USING ERROR AUGMENTATION IN IMMERSIVE VIRTUAL REALITY FOR BIMANUAL UPPER-LIMB REHABILITATION

by

Leia Carmel Shum

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis/dissertation entitled:

Using Error Augmentation in Immersive Virtual Reality for Bimanual Upper-Limb Rehabilitation

submitted by Leia Carmel Shum in partial fulfillment of the requirements for the degree of Master of Applied Science in Biomedical Engineering

Examining Committee:

Professor H.F. Machiel Van der Loos
Supervisor

Dr. Bulmaro Valdés
Co-supervisor

Professor Nicola Hodges
Supervisory Committee Member

Professor Roger Tam (Chair)
Additional Examiner

Additional Supervisory Committee Members:

Professor Tal Jarus
Supervisory Committee Member

Supervisory Committee Member
Abstract

A common treatment for people with motor disabilities due to neurological injuries, such as Cerebral Palsy, is physiotherapy. However, the repetitive nature of clinical upper-limb rehabilitation exercises can lead to a decrease in patient adherence, and so, there is a need for more engaging methods of motor task training that can be used in inexpensive at-home programs. One such alternate solution is the use of exergaming technology, which harnesses commercially available motion-tracking gaming hardware to administer rehabilitative exercises that provide automated real-time feedback and engaging game mechanics.

In addition to real-time feedback during exercises in the form of binary visual cues, reminders, and scores, Error augmentation (EA), or dynamic feedback based on deviation from desired movement patterns, has been shown to provide an increased rate of improvement in motor ability. The goal of this thesis study was to build upon the idea of training with EA and to evaluate the effectiveness of the amplification of asymmetry between the two upper limbs during a bilateral reaching movement. To test if this mode of error augmentation increases symmetry in the forward-reaching direction, a bimanual training task was developed in an immersive virtual reality environment.

A single-session crossover study design was used to test if participants could reach with more bilateral symmetry when training with EA. Participants with hemiplegia and healthy age-matched participants completed training sets with and without EA. Results found a significant difference in symmetry between the two sets in the typically developing participant group. Both primary and secondary outcomes showed high variability in between-participant averages; it is suggested that a future study be conducted with a larger sample size of participants with hemiplegia. While statistically significant differences could not be found for the target clinical population, the effect of EA on the typically developing participant group provides a promising indication of a useful feedback modality that could be used in future upper-limb rehabilitation tools.
Lay Summary

Children with motor disabilities often struggle to handle daily activities without lots of physiotherapy and practice. It is important to provide engaging ways to encourage them to keep participating in their exercises. One way is to use gaming technology, which gives immediate and constant feedback, even without a physiotherapist present. This study tested a new method of training feedback that targets improving symmetry between left and right hands during two-handed reaching movements. The study used a simple game in virtual reality that allowed the user to see in 3D. Results found that the feedback improved symmetry in a group of healthy teens and young adults. Five participants with motor disabilities were also able to improve in symmetry, but it was difficult to make a definite conclusion since participants had varying levels of improvement. This feedback method could be used in future rehabilitation programs to increase adherence to practice goals.
Preface

This research was performed under the supervision of Dr. H.F. Machiel Van der Loos and Dr. Bulmaro Valdés with the Department of Mechanical Engineering and the School of Biomedical Engineering at the University of British Columbia. The author was responsible for performing background literature review, developing the virtual environment, integrating the software and hardware components of the technical setup, recruiting subjects, conducting the experiment and data analysis, and writing the manuscript. Both supervisors and members of the supervisory committee, Dr. Nicola Hodges and Dr. Tal Jarus, provided guidance and review of study protocols and manuscripts.

The main human-subjects experiment was conducted with the approval of the UBC Clinical Research Ethics Board under application number H17-01126, “FEATHERS 2.0”. Part of the data processing script used during data analysis was developed by Candy Lin, an undergraduate student who worked under the author’s direct supervision, and part of the study recruitment process was completed with the support of Daphne O’Young, a physiotherapist at BC Children’s Hospital.

A paper reporting preliminary results with two of the participants from the main study was accepted for presentation at RehabWeek 2019 in the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) as a podium presentation.
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List of Abbreviations

ABI – Acquired Brain Injury
BCCH – BC Children’s Hospital
BFMF – Bimanual Fine Motor Function (clinical assessment)
CHP – Clinical Hemiplegic Population (participant group)
CIMT – Constraint-induced movement therapy
CP – Cerebral Palsy
CSV – Comma-separated values (file type)
D/LA – Dominant /Less-Affected
EA – Error Augmentation
HMD – Head-mounted Display
IQR – Interquartile Range (used as Median (IQR))
MACS – Manual Ability Classification System (clinical assessment)
ND/A – Non-dominant /Affected
RMSE – Root-mean-squared Error (performance metric)
ROM – Range of Motion
STD – Standard Deviation (used as Average ± STD)
SUS – System Usability Scale
TDP – Typically Developing Population (participant group)
VR – Virtual Reality
List of Symbols

\( A \) – overall change, a performance curve parameter that measures the overall change during a repeated task training set

\( B \) – rate of change, a performance curve parameter that measures how quickly the change in performance over repeated trials plateaus

\( C \) – final performance value, a performance curve parameter that measures what the performance metric should be after changes in motor adaptation plateau

\( G \) – Augmentation gain factor, a constant value of 2 times the true error.

\( Z_{asy} \) – the forward reaching position of the ND/A side after 70\% asymmetry was applied

\( Z_{ND/A} \) – the forward reaching position of the ND/A side in the z-axis

\( Z_{D/LA} \) – the forward reaching position of the D/LA side in the z-axis

\( \eta^2_{partial} \) – partial-eta-squared, used to measure the effect size of an ANOVA test

\( d \) – Cohen’ d, used to measure the effect size of paired t-tests
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Dedication

For the kids!
Chapter 1: Introduction

Cerebral Palsy (CP) is the most common neurodevelopmental motor disability, occurring in approximately 1 in 500 births worldwide [1], [2]. Approximately 25% of people with CP have hemiplegia [3], in which one side of the body is more affected than the other. Children with CP have permanent physical disabilities that often require them to have extended assistance for self-care. Additionally, these children exhibit abnormal muscle tone and loss of voluntary motor control of the upper limbs which can limit the daily activities they are able to do [4]. Both people with CP and their caretakers are reported to have a significantly lower quality of life due to these motor impairments [5], [6]. Children who have more severe motor impairment (lowest 36% of the population) never recover enough function to act independently [7], and some children may also develop secondary musculoskeletal problems over time [8]. To restore, improve, and maintain functional motor ability, physical therapy is commonly presented as a key rehabilitative treatment to neurological impairments like CP [9].

1.1 Motivation

There are several important challenges and unmet needs in current motor rehabilitation practices. Traditional repetitive-task motor rehabilitation can be tedious, and the lack of stimulation and motivation in patients can prevent these exercises from being more effective [10]. In studies regarding stroke rehabilitation in adults, it was found that there is typically a large disparity between the number of repetitions received in therapy and the number required to elicit functional change [11], [12]. A systematic review by Cope [13] found a lack of studies researching the number of repetitions required for children with CP to see functional motor improvement. The 2016 American National Survey of Children with Special Health Care Needs found 1 in 5 children with self-reported unmet therapy needs [14]. The adolescent or young adult population make up a large proportion of individuals with CP who no longer receive clinical therapy after initial hospital admittance [15]. This lack of adherence to any continuing therapy exercises could lead to an early decline in functional ability.

Deterioration of unused motor capabilities can also be caused by maladaptive motor patterns or compensation techniques [16], such as excess trunk flexion or elbow elevation during forward
reaching. These techniques can occur during exercises without additional feedback from either a therapist or a restrictive physical constraint and may limit the recovery of normal reaching patterns of the arm or cause secondary complications in muscle tone and joint misalignment [17]. Acquired inactivity of the affected limb after a neurological injury, defined as “learned non-use” [16], can be detrimental to motor recovery and is more difficult to reverse and replace with the desired movement pattern over time. More active and adaptive corrective feedback to prevent the development of these unfavourable movement patterns is crucial for successful upper-limb rehabilitation.

In order to reduce the use of compensation techniques used during rehabilitative exercises, consistent feedback cues are required from either a physiotherapist or an adaptive tool. Quantifying active and passive range of motion, joint torques, use of compensatory movements, and other movement kinematics may prove to be of benefit to motor rehabilitation goals. These measurements can provide live feedback about movement patterns and present adaptive cues without the constant presence of a physiotherapist. Quantitative tracking tools integrated into rehabilitation platforms have also been found to be useful in making direct comparisons between different rehabilitation regimens and to track day-to-day progress with more detail than clinical scores [18]. These tools may also better facilitate the implementation of adaptive difficulty levels of existing rehabilitative training regimens based on individual progress to prevent loss of motivation and dropout [19].

Motor rehabilitation programs based on at-home, low-cost, commercial gaming devices have been shown to improve upper-limb performance [20]–[23]. A comparison of traditional therapy to therapy using active gaming tools found that the number of repetitions increased immediately with the inclusion of active gaming during the rehabilitative session [24]. With the emergence of commercially available immersive virtual reality (VR) technology with motion-tracked controls such as the Oculus Rift and HTC Vive – both released in early 2016, further exploration into using VR in active gaming is warranted [25].

Other motor training techniques could also be combined with active gaming technology to promote better rehabilitative results. The alignment of the weak and strong sides in motor rehabilitation has been shown to increase neuroplastic growth [26] via the linking of cerebral
hemispheres during symmetric bimanual tasks [27], [28]. Additionally, the combination of motion-tracked controls and digital displays presents an opportunity to explore dynamic and augmented feedback based on individual movement patterns. One such feedback modality is error augmentation (EA), in which deviations from desired movement patterns are measured and used to scale feedback provided during the rehabilitative task.

1.2 Thesis Overview

The objective of this thesis is to evaluate the effectiveness of augmented visual feedback that could be implemented in engaging home-based physical therapy systems for persons with upper-limb motor impairments. The main purpose of this study was to explore the effect of using an immersive VR environment to manipulate visual feedback by creating an engaging space with active feedback, as well as allowing 3-dimensional (3D) movements paired with more veridical visual depth than would be seen on a computer screen.

