to his/her comfort level in terms of speed, difficulty, range of motion, and so on. We noticed that even participants with the best intention of using only the weak arms switched to the strong arms when the game speed and range of motion required far exceeded their comfort level.
(2) Design the game flexibly so that it can accommodate a wide range of user strategies, as long as these strategies are in line with therapy goals (e.g., if the therapy goal is to make sure that user moves his/her arms with the widest possible ranges of motions, then make sure that the game mechanics can accommodate those who prefer to swipe their arms in circular, horizontal, or vertical fashions.
(3) Unless it violates therapy goals, always provide game pause feature to allow for users to rest when they feel fatigue, pick up the controller that fell, or explain the game mechanics again to the users.

While this game is a step towards improving mCIT into a more engaging experience, there are future plans for the game and study designs. After exploring the increased adherence and feasibility of using Project Star Catcher in this study, we aim to perform a longer term study with a larger user group. Our experimental design was a snapshot design in a controlled environment. We plan to perform a long-term study in a naturalistic setting (in our case, either at Hope Services exercise room, at user homes or at Cabrillo College). We also aim to explore Project Star Catcher's data output into potentially integrating the use of machine learning with the physical rehabilitation process. The HTC Vive Trackers can be integrated to perform full body motion capture that will integrate the whole human body as a controller, eliminating the need to develop methods to hold the controller. This change will also enable PSC to provide full body data for therapists. Lastly, Project Star Catcher can benefit from the creation of a cloud-based therapist interface to make the collection and visualization of data more impactful.

In closing, we believe that we are in the right direction in developing a VR game based on an established therapy program that is portable, engaging, and understandable while being able to provide compliance, adherence, and performance data in an efficient way.

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REFERENCES

Gilda Aparecida de Assis, Ana Grasielle Dionísio Corrêa, Maria Bernardete Rodrigues Martins, Wendel Goes Pedrozo, and Roseli de Deus Lopes. 2016. An augmented reality system for upper-limb post-stroke motor rehabilitation: A feasibility study. *Disabil. Rehabil. Assist. Technol.* 11, 6 (2016), 521–528.

Alejandro Baldominos, Yago Saez, and Cristina García del Pozo. 2015. An approach to physical rehabilitation using state-of-the-art virtual reality and motion tracking technologies. *Proced. Comput. Sci.* 64 (2015), 10–16.

Stacy J. Morris Bamberg, Ari Y. Benbasat, Donna Moxley Scarborough, David E. Krebs, and Joseph A. Paradiso. 2008. Gait analysis using a shoe-integrated wireless sensor system. *IEEE Trans. Inf. Technol. Biomed.* 12, 4 (2008), 413–423.

Rosa María Baños, Cristina Botella, Mariano Alcañiz, Víctor Liaño, Belén Guerrero, and Beatriz Rey. 2004. Immersion and emotion: Their impact on the sense of presence. *CyberPsychol. Behav.* 7, 6 (2004), 734–741.

Corey J. Bohil, Bradly Alicea, and Frank A. Biocca. 2011. Virtual reality in neuroscience research and therapy. *Nat. Rev. Neurosci.* 12, 12 (2011), 752–762.

Nancy N. Byl, Gary M. Abrams, Erica Pitsch, Irina Fedulow, Hyunchul Kim, Matt Simkins, Srikantan Nagarajan, and Jacob Rosen. 2013. Chronic stroke survivors achieve comparable outcomes following virtual task specific repetitive training guided by a wearable robotic orthosis (UL-EXO7) and actual task specific repetitive training guided by a physical therapist. *J. Hand Ther.* 26, 4 (2013), 343–352.

Mónica S. Cameirão, S. Bermúdez, and P. F. M. J. Verschure. 2008. Virtual reality based upper extremity rehabilitation following stroke: A review. *J. CyberTher. Rehabil.* 1, 1 (2008), 63–74.