This thesis addresses the question of whether error augmentation aids in the rehabilitation of the affected upper limb in youth with hemiplegia when practicing bimanual tasks. Specifically: Does visual amplification of hand position asymmetry in an immersive VR environment during bimanual task training increase movement quality in the more affected upper limb? An experiment was set up to test if this visual augmentation would positively affect one’s ability to maintain symmetry during a bilateral forward reach. A study was performed to explore the use of error augmentation of the difference between reaching positions of the upper limbs. Motor adaptation to lateral symmetry in a forward bimanual reaching task was used as a starting point to explore possible new motor learning techniques that could be better promoted by active gaming programs.

This thesis begins with a review of existing literature in Chapter 2, in which three key components used within the research study are described: symmetrical bimanual task training, immersive VR technology, and visual error augmentation feedback. This information was used to determine specific factors to test within the main experiment. Chapter 3 details the technical and structural design considerations for a virtual environment with an augmentable upper-limb reaching task. A single-session crossover study design is described, and the calculation of primary and secondary kinematic outcomes is explained. Key results from the study are
presented in Chapter 4: the primary outcome data from typically developing participants were tested for statistical significance, a summation of data from clinically relevant populations was used to provide a prediction of similar patterns, and the two populations were compared in terms of both kinematic and qualitative outcomes. Chapter 5, Discussion, further explores the implications of the study results in relation to the research question. Limitations of the study design are discussed and suggestions for future studies were outlined.
Chapter 2: Background and Literature Review

The following section is a review of existing methods used for recovering upper-limb motor function in persons with hemiplegia. Existing scientific literature on training with feedback based on two-handed symmetry, training in an immersive virtual environment, and training with visual error augmentation was evaluated for potential benefits and gaps in research needs. The development of this thesis project was founded on these three key concepts used in upper-limb motor rehabilitation.

2.1 Physiological Mechanisms in Hemiplegic Neural Injuries

Hemiplegia is defined as weakness on one side of the body causing lateral asymmetry in upper and lower limb mobility [29]. This type of motor impairment is found in many groups with neurological injuries including Cerebral Palsy, Acquired Brain Injury (ABI), and stroke in the paediatric, adult, and elderly populations. Hemiplegia is among the most common motor syndromes, presenting in about 25% of the CP population [3]. Furthermore, children who suffer hemiplegic motor impairment from similar neural injuries - typically diagnosed as ABI or paediatric stroke at 3 years of age and onwards - are not always accounted for in combined incidence analyses [30]. Paediatric hemiplegia and adult stroke have similar injury mechanisms in that lesions are commonly isolated to the side of the brain that is contralateral to the limb with higher motor deficiency [31].

While impairment can also affect both sides, the motor dysfunction is classified as hemiplegia when one side is more affected than the other. In most cases, the upper limb is affected not only in range of motion, but in gross and fine motor control as well. Motor impairments can be further described based on movement patterns or behaviours such as spasticity, a lack of voluntary isotonic muscle control, ataxia, a lack of motor coordination, or dystonia, sustained or repetitive muscle contractions. People with hemiplegia commonly exhibit a combination of these symptoms [32].

Reviewed literature in Chapter 2 includes studies on hemiplegic motor disabilities of all ages as similar outcomes are expected if the disorder is caused by a non-progressive neural injury. However, there may be some differences in neuroplastic learning capabilities, skill recovery, and
delayed skill acquisition between the paediatric and adult populations [33]. In order to avoid any confounding factors, this thesis will only collect experimental data from the pediatric population.

2.2 Upper-Limb Motor Rehabilitation for Hemiplegia

Since the injury mechanisms in hemiplegic motor disorders are not progressive or degenerative, treatment typically focuses on strengthening and preventing deterioration of existing motor function through consistent practice and rehabilitative physiotherapy. Repetitive task therapy, in which patients will engage their affected limbs in a practice movement or task repeatedly, is the most common method of rehabilitation for upper-limb function [34]. However, as discussed in Chapter 1:, the average number of repetitions during therapy sessions is often insufficient to achieve measurable functional changes in motor ability.

There are many programs and additional treatment protocols that can be prescribed in conjunction with repetitive task training to increase the rate of functional improvement in the upper limb. Some children with motor deficiencies caused by CP may undergo orthopaedic surgical procedures to provide permanent constraints on spastic movements. Surgical tendon transfer or muscle lengthening can also ease movement constraints created by muscles with excess tone [35], [36]. As these procedures make permanent changes to the biomechanical structure of the patient, they are usually recommended as ‘last-resort’ interventions and still require concurrent physiotherapy treatments [37]. Non-permanent constraints in the form of splinting and botulinum toxin treatments can be prescribed to children with low selective motor control or dystonia in specific muscle groups [38]. Splints and injection treatments aim to constrain these muscle groups and allow patients to focus on exercising weaker muscles that would otherwise be negated by the involuntary muscle tone [39]. However, the benefits of non-permanent constraints were found to diminish once the constraints are removed [40].

A type of therapeutic programming that intentionally uses non-permanent constraints is Constraint-Induced Movement Therapy (CIMT). CIMT is specific to hemiplegic motor dysfunction as physical constraints are placed on the less-affected upper limb to encourage use and practice with the more affected side [41]. A study by Gilmore [42] found that for CIMT programs to succeed, the functional outcome and motivation must outweigh patient frustration or discomfort. CIMT may elicit better functional improvement in younger children, as older
children who have more learned non-use may find restraints more frustrating [43]. Some CIMT programs found success in improving functional ability in the more affected limb in children with CP; however, many successful programs also append a bimanual therapy component after initial CIMT training [44], [45] to increase the transfer of treatment gains to real-world activities.

Bimanual task training offers rehabilitative practices that involve both the less and more affected upper limbs. Children with hemiplegic motor disorders may participate in weekly physiotherapy clinic visits or in intensive day-camp programs, such as HABIT, a successful bimanual training program for children with hemiplegic CP [46]. Patients are enrolled in different levels of therapy programming depending on the severity of the injury’s effect on their daily quality of life. In studies comparing CIMT and bimanual task training, it was recommended that these practice styles should not be used exclusively of each other, but used together to train different aspects of functional motor ability development [47], [48].

2.2.1 Symmetry in Bimanual Task Training

The use of bimanual task training, defined as training with tasks requiring both left and right upper limbs used together to promote the use of the affected limb, has been suggested to engage neuroplastic growth mechanisms by encouraging cross-hemispheric activity and cortical reorganization [27]. A study using near-infrared spectroscopy (NIRS) with healthy individuals during a tracked trajectory-following task found increased cerebral activation in a bimanual mode in comparison to the parallel unimanual task [49], while Walsh [50] reported that tasks requiring simultaneous bimanual movement excited more cortical networks than the sum of two unimanual tasks performed with opposite upper limbs. Previous analysis by Summers [51] and Cauraugh [52] found support for the inclusion of bilateral movement training to rehabilitative regimens for neuroplastic recovery in unilateral stroke.

Transfer of improvement in bimanual task training to other functional motor capabilities has also been found. Significant improvement in both practiced and unpracticed functional tasks used for self-care and daily living was reported by de Brito Brandao [53] and Gordon [54] in studies evaluating bimanual therapy programs for children with CP. In a robotic training task tested with healthy adults, positive results were found showing transfer from bimanual training to unimanual training [55]. Post-stroke bimanual training also proved to be at least as efficient as unimanual
practice in improving overall affected-limb function [56]. As there are many daily bimanual activities, like moving trays, folding laundry, and pushing chairs, that require symmetric interaction, persons with asymmetric upper-limb motor capabilities may require training specifically to improve symmetry to independently complete these tasks [57].

There is some discrepancy in studies reporting the advantages and disadvantages of symmetric bimanual task training over asymmetric coordination practice. Sleimen-Malkoun [58] warned against inappropriate coupling of bilateral movements that could cause maladaptive motor behaviour and recommended training with coordinated synergies for specific functional tasks used in activities of daily living. The publication stated that bilateral training may only be beneficial for the more affected upper limb when bimanual coupling is unimpaired. In contrast, Smorenburg [59] reported that having a mirror comparison to follow during bimanual upper-limb reaching improved position sense in the impaired arms of children with spastic hemiplegia. The study suggested that the target reaching error immediately decreased due to the real-time symmetric visual feedback during the bimanual portion of the experiment. This finding coincides with a study by Cohen [60], which concluded that mirror symmetry, in which the same muscle groups were engaged on either side, provided more synchronous movements than joint-space symmetry, in which the contralateral upper limbs recruited non-homologous muscle groups. Mirror therapy with patients with subacute stroke was also found to improve clinical motor scores more than conventional practice [61].

Currently, there is a limited amount of research dedicated to the development of engaging rehabilitation technology involving bimanual task training for the younger hemiplegic population. At least one existing gaming system used for neurorehabilitation, the Rehabilitation Gaming System (RGS) [62], presented improvement in the upper-limb movement of chronic stroke patients and significant transfer to real-world tasks but was not tested specifically with synchronous bilateral tasks or a developing paediatric population. The Functional Engagement in Assisted Therapy Through Exercise Robotics (FEATHERS) system [63], a platform adapted from commercially available gaming technology, explored bimanual movement and hemiplegic populations of all ages. It was found from usability testing that the majority of participants enjoyed playing games with the motion tracked controls [64], but no kinematic changes were reported from this project.
2.3 Exergaming and Gamification in a Rehabilitative Setting

Exergaming, ‘active gaming’, or the use of game design elements and motion-tracking controls to promote exercise, provides abundant opportunities to develop new and engaging tools for repetitive task training and real-time feedback methods to encourage higher quality bimanual movement. Gaming systems adapted successfully for rehabilitative purposes include protocols using the Nintendo Wii [20], [21], [65], Microsoft Kinect [22], [23], [66], and PlayStation Move [63]. Custom-developed systems for exergaming specific to motor rehabilitation for paediatric populations have also been employed effectively in clinical and at-home programs [67], [68]. Each of these rehabilitation tools was able to track and quantify movement, and thus could also provide higher resolution measures of motor ability to complement clinical motor classification systems and better track therapy goals and progression [18]. The use of exergaming technology allows integration of patient assessment and monitoring into the practice portion of a rehabilitation session [69].