R. Campbell, M. Evans, M. Tucker, B. Quilty, P. Dieppe, and J. L. Donovan. 2001. Why don't patients do their exercises? Understanding non-compliance with physiotherapy in patients with osteoarthritis of the knee. *J. Epidemiol. Commun. Health* 55, 2 (2001), 132–138.

Stephanie K. Carter and John A. Rizzo. 2007. Use of outpatient physical therapy services by people with musculoskeletal conditions. *Phys. Ther.* 87, 5 (2007), 497.

Derwin K. Chan, Chris Lonsdale, Po Y. Ho, Patrick S. Yung, and Kai M. Chan. 2009. Patient motivation and adherence to postsurgery rehabilitation exercise recommendations: The influence of physiotherapists' autonomy-supportive behaviors. *Arch. Phys. Med. Rehabil.* 90, 12 (2009), 1977–1982.

Luca Chittaro, Riccardo Sioni, Cristiano Crescentini, and Franco Fabbro. 2017. Mortality salience in virtual reality experiences and its effects on users attitudes towards risk. *Int. J. Hum.-Comput. Stud.* 101 (2017), 10–22.

Davide Corbetta, Federico Imeri, and Roberto Gatti. 2015. Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: A systematic review. *J. Physiother.* 61, 3 (2015), 117–124.

GSV Capital Corp. 2013. GSV Capital Corp. The Pioneer Building. Retrieved from http://gsvcap.com/wp/market-commentary/project-runway/.

Patrick J. Costello. 1997. *Health and Safety Issues Associated with Virtual Reality: A Review of Current Literature.* Advisory Group on Computer Graphics.

J. H. Crosbie, S. Lennon, J. R. Basford, and S. M. McDonough. 2007. Virtual reality in stroke rehabilitation: Still more virtual than real. *Disabil. Rehabil.* 29, 14 (2007), 1139–1146.

Mónica da Silva Cameirão, Sergi Bermúdez i Badia, Esther Duarte, and Paul F. M. J. Verschure. 2011. Virtual reality based rehabilitation speeds up functional recovery of the upper extremities after stroke: A randomized controlled pilot study in the acute phase of stroke using the rehabilitation gaming system. *Restor. Neurol. Neurosci.* 29, 5 (2011), 287–298.

Julieta Dascal, Mark Reid, Waguih William IsHak, Brennan Spiegel, Jennifer Recacho, Bradley Rosen, and Itai Danovitch. 2017. Virtual reality and medical inpatients: A systematic review of randomized, controlled trials. *Inn. Clin. Neurosci.* 14, 1–2 (2017), 14.

Judith E. Deutsch, Jeffrey A. Lewis, and Grigore Burdea. 2007. Technical and patient performance using a virtual reality-integrated telerehabilitation system: Preliminary finding. *IEEE Trans. Neur. Syst. Rehabil. Eng.* 15, 1 (2007), 30–35.

Julia Diemer, Georg W. Alpers, Henrik M. Peperkorn, Youssef Shiban, and Andreas Mühlberger. 2015. The impact of perception and presence on emotional reactions: A review of research in virtual reality. *Front. Psychol.* 6, Article 26 (2015), 1–9.

Sheryl Flynn, Phyllis Palma, and Anneke Bender. 2007. Feasibility of using the sony playstation 2 gaming platform for an individual poststroke: A case report. *J. Neurol. Phys. Therapy* 31, 4 (2007), 180–189.

AMP New Ventures Follow. 2016. Virtual Reality (VR) Continuum—AMP New Ventures. Retrieved from https://www.slideshare.net/ampnewventures/virtual-reality-vr-continuum-amp-new-ventures.

Centers for Medicare and Medicaid Services. 2016. U.S. Department of Health and Human Services Centers for Medicare & Medicaid Services (CMS). Report to the Congress: Medicare Payment Policy. Technical Report, 2016. Retrieved February 7, 2016 from http://www.medpac.gov/docs/default-source/reports/march-2016-report-to-the-congress-medicare-payment-policy.pdf?sfvrsn=0.

Helena Grillon, Françoise Riquier, Bruno Herbelin, and Daniel Thalmann. 2006. Virtual reality as a therapeutic tool in the confines of social anxiety disorder treatment. *Int. J. Disabil. Hum. Dev.* 5, 3 (2006), 243–250.

Diane Gromala, Xin Tong, Amber Choo, Mehdi Karamnejad, and Chris D. Shaw. 2015. The virtual meditative walk: Virtual reality therapy for chronic pain management. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 521–524.

Sophie Heins, Stéphanie Dehem, Vincenza Montedoro, Franz Rocca, Pierre-Henri de Deken, Martin Edwards, Bruno Dehez, Matei Mancas, Gaëtan Stoquart, Thierry Lejeune, et al. 2017. Robotic-assisted serious game for motor and cognitive post-stroke rehabilitation. In *Proceedings of the 5th IEEE Conference on Serious Games and Applications for Health*.

Hunter G. Hoffman, Gloria T. Chambers, Walter J. Meyer, Lisa L. Arceneaux, William J. Russell, Eric J. Seibel, Todd L. Richards, Sam R. Sharar, and David R. Patterson. 2011. Virtual reality as an adjunctive non-pharmacologic analgesic for acute burn pain during medical procedures. *Ann. Behav. Med.* 41, 2 (2011), 183–191.

Jerome Iruthayarajah, Amanda McIntyre, Andreea Cotoi, Steven Macaluso, and Robert Teasell. 2017. The use of virtual reality for balance among individuals with chronic stroke: A systematic review and meta-analysis. *Top. Stroke Rehabil.* 24, 1 (2017), 68–79.

Kirsten Jack, Sionnadh Mairi McLean, Jennifer Klaber Moffett, and Eric Gardiner. 2010. Barriers to treatment adherence in physiotherapy outpatient clinics: A systematic review. *Manual Therapy* 15, 3 (2010), 220–228.

Eun-Kyu Ji and Sang-Heon Lee. 2016. Effects of virtual reality training with modified constraint-induced movement therapy on upper extremity function in acute stage stroke: A preliminary study. *J. Phys. Ther. Sci.* 28, 11 (2016), 3168–3172.

Dahlia Kairy, Michel Tousignant, Nancy Leclerc, Anne-Marie Côté, Mélanie Levasseur, et al. 2013. The patients perspective of in-home telerehabilitation physiotherapy services following total knee arthroplasty. *Int. J. Environ. Res. Publ. Health* 10, 9 (2013), 3998–4011.

Michelle R. Kandalaft, Nyaz Didehbani, Daniel C. Krawczyk, Tandra T. Allen, and Sandra B. Chapman. 2013. Virtual reality social cognition training for young adults with high-functioning autism. *J. Autism Dev. Disord.* 43, 1 (2013), 34–44.

Oliver Kreylos. 2016. Lighthouse tracking examined. Retrieved from http://doc-ok.org/?p=1478.

Danielle E. Levac, Stephanie M. N. Glegg, Heidi Sveistrup, Heather Colquhoun, Patricia Miller, Hillel Finestone, Vincent DePaul, Jocelyn E. Harris, and Diana Velikonja. 2016. Promoting therapists use of motor learning strategies within virtual reality-based stroke rehabilitation. *PloS One* 11, 12 (2016), e0168311.

Mindy F. Levin, Osnat Snir, Dario G. Liebermann, Harold Weingarden, and Patrice L. Weiss. 2012. Virtual reality versus conventional treatment of reaching ability in chronic stroke: Clinical feasibility study. *Neurol. Ther.* 1, 1 (2012), 3.

Robert W. Lindeman, Yasuyuki Yanagida, Kenichi Hosaka, and Shinji Abe. 2006. The tactapack: A wireless sensor/actuator package for physical therapy applications. In *Proceedings of the 2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 337–341.