In addition to the advances in quantitative goal tracking that exergaming provides to rehabilitative exercise, the use of gaming technology may increase engagement in the exercise task, leading to better learning and skill retention [70]. The use of commercially available technology allows for continued at-home rehabilitation after limited repetitions performed in clinical therapy [71] and can increase total repetitions overall [72]. Commercial gaming in rehabilitation has been a major positive prospect in development towards engaging environments for both motor and behavioural therapy [73].

2.3.1 Immersive Virtual Reality Interfacing Technology

The provision of a repeatable, yet appealing alternative to the clinical rehabilitation environment is one of the many benefits provided by exergaming and VR technologies. In a motor training task with healthy participants, a study by Torodov [74] found that the additional feedback from VR training, in comparison to verbal coaching, increased learning speed and task performance. Jaffe [75] reported similar results in individuals with post-stroke hemiplegia when studying walking gait.
Some exergaming rehabilitation tools, while labelled as ‘virtual reality’ technologies, can consist of 2D screen interaction that requires indirect movement mapping from the user to the cursor or to abstracted on-screen control mechanisms [76]. Abdollahi [77] showed that the use of two hands to reach two targets, as opposed to a combination of movements from two hands to reach a single target, allowed for more target accuracy. While there are some popular technologies that map and reproduce a visual display of full-body movement, such as in active gaming using the Kinect or IREX [78], these mirror images or avatars do not map the position of the upper limb to a first-person view. It was found by Bertrand [79] that movements made in VR that better reflect real-world movements allowed better learning transfer from a virtual simulation. Palacios-Navarro [80] hypothesized that 2-D virtual environments without stereovision would provide lower movement quality as it requires more cognitive translation. It was found in a review of VR as a tool for upper-limb rehabilitation that 3D VR systems match movements made in physical environments more closely than 2D game platforms [25]. By eliminating the amount of translation from physical movement to in-game controls, it is likely that the movements made during repetitive practice will be more reflective of movements in activities of daily living and result in better transfer to functional goals.

Immersive VR technologies with 3D display capabilities, forward depth, first-person views or avatars, and larger fields of view may provide more variation in tasks by creating the possibility of having more open learning environments. Projector-based VR or room-scale VR systems tend to be more suitable for walking or mobility rehabilitation [81] as the equipment involves expensive custom-built systems installed in clinics or specialized facility locations. Virtual environments facilitated through head-mounted display (HMD) technology (e.g. Figure 2.1) have been created mostly for gaming and entertainment purposes.
Figure 2.1: Commercially-available head-mounted display used for facilitating 3D stereoscopic virtual environments. The Oculus Rift headset provides 1080x1200 pixel resolution screen to each eye and binaural sound.

However, early research with immersive VR technology has found potential for future growth as a rehabilitation platform, particularly in programs requiring upper-limb tracking that can be conducted in an at-home setting [82]–[84].

Allowing for a first-person view of the upper limb could more closely link visual to proprioceptive feedback, but further work is required to determine if these effects exist when using immersive VR technology. A preliminary study on the use of immersive VR with children [85], [86] could not find enough evidence to determine whether long-term use of VR systems lacking in positional fidelity to real-world motion would cause adverse effects to real-life stereoacuity and postural stability. Stansfield found no immediate adverse effects on proprioceptive sensing in children after a single session of testing [87]. One confirmed adverse effect found when using HMD-based VR systems is cybersickness. Symptoms of cybersickness can include nausea, dizziness, headaches, and other short-term effects similar to those found in motion sickness. Cybersickness when using immersive VR technology is likely caused by an effect called sensory-conflict, in which there are conflicting states of motion being fed to the participant. Visually, the virtual world may be moving but the stationary real-world equivalent sensed by the participant’s vestibular system causes some perceptive dissonance [88]. When designing VR games with moving environments, it is necessary to wary of potential adverse effects cybersickness may cause.
2.4 Augmented Feedback Modalities in Motor Training

One key advantage of using immersive VR technology is the ability to quantitatively adjust the real-time feedback given to the user. Non-immersive VR error augmentation uses 2D screens and may require a visual translation from the upper limb to the cursor position. By using immersive VR technology, a disconnect between virtual visual presence and any conflicting real-life positioning can also be achieved, while still presenting a 1:1 3D environment. Judkins [89] determined that visual feedback dominates proprioception for reaching performance, and a clearer visual representation of limb positioning can override any conflicting proprioceptive feedback participants may sense. HMD technology also allows for full occlusion of true visual positioning when augmentation of visual feedback is used.

Error augmentation adjusts the feedback given based on the amount of error specified by the user’s rehabilitative goals. This type of adaptive feedback keeps the user engaged in the task goal by accentuating error to elicit additional neuromotor responses [90] and further motivates the user to reduce movement errors [91]. In a study comparing EA and haptic guidance in a timing-based motor task, it was reported that EA activates the cerebellum and the left and right angular gyri brain regions [92]. These findings suggest that both motor skill acquisition involving cerebellar activity, and explicit learning through active correction using the right gyrus, are mechanisms behind improvement when training with EA; however, greater activation of the gyri in EA in comparison to haptic guidance may indicate more reliance on immediate feedback and strategic error-detection. Heuer demonstrated that active correction of error was a more effective method to adapt to a rotated upper-limb reach [93]. For people with neuromotor disabilities may not be as sensitive to small errors and error augmentation aims make errors in movement more noticeable above other sensory feedback [94].

Most studies examining visual error augmentation for upper-limb motor training have focused on unimanual reaching and error augmentation for achieving path smoothness in the lateral plane. Studies by Sharp [95] and Abdollahi [96] found positive results when using the Virtual Reality and Robotic Optical Operations Machine (VRROOM) system for visual error augmentation in forward bimanual reaching tasks. However, only the augmentation of the reaching path based on unimanual error of the affected side was tested, and the use of a visual comparison of the
contralateral limb position as an augmentation factor was not explored. Majeed [97] successfully used visual error augmentation to improve upper limb motor function by comparing upper-limb positions during a bimanual reaching task; however, the only the overall distance between the hands was amplified in an attempt to increase the distance between the participants’ more and less-affected upper limbs to prevent deviation for the forward direction during reaching. Using the unaffected side as an augmented mirror comparison may provide helpful feedback to highlight any maladaptive movement patterns in the affected side. Studies on mirroring movements from the less affected to the more affected side in stroke survivors reported better improvement than a unimanual practice equivalent [98], [99]. It was predicted that error augmentation based on the difference between forward reaching positions in the left and right hands would similarly affect motor adaptation by decreasing the amount of symmetrical reaching error between the more and less affected upper limbs in comparison to training without EA.

Error augmentation can be subdivided based on the direction of scaling (amplification or reduction) and type of augmentation factor (constant offset or linearly scaled). A review of error augmentation techniques in robotic upper-limb rehabilitation therapies [100] suggested that while the use of error amplification was more effective than conventional therapy, error reduction showed no such benefits. Celik [101] claimed that error amplification scaled to lateral path deviation by a factor of 2.0 during point-to-point reaching tasks promoted more complete learning over having a constant position offset.

Error augmentation attempts to deliver active feedback without any physical constraints to the less affected side. The benefits of bimanual task training may be circumvented if the user makes two consecutive unimanual movements (the less affected side moving first, and the more affected side lagging behind) to reach a symmetrical goal point. Some on-going projects focus on evaluating hardware or physical constraints to conjoin the motion of the more and less-affected sides of persons with hemiplegia such as the ableX handlebar (ableX Healthcare Limited, Auckland, New Zealand) and the Pablo+ Multiboard (Tyromotion GmbH, Graz, Austria). However, this type of practice could allow persons with hemiplegia to compensate for a lack of function in the more affected limb by decreasing the use of the less affected limb to remain within the restrained distance. The less affected limb could also be used push the more affected side passively, and thus, these physical restraints may be ineffective against maladaptive learned
non-use. A study by Ballester [102] found that the visual amplification of upper-limb movement in a hemiplegic stroke rehabilitation program promoted the use of the more affected side after learned non-use without physical constraints.

Force feedback may be a way of providing active physical constraints as the amount of opposing force can be scaled based on the amount of movement error produced. Robotic devices have been previously used in error augmentation studies as force feedback tools and have been found to increase the rate of motor task acquisition more so than with visual feedback alone [94]. A study by Valdés [103] found force feedback provided by robotic manipulators to be equally as useful as visual feedback for the reduction of trunk compensation during bimanual forward reaching. Unfortunately, robotic devices are often too large and expensive to be commercially accessible to the general public [104] and are not conducive for at-home use in extended rehabilitation regimens. Hung [105] tested a bimanual task training system with a more affordable alternative – vibrotactile feedback. Held [106] found stroke survivors preferred vibrotactile feedback over visual and acoustic feedback when practicing activities of daily living. However, both wearable devices were only tested to see if it could provide better motor adaptation and were not directly compared to using only visually augmented feedback. It was determined that further exploration of visual error augmentation would be useful prior to testing combinations of force and visual augmentation together for rehabilitation programs.
2.5 Definition of Project Scope

From the review of related literature in Chapter 2, many elements within upper-limb rehabilitation methods appear insufficiently studied. Based on the existing results, number of parameters tested in the thesis study need to be specified to set a definite project scope:

1. As mentioned in Section 2.1, the thesis study only evaluated participants with motor impairments in an adolescent and young adult population. It was anticipated that in addition to being a neglected population, this age demographic would be more enthusiastic about the use of video games than the aging population.

2. The experiment tested a bilateral symmetric reaching movement. Despite mixed results on the benefits and drawbacks of bilateral coupling, a lateral comparison was chosen as it was expected that differences in symmetry would be easy to notice in this plane.

3. Immersive virtual reality technology was employed. Previous studies have already confirmed the benefits of screen or avatar-based gaming technology in motor rehabilitation protocols.

4. Visual Error Augmentation was evaluated without any physical constraint or force feedback. No permanent physical adaptations were made to the commercial hardware used that added physical constraints to reaching movements.

5. Error Amplification was evaluated using bilateral symmetry as the scaling factor.
Chapter 3: Methods

The objective of the proposed study was to evaluate the effects of visual error augmentation (EA) on short-term motor adaptation of upper-limb symmetry during bilateral reaching. Chapter 3 describes the technical and experimental design of the study. A commercially-available immersive VR system and motion tracking technology were combined to allow 3D upper-limb tracking and veridical display of participants’ hands in a virtual environment.