Roberto Lloréns, Enrique Noé, Carolina Colomer, and Mariano Alcañiz. 2015. Effectiveness, usability, and cost-benefit of a virtual reality–based telerehabilitation program for balance recovery after stroke: A randomized controlled trial. *Arch. Phys. Med. Rehabil.* 96, 3 (2015), 418–425.

Keith R. Lohse, Courtney G. E. Hilderman, Katharine L. Cheung, Sandy Tatla, and H. F. Machiel Van der Loos. 2014. Virtual reality therapy for adults post-stroke: A systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS One* 9, 3 (2014), e93318.

Peter S. Lum, Gitendra Uswatte, Edward Taub, Phillip Hardin, and Victor W. Mark. 2006. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J. Rehabil. Res. Dev.* 43, 3 (2006), 391.

Victor W. Mark and Edward Taub. 2004. Constraint-induced movement therapy for chronic stroke hemiparesis and other disabilities. *Restor. Neurol. Neurosci.* 22, 3–5 (2004), 317–336.

Gary Marshall. 2016. Best VR controller: HTC Vive vs Oculus Rift vs PlayStation VR vs Gear VR. Retrieved April 30, 2017 from http://www.techradar.com/news/gaming/best-vr-controller-htc-vive-vs-oculus-rift-vs-.

R. R. Mellecker and A. M. McManus. 2014. Active video games and physical activity recommendations: A comparison of the Gamercize Stepper, XBOX Kinect and XaviX J-Mat. *J. Sci. Med. Sport* 17, 3 (2014), 288–292.

Nexhmedin Morina, Hiske Ijntema, Katharina Meyerbröker, and Paul M. G. Emmelkamp. 2015. Can virtual reality exposure therapy gains be generalized to real-life? A meta-analysis of studies applying behavioral assessments. *Behav. Res. Ther.* 74 (2015), 18–24.

Hossein Mousavi Hondori and Maryam Khademi. 2014. A review on technical and clinical impact of microsoft kinect on physical therapy and rehabilitation. *J. Med. Eng.* 2014 (2014).

Maria V. Nararro-Haro, Hunter G. Hoffman, Azucena Garcia-Palacios, Mariana Sampaio, Wadee Alhalabi, Karyn Hall, and Marsha Linehan. 2016. The use of virtual reality to facilitate mindfulness skills training in dialectical behavioral therapy for borderline personality disorder: A case study. *Front. Psychol.* 7, Article 1573 (2016), 1–9.

Diederick C. Niehorster, Li Li, and Markus Lappe. 2017. The accuracy and precision of position and orientation tracking in the HTC vive virtual reality system for scientific research. *i-Perception* 8, 3 (2017), 2041669517708205.

NINDS. 2014. Post-Stroke Rehabilitation. NIH Publication No. 14 1846. Retrieved April 30, 2017 from https://stroke.nih.gov/materials/rehabilitation.html.

Stephen J. Page, Peter Levine, Sueann Sisto, Quin Bond, and Mark V. Johnston. 2002. Stroke patients' and therapists' opinions of constraint-induced movement therapy. *Clin. Rehabil.* 16, 1 (2002), 55–60.

Marco Pasch, Nadia Berthouze, Betsy Dijk, and Anton Nijholt. 2008. Motivations, strategies, and movement patterns of video gamers playing Nintendo Wii boxing. In *Proceedings of the Facial and Bodily Expressions for Control and Adaptation of Games Workshop.*

Lamberto Piron, Andrea Turolla, Michela Agostini, Carla Zucconi, Feliciana Cortese, Mauro Zampolini, Mara Zannini, Mauro Dam, Laura Ventura, Michela Battauz, et al. 2009. Exercises for paretic upper limb after stroke: A combined virtual-reality and telemedicine approach. *J. Rehabil. Med.* 41, 12 (2009), 1016–1020.

Barbara Olasov Rothbaum, Matthew Price, Tanja Jovanovic, Seth D. Norrholm, Maryrose Gerardi, Boadie Dunlop, Michael Davis, Bekh Bradley, Erica J. Duncan, Albert Rizzo, et al. 2014. A randomized, double-blind evaluation of D-cycloserine or alprazolam combined with virtual reality exposure therapy for posttraumatic stress disorder in Iraq and Afghanistan War veterans. *Am. J. Psychiat.* 171, 6 (2014), 640–648.