The study was designed to test a target clinical hemiplegic population (CHP) and typically developing participant population (TDP) of the same age range. The TDP participant group was used to simulate the effects of visual augmentation with a larger sample size. The virtual environment and experimental setup were developed for both participant groups with minor changes based on motor capabilities. Participants were asked to perform a symmetric bimanual forward reach as the repeated trial task. For the TDP group, a shift in visual position of the non-dominant hand was applied to simulate impairment in bilateral symmetry and create a movement pattern goal that required motor adaptation. The visual positioning of the non-dominant or affected (ND/A) limb of the study participant was then augmented, and the calculation of this feedback was based on the symmetric error between the two hands, as explained in Section 3.1.4. The dominant side in the TDP and less affected side in the CHP (D/LA) remained completely un-augmented for the study. A single session crossover study was set up in which participants completed a training set with and without the use of error augmentation in order to maximize group size from a smaller sample population.

Section 3.1 describes the hardware and tracking technology, as well as the virtual environment and virtual objects that were used for the reaching task. Section 3.2 presents the experimental design and Section 3.3 introduces the outcome measures and proposed analysis methodology.

3.1 Technical Setup Design

3.1.1 Motion Tracking Technology and Hardware

The Oculus Rift (Oculus VR, LLC., Menlo Park, CA, USA) system, including the HMD Headset, the Oculus Touch controller pair (Figure 3.1), and 2 Oculus Sensors, was used to
facilitate the VR environment. The Oculus’ tracking system was chosen as it provides high positional accuracy of less than 10mm (Appendix A) and an ergonomic controller set that allows for motion tracking of the hands. Gripper and trigger buttons were placed in locations in which natural grasp can be used to intuitively interact with virtual objects.

![Oculus Touch Controller](image)

**Figure 3.1: Oculus Touch Controller (right-handed).** The Oculus Touch controller set comes with two mirrored controllers - one for each hand. Only the front trigger and side gripper buttons were employed in this experiment.

The availability of this newer, more accurate and ergonomic controller set in comparison to previous commercial tracking technology such as the PlayStation Move (Sony Interactive Entertainment LLC, San Mateo, USA) or Wii Mote (Nintendo Co., Ltd, Kyoto, Japan), should allow for more fluid interfacing with rehabilitative research focuses.

During the experiment, the participant’s position, orientation, and the visual representation of their hands were rendered using the OVRAvatar package within a 3D virtual environment developed in the open source game engine platform Unity 3D 5.0 2017 (Unity Technologies, San Francisco, USA). Kinematic upper body joint position was recorded via a Kinect v2 (Microsoft Corporation, Redmond, USA) through the same Unity 3D interface, but no joint data was rendered as part of the upper-limb model in the virtual environment due to the lower positional accuracy (1-5cm [107], [108]), high latency, and large amount of jitter. The lack of full arm representation in the virtual environment was not expected to affect the accuracy of upper-limb
reaching [109]. The Kinect v2 was also used to record video data to verify if there were any large errors in joint data recordings caused by inaccuracies in the Kinect skeleton joint calculations.

The physical “play-space” was defined as the area in which the user was allowed to move in order to interact with the virtual environment without any physical obstructions. The play-space was set to approximately 2m x 2m using the built-in Oculus Rift calibration setup tool and “Guardian System” to optimize tracking with the Oculus Sensors. A chair was placed both physically and virtually in the centre of the play-space. Figure 3.2 shows the motion tracking device placement within the defined play-space.

![Figure 3.2: Experimental setup sensor layout and tracking area. The defined coordinate system in the virtual environment is shown such that the origin was placed on the floor approximately in the centre of the participant’s seated location. The participants started with their chair above this origin but were allowed to adjust their seating position based on comfort in relation to the position of the virtual objects. The passive Oculus Sensors and Kinect v2 were placed 1.5m away from the play-space origin to maximize the field of view used. Angles and distances are not to scale.]()
To mitigate the occurrence of cybersickness, the virtual environment was developed so that there was no simulated motion, such as teleportation or joystick-based movement, that did not directly map to the participants’ movements. The environment and task also did not require extensive movement outside of the participants’ natural standing reach.

### 3.1.2 Virtual Environment and Task Design

The local coordinate systems from the Oculus HMD, Touch controllers, and Kinect v2 were unified through Unity 3D in which X represented the horizontal lateral movement (positively towards the right), Y was vertical movement (positively against gravity), and Z was forward anteroposterior movement as seen in Figure 3.3. Participants were asked to perform a reaching task with four possible interactable object models that required them to pick up and move the virtual objects to a specified location with both hands simultaneously. Some non-interactable scenery was added to create a visual setting outside of the user play-space. The scenery and food-related tasks were designed to reflect food preparation, as it is a category of common bimanual practice tasks for persons with hemiplegia [110]–[112] and the topic of some current kid-friendly commercial VR games such as Diner Duo (Whirlybird Games, Uddevalla, Sweden) and VR Job Simulator (Owlchemy Labs, Austin, USA).

![Figure 3.3: Orthographic view of the virtual scene as seen in the development environment. The sun symbol denotes the location of the lighting source for the graphics engine to render. A picture-in-picture view (bottom-left) shows the virtual environment from the user's perspective. The axes origin shown behind the hotdog cart matches the axes in the physical space marked in Figure 3.2.](image)
As the reaching movement was performed, the instantaneous position difference between hands in the forward direction was calculated. This difference was used to visually amplify the symmetrical error by adjusting the rendered position of the user’s ND/A hand (Figure 3.4). The ‘forward’ position of the hands was determined in reference to a global orientation axis that remained static throughout the entire study.

Figure 3.4: Diagram of the reaching task (left) and visual error augmentation effect (right). The sphere above the ND/A side denotes the true position of the participant's hand in the real world. During the experiment, the sphere was hidden from the user and they only saw the rendered augmented hand position. $Z_{ND/A}$ represents the forward position of the non-dominant/affected side that was visually augmented, and $Z_{D/LA}$ represents the forward position of the strong or dominant/less-affected side. A colour gradient was added to the object such that an increase in asymmetry would change the object from red (left) to green (right).

The location of the end goal was customized for each participant by measuring their baseline maximum reaching distance prior to completing any recorded study trials. Participants were asked to reach as far as comfortably possible and this distance was recorded. Only augmentation in the Z direction occurred as this was the direction of reaching. Augmentation in the Z direction was based on the global axes since the reaching direction and orientation of the starting and end goal position did not change.
The amount of additional visual and interactive game objects in the virtual environment was limited in order to provide an engaging environment without distracting the user from focusing on completing the task with minimal symmetry error. In addition to the visual symmetry EA, a gradient colour cue was used throughout the experiment to visualize symmetry error (Figure 3.4). The interactable object model would change from red to green based on the difference in z-axis distance between the D/LA and ND/A sides. A reach quality score per trial and a cumulative score were updated and displayed as a form of reward-based motivation, shown as blue text in Figure 3.3. In a study examining feedback modalities provided to people with stroke during an upper-limb robotic reaching exercise, Valdés [113] found that the majority of participants preferred to have scores included as additional feedback instead of just receiving visual and force feedback. However, Kimberley [114] found that the cognitive load on the bilateral premotor area of the brain measured by fMRI increased with more visual feedback elements and recommended a cautious balance between providing an engaging task and not overwhelming any limited cognitive resources. To compromise, reward-based feedback was only displayed between trials.

Four different food items were rendered as the virtual object to be manipulated using both hands: a hotdog onto a bun, meat into a dumpling, rice onto nori, and shrimp into a sushi roll. Different objects were used to provide some variety in the task and encourage engagement. The objects were presented randomly. Models of these objects are shown in Figure 3.5.

![Figure 3.5: 4 possible virtual objects that could be manipulated in VR. Clockwise from the top-left image, the objects shown are the hotdog, shrimp, meat, and rice. The axes displayed in the object centre match the orientation of the global coordinates. The mesh spheres (made visible in development view) were visible to the participant only when colliding with their hand and show the volume in which the interactable object could be picked up.](image-url)
When the participant hovered over the food item with both hands, two "interaction spheres" were highlighted, which represented the area in which their virtual hands could pick up the object using the controller's gripper buttons (Figure 3.5). If the "interaction spheres" were highlighted and the participant squeezed the gripper buttons, the object position would follow the position of the virtual hands. The objects could stretch and skew up to two times the original length of the item, constrained only by the position of the interaction spheres in the user's hands.

3.1.3 Differences in Setup Between Sample Populations

The majority of the experimental and technical setup remained the same for sessions with the TDP and CHP participant groups; however, some changes were implemented based on differences in upper-limb motor ability. Since a large portion of the clinical population with hemiplegia also suffers from loss of grasp control [115], using the gripper button would not have been an effective way to pick up and interact with virtual objects. For the main two-handed objects, a grasp action for each hand was detected when the space of the virtual hand mesh coincided with the interaction sphere of the object. This “sticky” function provided the CHP group with a much easier way to interact with the objects as simply touching them would cause them to be picked up.

For the TDP group, an additional scaled asymmetry factor of 0.7 or 70% of a full reach was applied to the participant’s ND/A side in order to simulate acquired asymmetry. Instead of augmenting the true error $E_z$ (as seen in Figure 3.4), instantaneous symmetry error was calculated between the true position of the D/LA side and the intermediate value $Z_{asy}$:

$$Z_{asy} = 0.7Z_{ND/A}$$

This forced the TDP participants to adapt their ND/A side movement to a reaching task which appeared visually symmetric but proprioceptively asymmetric and resulted in a final reaching position in which the participant’s ND/A side was further than the D/LA side in the positive z-direction. 70% asymmetry was chosen as an arbitrary value below the amount of reaching that normally requires some trunk compensation in healthy individuals [116], [117].
3.1.4 Error Augmentation Feedback Loop

The main feedback modality of this study was visual error augmentation that was used to exaggerate the participant’s reaching asymmetry during the bimanual task. As the main movement of the task was in the forward z-axis direction, the visual EA was fixed to only change the z component of the ND/A side’s position. A constant scaling EA factor $G$ of 2.0 was used to amplify the error between the D/LA and ND/A sides such that the position of the ND/A side would appear double the true distance away from the D/LA side’s forward reaching position, as seen in Figure 3.4. The augmented visual position $Z_{aug}$ was calculated as follows:

$$Z_{aug} = Z_{ND/A} - (G \times E_z)$$

where the instantaneous reaching symmetry error in the z-direction $E_z$ is:

$$E_z = Z_{D/LA} - Z_{asy}$$ for TDP participants

$$E_z = Z_{D/LA} - Z_{ND/A}$$ for CHP participants

An estimation of the numerical value of the EA factor was required since no previous studies testing augmentation of forward reaching symmetry could be found at the time of the study. While conducting experiments examining susceptibility to rotational visual augmentation, Shirzad [19], Celik [101], and Wei [118] found effective EA factors above 1.65, around 2.0, and up to 3.1 respectively. The EA factor $G$ of 2.0 was chosen from these values to be high enough to significantly affect movement patterns, but not so high that the task goal seemed impossible to attain. The factor selected was lower than the average of the previous studies’ values, as the use of an immersive environment providing realistic 1:1 positioning and a constant lateral comparison with the D/LA side should make the augmentation more noticeable than in rotational visual augmentation.
The mathematical flow of calculated position with TDP asymmetry is presented in Figure 3.6.

Figure 3.6: Flow diagram of the visual asymmetry and error augmentation calculation. $Z_{ND/A}$ represents the forward reaching position of the ND/A hand and $Z_{D/LA}$ represents the forward reaching position of the D/LA hand. $Z_{aug}$ and $Z_{asy}$ represent the position after application of EA and asymmetry respectively. For CHP participants, $Z_{ND/A}$ and $Z_{asy}$ are the same, as seen in the calculation above in this section.

In the case in which there was zero error between the ND/A and D/LA sides, no error augmentation would be visible and $Z_{aug}$ would equal $Z_{asy}$ for the TDP group and $Z_{ND/A}$ for the CHP group. Figure 3.7 describes the direction of visual augmentation from a top-down (X-Z plane) view for the TDP group in which participants trained to reach asymmetrically. The figure shows an ideal reach in which the participant correctly reaches with perfect 70% asymmetry (left) and a reach in which EA is visible on top of the asymmetry (right).
Figure 3.7: Visual representation of error in the X-Z plane (top-down) view. The light blue hand models represent the visual position of the controllers rendered in VR and the dark brown hand is the true position of the ND/A hand in physical space at time point $t_3$. $E_x$ represents instantaneous error in time $t_x$ measured by the difference in z-direction position between the D/LA and asymmetric ND/A hands. The small circle (right) represents an intermediate position used for calculating the final augmented position from the ‘perfect 70%’ position when reaching with asymmetry. In the ideal case (left), the visual position matches the perfect 70% position of the circle. Asymmetry at 70% and augmentation factor x2.0 are not to scale.

In the scenario shown in Figure 3.7 (left), the reach is physically asymmetrical (brown) as required for TDP participants, but in VR, would look visually symmetrical (blue). The right hand, simulating the unaffected side, will have veridical forward reaching so the physical and virtual position of the D/LA side are the same and overlap, as shown in Figure 3.7. If the TDP participant does not reach with the correct amount of physical asymmetry or visual symmetry (right), a non-zero visual augmentation is produced, decreasing the z-position of the affected side even further during the forward reach. The time points in Figure 3.7 (right) show the difference between the ‘correct’ asymmetrical reach (dotted) and the position causing non-zero EA.
3.1.5 Data Collection and Processing

A separate internal script was developed in Unity 3D to collect and export kinematic tracking data from the Oculus Rift HMD, Touch controllers, and Kinect skeleton, so that each tracking device generated data at the same timestamp. The kinematic data was sampled at a varying frame rate between 50-100 Hz. Raw kinematic data was recorded from the creation of an instance of the interactable object described in Figure 3.5 until the object collided with the end goal object. The point when the two virtually rendered hands collided with the two spheres on the object was chosen as the starting point of processed outcome data. The distance between the two hands along the z-axis was calculated within the script at each sample point and exported along with the raw kinematic tracking data.

A multithreaded process was used to save each sample point in a queue. Data in the queue was written into a .csv (comma-separated values) file at 2Hz to prevent overuse of computing power for data logging processes.

Custom-developed MATLAB 2018b (MathWorks, Natick, USA) scripts were used to process all kinematic data. As the position and orientation data in Unity 3D were recorded at a variable sample rate, any calculations requiring post-collection data filtering, derivation, or averaging over time required resampling.

Hand velocity was calculated by taking the finite differentiation of the raw position data. The position data was resampled at 30Hz, the lowest possible hardware sampling rate given by the Microsoft Kinect v2, before calculating the ‘instantaneous’ velocity. A low-pass Butterworth filter with a cut-off frequency of 6Hz was used to smooth the reaching velocity profile of each trial. The cut-off frequency of 6Hz was used as an approximation of the bandwidth of kinematic gross upper-limb motion from previous related studies [119]–[121].

Finally, to analyze average reaching profiles over time, peak velocity per reach was calculated, and the previously marked starting point was trimmed from the point in time when the participant gripped the object with both hands, to the point when 10% of the peak velocity was reached [122], [123]. Figure 3.8 shows an example of the resampling, filtering and start point calculation process. In cases in which a participant started reaching long after picking up the
virtual object, the additional “non-moving” data at the beginning of the recording would be removed if it was less than 10% of the peak velocity. The second starting point allowed for better comparison between trials as the reaching profiles would be more aligned timewise. If there were multiple points at which the velocity crossed to above 10% of peak velocity either from corrective or jerky movement, the point before and closest to the maximum peak velocity was chosen as the new starting point.

Figure 3.8: Line plot set of an example reach trial showing recorded position for the ND/A side. A small difference between visual (VR) and real positioning is seen with EA applied. Velocity was calculated from the resampled position data and then filtered using a 6Hz Butterworth filter. The point at which 10% of the peak velocity occurred was marked as the new starting point for other kinematic analysis.
3.2 Experimental Design

3.2.1 Study Participants

Participants in the TDP group were recruited by word-of-mouth, flyers distributed in community centres through Lower Mainland Vancouver, flyers at the University of British Columbia, and through promotional talks at high-school level after-school programs.

Adolescents and young adults with hemiplegia, including persons with CP, ABI, or Paediatric Stroke, were recruited from community rehabilitation centres, through their collaborating therapist at BC Children’s Hospital (BCCH), and through flyers distributed to private clinics in the Lower Mainland Vancouver area. The study protocol was approved by the UBC Clinical Research Ethics Board (H17-01126). Consent forms, recruitment information sheets, and advertising material can be found in Appendix B. The single-session experiments were conducted at one of three locations, depending on the participants’ preferences:

1. UBC CARIS Lab
2. BC Children’s Hospital, Occupational Therapy and Physiotherapy Unit
3. Participant’s private home location

Participants were required to fit the following criteria to be selected for the study:

i. Within the ages of 13 to 21
ii. The ability to follow instructions and answer questions in English
iii. Ability to visually interact using a stereoscopic device that allows a minimum interpupillary distance of 58mm
iv. Ability to comfortably support regular head motion while wearing a 470g head-mounted display
v. The ability to stand or sit independently for 15 minutes at a time in a chair without arm supports for a total of up to 120 minutes
vi. No known high susceptibility to cybersickness effects as reported by the participant

TDP participants must not have had any cognitive or physical impairments that affected movement in the upper limbs.
Additional criteria for the CHP participants included:

i. Hemiplegia as a result of a neurological impairment (CP, ABI, paediatric stroke, etc.)

ii. The ability to move both arms away from their body at least some distance such that their affected hand reached the middle of their thigh around waist level without any help from the less affected hand, as reported by participant or adjoining therapist

iii. Having not had orthopaedic surgery in the past 6 months

Study recruitment and data collection occurred over 8 months from August 2018 to March 2019. A total of 17 participants were recruited for the study: 12 typically developing adolescents and young adults aged 13-21 (17 ± 3 years old, 3 female, 0 left-handed) and 5 hemiparetic clinical participants aged 14-21 (17 ± 3, 2 female, 3 left-handed).

TDP participants were recruited from the community population and all 12 recruited participants completed the full study session. As all TDP participants were right-handed, asymmetry and augmentation factors were applied to their left, non-dominant arm. A consort flow diagram in Appendix C can be found to fully describe the enrollment progression for recruitment of the TDP group.

Recruitment efforts for potential CHP participants included posting material in 6 private therapy clinics, 3 community groups for persons with disabilities, and 1 community-based rehabilitation centre. A therapist on the study team contacted clients from BC Children’s Hospital and 3 participants from previous studies in related topics were contacted. Figure 3.9 shows the progression of potential participants from contact response to study completion.
Figure 3.9: Flow diagram following CHP participant recruitment and study progress as recommended by CONSORT [124]. The one participant (n=1*) noted during analysis wore a chest strap with their wheelchair and their data set was excluded from the analysis on trunk compensation in Section 4.2.2. Analysis for the primary outcome continued with n=3 in the group that trained without EA first.
Of the 5 CHP participants that completed the study session, 4 were recruited through BCCH and one from previous studies. All participants were clinically diagnosed with Cerebral Palsy. All CHP study sessions were conducted at BCCH.

In Table 3.1, a summary of the CHP participants’ baseline demographics and clinical characteristics is presented:

Table 3.1: CHP participant demographics and clinical information on motor disability classification.

<table>
<thead>
<tr>
<th>ID #</th>
<th>Sex</th>
<th>Age</th>
<th>Weaker Side</th>
<th>MACS</th>
<th>BFMF</th>
<th>Time of Injury</th>
<th>Lesion Cause</th>
<th>Additional Affected Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP-1</td>
<td>M</td>
<td>14</td>
<td>Left</td>
<td>II</td>
<td>II</td>
<td>Perinatal</td>
<td>Intraventricular Hemorrhage</td>
<td>Synkinesis, Stereognosis</td>
</tr>
<tr>
<td>CHP-2</td>
<td>M</td>
<td>19</td>
<td>Right</td>
<td>I</td>
<td>II</td>
<td>Perinatal</td>
<td>Periventricular Hemorrhage</td>
<td></td>
</tr>
<tr>
<td>CHP-3</td>
<td>M</td>
<td>16</td>
<td>Left*</td>
<td>III</td>
<td>I</td>
<td>Age 2</td>
<td>Hemolytic Uremic Syndrome resulting in Cerebral Ischemia</td>
<td>*Left UE weaker, Right LE weaker</td>
</tr>
<tr>
<td>CHP-4</td>
<td>F</td>
<td>21</td>
<td>Right</td>
<td>II</td>
<td>II</td>
<td>Perinatal</td>
<td>Hypoxia from Nuchal Cord</td>
<td>Spasticity in both UE</td>
</tr>
<tr>
<td>CHP-5</td>
<td>F</td>
<td>17</td>
<td>Right</td>
<td>III</td>
<td>III</td>
<td>Neonatal</td>
<td>Encephalopathy with microcephaly</td>
<td>Intellectual Impairment, Epilepsy</td>
</tr>
</tbody>
</table>

These characteristics were used to evaluate possible correlation between current motor ability and susceptibility motor adaption from the application of visual EA and these results are presented in Section 4.2.3.