Anil K. Roy, Yash Soni, and Sonali Dubey. 2013. Enhancing effectiveness of motor rehabilitation using kinect motion sensing technology. In *Proceedings of the 2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS'13).* IEEE, 298–304.

Mar Rus-Calafell, José Gutiérrez-Maldonado, and Joan Ribas-Sabaté. 2014. A virtual reality-integrated program for improving social skills in patients with schizophrenia: A pilot study. *J. Behav. Ther. Exp. Psychiat.* 45, 1 (2014), 81–89.

Yasser Salem, Stacy Jaffee Gropack, Dale Coffin, and Ellen M. Godwin. 2012. Effectiveness of a low-cost virtual reality system for children with developmental delay: A preliminary randomised single-blind controlled trial. *Physiotherapy* 98, 3 (2012), 189–195.

Gustavo Saposnik, Mindy Levin, Stroke Outcome Research Canada (SORCan) Working Group, et al. 2011. Virtual reality in stroke rehabilitation. *Stroke* 42, 5 (2011), 1380–1386.

Gustavo Saposnik, Robert Teasell, Muhammad Mamdani, Judith Hall, William McIlroy, Donna Cheung, Kevin E. Thorpe, Leonardo G. Cohen, Mark Bayley, et al. 2010. Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation. *Stroke* 41, 7 (2010), 1477–1484.

Dante D'Orazio Savov and Vlad. 2015. Valve's VR headset is called the Vive and it's made by HTC. Retrieved from https://www.theverge.com/2015/3/1/8127445/htc-vive-valve-vr-headset.

Yue X. Shi, Jin H. Tian, Ke H. Yang, and Yue Zhao. 2011. Modified constraint-induced movement therapy versus traditional rehabilitation in patients with upper-extremity dysfunction after stroke: A systematic review and meta-analysis. *Arch. Phys. Med. Rehabil.* 92, 6 (2011), 972–982.

Youssef Shiban, Iris Schelhorn, Paul Pauli, and Andreas Mühlberger. 2015. Effect of combined multiple contexts and multiple stimuli exposure in spider phobia: A randomized clinical trial in virtual reality. *Behav. Res. Ther.* 71 (2015), 45–53.

Fabian Soffel, Markus Zank, and Andreas Kunz. 2016. Postural stability analysis in virtual reality using the HTC vive. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*. ACM, 351–352.

Digital Trends Staff. 2017. Oculus Rift vs. HTC Vive. Retrieved from https://www.digitaltrends.com/virtual-reality/oculus-rift-vs-htc-vive/.

Sofia Straudi, Giacomo Severini, Amira Sabbagh Charabati, Claudia Pavarelli, Giulia Gamberini, Anna Scotti, and Nino Basaglia. 2017. The effects of video game therapy on balance and attention in chronic ambulatory traumatic brain injury: An exploratory study. *BMC Neurol.* 17, 1 (2017), 86.

Daria Tsoupikova, Kristen Triandafilou, Saumya Solanki, Alex Barry, Fabian Preuss, and Derek Kamper. 2016. Real-time diagnostic data in multi-user virtual reality post-stroke therapy. In *Proceedings of the SIGGRAPH ASIA 2016 VR Showcase (SA'16)*. ACM, New York, NY. DOI: https://doi.org/10.1145/2996376.2996387

Pan Wang, Gerald Choon Huat Koh, Christian Gilles Boucharenc, Tian Ma Xu, Hamasaki, and Ching Chiuan Yen. 2017. Developing a tangible gaming board for post-stroke upper limb functional training. In *Proceedings of the 11th International Conference on Tangible, Embedded, and Embodied Interaction (TEI'17)*. ACM, New York, NY, 617–624. DOI: https://doi.org/10.1145/3024969.3025080

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