3.2.2 Study Design

The study was a single-session experiment that evaluated repetitive reaching movements when training with and without visual EA. The study used a crossover counterbalanced design with two conditions and participants were randomized to start training with or without EA. Blocked randomization was used to allocate participants and blocks of 2 participants were used so that the number of participants in each group was as equal as possible with any number of participants.
At least 24 hours prior to the study session, the willing participant was presented with the consent form. At the beginning of the session, the consent form was explained in detail and any study-related questions were answered. Each participant provided written consent and basic demographic data (age, gender, and handedness).

The participant was introduced to the setup and hardware to be used in the study. An initial fitting test followed in which the participant familiarized themselves with the immersive environment and ensured that they were comfortable in the environment and task. The task goal was explained at the beginning of the session and participants were told that the study would be modifying visual feedback to help improve reaching symmetry in some manner. The full set of verbal checks and instructions are provided in Appendix D.

After becoming familiar with the system, participants were asked to perform augmented symmetrical bimanual movements using their upper limbs. As the order in which they performed the augmented and non-augmented set was randomized, they were not told whether the set included the modified feedback condition. Participants were only reminded of the goal of symmetrical bimanual reaching. As participants completed the trial sets, any occurrence of difficulties encountered during the study, such as struggling with object interaction or difficulties grasping the controllers, was also qualitatively recorded.

After the session was completed, the participant was asked to answer a post-session questionnaire including questions about system usability, engagement, and VR immersion. A few questions were asked to check for possible symptoms of cybersickness.

3.2.3 Clinical Classification Assessment

A short clinical assessment for the CHP participant group was conducted during the main experiment after the collection of participant demographic data. These motor ability scores were used to describe the experimental sample with respect to the overall clinical population. This classification was also used to provide an indication of the level of motor ability most susceptible to changes in motor adaptation caused by using visual error augmentation. The clinical assessment systems used were the Manual Ability Classification System (MACS) and Bimanual
Fine Motor Function (BFMF) assessment – recommended by NINDS\(^{[1]}\) as a harmonized classification system for assessing upper-limb mobility in children with Cerebral Palsy. High inter-rater reliability has been confirmed for both the MACS [125] and BFMF [126] classification systems.

### 3.2.4 Trial Design

The study session was broken into two sets of various types of reaching trials, one for training with EA and one without, with a mandatory 5-minute break in between during which the participant was instructed to remove the Oculus HMD. At least 3 reaches were performed prior to any recording to allow the participant to gain an understanding of the task and setup, with no visual augmentation applied. The following are descriptions of the types of trials and their purposes within each trial set with or without EA:

1. **Baseline** - 5 reaches were used to measure baseline symmetric position error between the ND/A and D/LA sides of the participant. The participant was asked to pick up the virtual object and reach as symmetrically and smoothly as possible to bring the object to its goal position.

2. **Blind** - 3 reaches were done without any visual positioning feedback. The hands rendered in the virtual environment were removed and the participant was asked to reach forward symmetrically as previously instructed without interacting with any of the visible objects. This was used to evaluate any proprioceptive learning that would otherwise be eliminated with immediate corrective visual feedback and to compare against washout effects.

3. **Training** - The participant did 60 reaches with, or 60 reaches without, the symmetrical EA algorithm applied, depending on their randomized allocation. This number of reaching movements was chosen as previous studies have found a plateau in performance improvement to be between 40-60 cycles for continuous visual feedback [118], [127]. Additionally, a recommended limit of 10-15 cycles for repetitive exercises for the target CHP

population [128] was followed by taking 1-3 minute breaks between sets. In order to clarify the naming convention used through this thesis, “training trials” was used to address these 60 trials, while the entire half-session cycle was defined as a “training set” or “training with or without EA”.

4. **Evaluation** – The participant performed 5 more reaches with the same application of visual asymmetry or augmentation as in the previous training trials. These 5 trials were averaged and used to compare to the baseline error.

5. **Washout** - In both sets with and without EA, the participant performed 15 reaches to serve as a washout period for any adaptation effects caused by the visual augmentation of the participant’s hand position by either the 70% asymmetry or x2.0 EA factor and as a test for immediate retention of task training. Participants were given veridical feedback with no asymmetry or augmentation and asked to reach normally. The clinical target group did one “sham” washout as they had one training set with neither asymmetry nor EA applied. In pilot testing, it was found that healthy participants de-adapted to training visual augmentation after at most 10 reaches. In a previous study, persons affected with hemiplegic stroke were able to adapt to motor correction feedback cues within at most 20 reaches [105].

After completing a cycle of these trial types, the participant performed a second set of these trials, in which EA was applied or removed, depending on whether the first set of training trials used EA or not. The TDP group had the asymmetry factor applied to both sets in the training and evaluation trials and both populations had error augmentation applied in one set in the training and evaluation trials. The order of trial types over the two training sets is shown in Figure 3.10.
Figure 3.10: Diagram of the order of different trial types used in the experiment protocol. Participants would be assigned to either Group A (top line) or Group B (bottom line) by blocked random allocation to determine the training set order in which Group A would train with EA in their first set and Group B would train without EA in their first set. Average symmetry RMSE values calculated for the 5 baseline and 5 mid-evaluation trials were represented by $E_Y^X$ in which X refers to the order in which the participant received the two training sets (Group A or B) and Y identifies the test order and specific trial type and set (1 and 3 for baselines, and 2 and 4 for evaluation). 70% asymmetry, shown for trial types with blue single line hatch was only applied for TDP participants. Orange cross-hatched trial types were sections in which EA was applied for CHP participants and both EA and asymmetry were applied for TDP participants. CHP participants were not asked to complete the blind trials to reduce muscle and cognitive fatigue.
After the first washout trials, participants were asked to remove the Oculus headset and look around the room for a break of at least 5 minutes, as Oculus Health and Safety [129] guidelines recommend headset usage to be limited to 30 minutes at a time.

Due to the close proximity of the LED screen and the nature of the headset, possible eyestrain or neck strain could have occurred during the experiment. While studies on neck and eye-strain using HMD technology with children are insufficient and scarce [85], [130], strict adherence to manufacturer warnings was observed. At the beginning of the study, participants were given the opportunity to try the setup. At this point, the participant or a consenting guardian assessed their capability to participate in the experiment. Eyestrain was mitigated by maintaining the proper interpupillary distance as assessed by the participant and/or a consenting guardian, as well as by taking breaks at least every 30 minutes.

Similar risks to those in general repetitive task exercises such as cognitive and muscle fatigue were identified as possible risks for this study. Each group of training trials was divided into 4 groups of 15 trials with optional breaks in between to mitigate this risk. The participants were informed of the all identified risks prior to participation. They were also informed that they could stop the experiment and rest or withdraw at any point if they felt the need to do so.

### 3.3 Outcome Measures

As the study occurred in a single session, the primary analysis looked at immediate motor adaptation patterns affected by error augmentation. The primary outcome measure of this study was the difference in centimetre error with or without visual symmetry EA, in which error was defined as the symmetry Root-Mean-Squared Error (RMSE) calculated from the instantaneous distance between the D/LA and ND/A side throughout each trial.

\[
RMSE = \sqrt{\frac{\sum(Z_{D/LA} - Z_{asy})_{inst}^2}{n_{points}}}
\]

It is noted that for the cases in which no asymmetry was applied, \(Z_{asy}\) is equivalent to \(Z_{ND/A}\).

RMSE was chosen as it penalizes larger differences and does not cancel out equal error in two opposite directions (i.e. if affected or unaffected limb lag at different points in time). This error
value increases regardless of whether the correction to symmetry is done in steps or only once at the end of the reach. In a study by Balakrishnan [131], the difference between the percent RMSE of each separate hand to the end target was defined to examine symmetry, and RMSE has been used in previous studies relating to target accuracy and path deviation [119], as well as symmetry as a secondary outcome [113].

The average RMSE presented at each evaluation set was compared to its respective baseline. The average RMSE from the 5 baseline and 5 evaluation trials for each training set was used to calculate percentage improvement for the entire set as:

$$\frac{E_{\text{baseline}} - E_{\text{evaluation}}}{E_{\text{baseline}}} \times 100\%$$

This formula was used as a normalization for TDP participants and is more indicative of percent change as natural symmetry was already shown in baseline trials. Percent changes from $E_1^A$ to $E_2^A$ and $E_3^B$ to $E_4^B$ (Figure 3.10) were be compared to changes from $E_1^B$ to $E_2^B$ and $E_3^A$ to $E_4^A$. Percent changes of secondary outcomes were calculated in a similar manner.

The following secondary measures were employed in this study:

**Motor Adaptation Performance Curves** - the change in symmetry RMSE per trial during the training trials over time was plotted as motor adaptation curves to investigate any differences between adaptation rates with and without augmented feedback. Changes in performance levels were evaluated by examining performance curve parameters. The training trials data was fit to the equation proposed by Wei [118]:

$$y = Ae^{-t/B} + C$$

Where $y$ is the average error in a specified reaching pattern for one trial and $t$ is the trial number over 60 trials. Terminology for the parameters $A$, $B$, and $C$ used by Shirzad [19] will be used to describe performance curve characteristics shown in Figure 3.11.
Figure 3.11: Example performance curve for change in upper-limb motor behaviours over several training trials. \( A \) is used to represent the total amount of improvement after training, \( B \) represents the approximate rate of learning (in which a lower \( B \) value indicates a faster rate), and \( C \) represents the final performance or convergence value of reaching accuracy.

**Reaching Range of Motion (ROM)** - the distance travelled of each arm away from the head was recorded in VR for each participant to evaluate if using EA increased or decreased ROM in the ND/A side. Reaching ROM of the D/LA side was also evaluated to see if there were any changes as a result of using EA or by the application of asymmetry.

**Peak Reaching Velocity** – the value of maximum velocity of each trial was considered a useful measure of movement quality. Participants were not asked to meet a certain time constraint; however, changes in reaching speed may correlate with adapting to training with EA.

**Time to Peak Velocity** - the time from the start of the reach to the time at maximum velocity. This metric, used previously for a bimanual target reaching experiment [132], was also examined as an indicator of the level of cognitive load that the task or augmentation factor may incur. While it was hypothesized that the TDP group would be able to adapt to a certain degree of asymmetry without augmented feedback, a decrease in time to peak velocity could indicate earlier reliance on EA as feedback information.
**Number of Velocity Peaks** – movement smoothness was measured by the number of local maximum velocity peaks that occurred within each trial since it is a common method of measuring reaching movement smoothness [122].

**Trunk Compensation** – A common compensation technique for impaired reaching is trunk or torso movement away from an upright sitting position. This was measured using the kinematic joint data collected from the “SpineShoulder” joint in the Kinect skeleton located approximately at shoulder level along the spine. Clinical participants were also monitored by the experimenter for other compensation techniques specific to the nature of their individual compensation habits, and the Kinect joint skeletons were referenced to evaluate these observations.

### 3.3.1 Statistical Analysis

A repeated measures ANOVA was used to compare the percent changes in RMSE from baseline to post-training, to determine whether error augmentation was more effective than having no visual augmentation during the bimanual reaching task. Percent improvement between training sets was tested as a within-subjects factor and the training set order was used as a between-subjects factor to test if results were affected by carry-over effects. A two-tailed paired t-test was used for further statistical analysis such as confidence interval and standard error after confirming that the effect of the training set order was found to be not statistically significant.

Differences between RMSE error in different trial types in each training set were analyzed descriptively as further analysis in Section 4.1.1. Multiple two-tailed t-tests were used to explore differences in secondary outcome measures.

A required sample size of 10-15 participants per group was estimated from previous studies on motor function outcomes for persons with upper-limb motor disorders [59], [76], [133]. In addition, a power analysis (power of 0.8 and alpha of 0.05) was conducted to confirm the expected sample size using preliminary pilot data from three healthy adult participants (n = 2 starting with no EA in their first training set). The analysis was conducted (Appendix E) in G-Power 3.1 [134], and a sample size of 7 was determined to be a minimum requirement for finding a significant difference in improvement in symmetry between training with or without EA. However, this assumes the TDP and CHP groups present similar results to healthy adults with extremely low between-subjects variation in both baseline error and percent improvements.
3.3.2 Qualitative Usability Survey

After participants completed the reaching exercise portion of the study session, they were asked to complete a qualitative usability survey, which was used to gain insight on the system’s viability as an at-home rehabilitation tool. The System Usability Scale (SUS) survey, developed by Brooke [135], was used to collect qualitative scores of the usability of the Oculus hardware and VR environment. The SUS survey was chosen as it is a quick usability test that has been previously administered for evaluating other game-based rehabilitation tools [136], [137]. Additional questions were added to the post-session survey to collect information about VR immersion, to check for cybersickness side effects, and to generate predictions about sub-populations that may or may not be more inclined to use exergaming technology. Standardized scores [138] from the SUS and qualitative survey responses were analyzed as descriptive exploratory results. The full post-test survey containing questions on comfort, real-world fidelity, immersion, and cybersickness can be found in Appendix F. In addition, any verbal mentions of specific cybersickness symptoms were noted by the experimenter. A list of possible effects was presented to participants before the session and could be referenced during the survey portion of the study session. The information sheet can be found in Appendix B. In addition to the written survey, all participants were asked verbally at the end of the session whether they noticed the added asymmetry or error augmentation. The session experimenter also recorded an ordinal level of exploration in the virtual environment from 1-3, in which 1 symbolized no exploration, 2, exploration when prompted by study staff, and 3, independently initiated exploration.
Chapter 4: Results

Chapter 4 presents the results of the analysis of the main and secondary outcome measures of this study. The primary outcome for TDP participants was tested for statistically significant differences and secondary outcomes were explored descriptively in Section 4.1. Given that the CHP group only included 5 participants, a descriptive analysis is presented in Section 4.2, instead of using statistical tests. This provided evidence of a pattern of improvement that could indicate possible directions for future studies. Finally, combined results from the TDP and CHP post-questionnaires were presented in Section 4.3.

4.1 Typical Response to Symmetry Augmentation in an Asymmetric Task

Bilateral symmetry EA was tested with TDP participants prior and concurrently to clinical population recruitment and data collection. The primary outcome measure presented in Section 4.1.1 was the amount of improvement in visual symmetry after training with the 70% asymmetry offset, in comparison to baseline symmetry. Changes in symmetry RMSE were compared between different trial types. Secondary outcome measures’ results compiled in Section 4.1.2 include range of motion in the reaching direction, peak velocity, and trunk compensation. Changes in these secondary metrics were evaluated from averaged baseline and evaluation trials.

4.1.1 Average RMSE in Bilateral Symmetry

The symmetry RMSE was collected from the position difference in the forward reaching direction between the D/LA and ND/A hand for the 5 baseline and 5 evaluation trials in each training set, with and without EA. These 5 trials were then averaged into single distance values for a baseline or evaluation set, as shown in Table 4.1 for each participant.
Table 4.1: Results from the primary outcome measure (symmetry RMSE average over 5 trials) for each participant.

<table>
<thead>
<tr>
<th>Starting Order</th>
<th>Participant ID #</th>
<th>No EA Set (cm) Baseline</th>
<th>Evaluation</th>
<th>With EA Set (cm) Baseline</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA First (Group A)</td>
<td>TDP-2</td>
<td>1.07 ± (0.48)</td>
<td>0.94 ± (0.53)</td>
<td>0.63 ± (0.17)</td>
<td>0.78 ± (0.49)</td>
</tr>
<tr>
<td></td>
<td>TDP-5</td>
<td>0.72 ± (0.33)</td>
<td>0.49 ± (0.18)</td>
<td>0.98 ± (0.16)</td>
<td>0.47 ± (0.10)</td>
</tr>
<tr>
<td></td>
<td>TDP-6</td>
<td>0.68 ± (0.14)</td>
<td>1.54 ± (0.46)</td>
<td>0.93 ± (0.29)</td>
<td>0.84 ± (0.49)</td>
</tr>
<tr>
<td></td>
<td>TDP-8</td>
<td>0.90 ± (0.28)</td>
<td>1.25 ± (0.30)</td>
<td>0.91 ± (0.21)</td>
<td>1.22 ± (0.12)</td>
</tr>
<tr>
<td></td>
<td>TDP-10</td>
<td>1.01 ± (0.29)</td>
<td>3.93 ± (1.06)</td>
<td>1.01 ± (0.06)</td>
<td>1.38 ± (0.53)</td>
</tr>
<tr>
<td></td>
<td>TDP-11</td>
<td>0.98 ± (0.55)</td>
<td>1.68 ± (0.61)</td>
<td>0.74 ± (0.33)</td>
<td>0.98 ± (0.14)</td>
</tr>
<tr>
<td></td>
<td>Avg. (n = 6)</td>
<td>0.89</td>
<td>1.64</td>
<td>0.87</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.16</td>
<td>1.20</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td>No EA First (Group B)</td>
<td>TDP-1</td>
<td>1.49 ± (0.65)</td>
<td>2.73 ± (0.76)</td>
<td>1.67 ± (0.66)</td>
<td>0.83 ± (0.39)</td>
</tr>
<tr>
<td></td>
<td>TDP-3</td>
<td>0.47 ± (0.11)</td>
<td>1.89 ± (0.18)</td>
<td>0.82 ± (0.23)</td>
<td>0.88 ± (0.27)</td>
</tr>
<tr>
<td></td>
<td>TDP-4</td>
<td>1.33 ± (0.61)</td>
<td>2.36 ± (0.63)</td>
<td>0.91 ± (0.27)</td>
<td>1.22 ± (0.64)</td>
</tr>
<tr>
<td></td>
<td>TDP-7</td>
<td>0.63 ± (0.43)</td>
<td>1.02 ± (0.42)</td>
<td>0.52 ± (0.25)</td>
<td>0.73 ± (0.24)</td>
</tr>
<tr>
<td></td>
<td>TDP-9</td>
<td>0.94 ± (0.28)</td>
<td>2.58 ± (2.08)</td>
<td>0.63 ± (0.25)</td>
<td>0.96 ± (0.24)</td>
</tr>
<tr>
<td></td>
<td>TDP-12</td>
<td>1.26 ± (0.17)</td>
<td>1.28 ± (0.61)</td>
<td>0.96 ± (0.29)</td>
<td>0.93 ± (0.60)</td>
</tr>
<tr>
<td></td>
<td>Avg. (n = 6)</td>
<td>1.02</td>
<td>1.98</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.41</td>
<td>0.71</td>
<td>0.40</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Using these baseline and evaluation error averages, each individual participant difference and the average difference in percent improvement between the two sets was calculated in Table 4.2.
Table 4.2: Difference in percent improvement from baseline to evaluation RMSE for TDP participants

<table>
<thead>
<tr>
<th>Starting Order</th>
<th>Participant ID #</th>
<th>Percent Improvement (%)</th>
<th>Difference between Training With or Without EA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No EA Set</td>
<td>With EA Set</td>
</tr>
<tr>
<td>EA First</td>
<td>TDP-2</td>
<td>12.2</td>
<td>-22.9</td>
</tr>
<tr>
<td>(Group A)</td>
<td>TDP-5</td>
<td>32.4</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>TDP-6</td>
<td>-127.3</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>TDP-8</td>
<td>-38.0</td>
<td>-33.8</td>
</tr>
<tr>
<td></td>
<td>TDP-10</td>
<td>-289.6</td>
<td>-37.2</td>
</tr>
<tr>
<td></td>
<td>TDP-11</td>
<td>-71.5</td>
<td>-32.5</td>
</tr>
<tr>
<td>Avg. (n = 6)</td>
<td>-80.3</td>
<td>-10.7</td>
<td>69.6</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>117.6</td>
<td>35.3</td>
<td>106.5</td>
</tr>
<tr>
<td>No EA First</td>
<td>TDP-1</td>
<td>-83.7</td>
<td>50.5</td>
</tr>
<tr>
<td>(Group B)</td>
<td>TDP-3</td>
<td>-303.3</td>
<td>-7.6</td>
</tr>
<tr>
<td></td>
<td>TDP-4</td>
<td>-77.7</td>
<td>-34.1</td>
</tr>
<tr>
<td></td>
<td>TDP-7</td>
<td>-61.8</td>
<td>-42.0</td>
</tr>
<tr>
<td></td>
<td>TDP-9</td>
<td>-174.4</td>
<td>-53.3</td>
</tr>
<tr>
<td></td>
<td>TDP-12</td>
<td>-1.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Avg. (n = 6)</td>
<td>-117.1</td>
<td>-13.9</td>
<td>103.2</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>106.8</td>
<td>38.0</td>
<td>108.2</td>
</tr>
<tr>
<td>Average (n = 12)</td>
<td>-98.7</td>
<td>-12.3</td>
<td>86.4</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>108.8</td>
<td>35.0</td>
<td>99.4</td>
</tr>
</tbody>
</table>

In many cases, participants were not able to return to their baseline visual symmetry error at the end of either training set. If the percent improvement is a negative value in Table 4.2, the evaluation set error is greater than the baseline set error, indicating that the participant was not able to recover equivalent visual symmetry as in their baseline reaching after the 60 training trials. If the difference between training sets is a positive value, this indicates that participants improved more in their training set with error augmentation.

The TDP data was tested for normality in SPSS v25 (IBM, Armonk, USA) using the Shapiro-Wilk’s test values. The distribution of percentage change for the 12 participants was found to be normal ($p > 0.05$) for both training sets with and without EA. Skewness test results were found
to be less than 1.96. Neither training set nor the calculated differences between the two sets required non-parametric analysis. Additionally, no outliers were found in either group regardless of training set order.

A comparison of the improvement in symmetrical error, split by participant Groups A and B \((n = 6)\) based on training set order is shown in Figure 4.1.

![Distribution of Symmetry Improvement in Training Sets Between Participants with Different Starting Orders](image)

**Figure 4.1:** Box-plots showing the distribution of percent improvement in bilateral symmetry when participants were divided between starting set order. The centre line in the boxplots are the median values, and height of the box and whiskers represent the interquartile range (IQR) and range, respectively.

A repeated-measures ANOVA was performed on the percent improvement with training set type (with or without EA) as the within-subjects’ condition and the training set order as a between-subjects factor. Significant differences were found \((F(1,10) = 7.780, p = 0.019)\) between improvement with and without EA with a medium effect size of \(\eta^2_{\text{partial}} = 0.438\). A statistically non-significant between-subjects effect \((F(1,10) = 0.292, p = 0.601)\) on percent improvement from training set order is demonstrated by the similar slopes of the lines in Figure 4.2.
Figure 4.2: Line graph of the difference in percent improvement between training with and without EA. Similar slopes indicate that there was little difference in percent improvement based on whether the training set was completed first or second. The type of training set completed is indicated by marker colour and arranged along the x-axis. The direction of the arrows indicates the chronological order of training sets for participants such that the training set at the tail end was completed first.

In Figure 4.2, the difference in percent improvement in the training sets with EA was very small. Participants reached similar percent improvements when training with EA, regardless of order, but participants who trained with EA first had higher improvement in their training set without EA in comparison to those who started training without EA. This difference may indicate that participants starting with EA carried over some practice adaptation effects that resulted in a higher percent improvement in error when they trained without EA, in comparison to the those who trained without EA first. As the repeated measures ANOVA did not find differences based
on training set order to be statistically significant, subsequent results analysis tested within-subject differences without dividing the sample population based on starting order.

The difference in percent improvement between the two training sets for each participant was calculated and used to find the additional statistical descriptors shown in Table 4.3. A two-tailed paired t-test found a statistically significant difference in error improvement ($t(11) = 2.883, p = 0.015$) between practice with and without visual EA when starting order groups were combined.

**Table 4.3: Descriptive differences and results of a paired two-tailed t-test performed on the average symmetry RMSE data between training sets with and without EA.**

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error Mean</th>
<th>95% Confidence Interval of Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>86.4</td>
<td>103.8</td>
<td>30.0</td>
<td>Lower: 20.5 Upper: 152.4</td>
<td>2.883</td>
<td>11</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Analysis of these results in G-Power found a large effect size (Cohen’s $d = 0.823$).

In addition to a difference in average symmetry RMSE with and without EA, the distribution of improvement between participants after training with EA had a smaller spread than training without EA, going from ±108.8% standard deviation to ±35.0% when training with EA between participants. Using a paired t-test, a significant difference was not found when comparing the participants’ standard deviations in symmetry RMSE (Table 4.1) within the 5 evaluation trials after training with and without EA ($t(11) = 1.959, p = 0.076$). The difference in percent change from baseline to evaluation standard deviations between training types was also not significant ($t(11) = -0.441, p = 0.668$). While the standard deviations within participants did not decrease significantly, there is a discernable decrease in between-participant spread.

While the single-session setup did not allow for evaluation of long-term motor learning, the blind trials (i.e. without any visual feedback of hand position) were used as part of an immediate retention test. The average RMSE error found during the blind trials performed before the first baseline was $1.43 \pm 0.54$ cm. The distribution of symmetry error in blind trials after both training sets is shown in Figure 4.3:
Figure 4.3: Double histogram of error in trials with no visual positioning feedback split by trials performed after training with or without EA (left) and a set of box-plots of the percent change of symmetry in blind trials in comparison to the average blind trials performed at baseline (right). The dots in the box-plots represent outlier data points found outside of 1.5 times the interquartile range.

The difference in centimetre symmetry error between blind trials after training with or without EA for each participant was small but the average over all had a comparably large standard deviation: participants were 0.18 ± 4.65 cm worse in blind trials after training without EA than after training with EA. Percent change in symmetry error was calculated against the blind trials performed before baseline to see if there were any changes in movement without visual feedback from training with or without EA. In comparison to the baseline blind trials performed before training, participants performed with more symmetry RMSE after training on an asymmetric reaching task. No difference in change was observed between training with or without EA, and 11 of 12 TDP participants increased in asymmetry after training when all visual feedback was removed. This high percentage of participants with increased asymmetry indicates that some asymmetry was retained from the previous training set.
The percent change in symmetry error from the 5 evaluation trials to the first 5 washout trials (performed without asymmetry or visual augmentation) was also calculated to explore immediate retention of training. The average change in error in washout trials after training with EA (107.8 ± 113.8%) was larger than after training without EA (32.4 ± 125.9%). This demonstrates that a larger amount of adaptation to movement with an asymmetry factor of 70% was retained from training with EA, resulting in a higher increase in error when returning to the symmetrical reaching trials.

### 4.1.2 Exploration of Secondary Outcomes

The symmetry RMSE values throughout the training trials for TDP participants were averaged and fit to performance curves using the equation \( y = Ae^{-t/B} + C \) to find parameters \( A \), \( B \), and \( C \) as described in Section 3.3. The average points and standard deviation, shown in the filled area, of all participants’ training trials with and without EA are provided in Figure 4.4.

![Symmetry RMSE Over Training Sets](image)

**Figure 4.4:** Line and filled area plots illustrating the symmetry RMSE for training sets with and without EA, averaged over all TDP participants. A performance curve equation was fit to the averaged data set and the filled area indicates the standard deviation of these averages at each trial number.
Training trials in both training sets with and without EA did not correlate highly to a performance curve with parameters $A$, $B$, and $C$, as seen by the low r-squared values 0.24 and 0.43 respectively. As seen in the primary outcome analyses, a high variation between participant symmetry error values exists. A high variation in error over subsequent trials within participants can be inferred from Figure 4.4 as both the average and standard deviation peak frequently and erratically. The overall learning, $A$, and rate of learning (approximated by the negative of $B$) were higher when training without EA; however, the average starting RMSE value was also higher, implying there may be more immediate adaptation within the first trial of the training phase with EA. The immediate adaptation to asymmetry in training trials is also reflected in the convergence value or final performance, $C$, which was better when training with EA.

Additionally, overall learning, $A$, does not appear to directly represent the change in error from the first trial to the convergence value. Therefore, equating the time constant, $B$, to the rate of learning may not be suitable for this data set.

Similar performance curve analysis (Figure 4.5) was performed for the washout trials:

Figure 4.5: Line and filled area plots for symmetry RMSE averaging the washout trials over 12 TDP participants.
Due to the smaller number of trials performed than in the training trials set, there were fewer peaks in average and lower standard deviation error over subsequent trials and higher r-squared values than in curves fit to the training trials data. Differences in parameters $A$, $B$, and $C$ between washout trials after training with and without EA were in the negative direction of differences in the training trials. After training with EA, de-adaptation to 70% asymmetry was higher in overall change, had a slower rate of change, and resulted in more symmetry error at final performance. A higher final performance value implies that training with EA slightly increased immediate retention of asymmetrical reaching.

The secondary outcomes performance curve parameters, reaching ROM, reaching velocity, and reaching smoothness were quantitatively explored using multiple t-tests; however, no correction factors were used as the outcomes were considered exploratory.

Table 4.4 presents averages and standard deviations for the secondary outcomes of reaching ROM, ND/A side peak velocity, and time to peak velocity. Reaching ROM is defined as the maximum forward distance (in the z-direction) per trial.

<table>
<thead>
<tr>
<th>Average Between Participants</th>
<th>Reaching Range of Motion (cm)</th>
<th>Peak Velocity (cm/s)</th>
<th>Time to Peak (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ND/A (Left)</td>
<td>D/LA (Right)</td>
<td></td>
</tr>
<tr>
<td>Without EA Baseline</td>
<td>37.55 ± 5.49</td>
<td>36.88 ± 5.66</td>
<td>42.46 ± 18.51</td>
</tr>
<tr>
<td>Without EA Evaluation</td>
<td>46.04 ± 4.68 *</td>
<td>33.69 ± 3.54</td>
<td>50.17 ± 18.92 *</td>
</tr>
<tr>
<td>$t(11) =$, $p$-significance</td>
<td>-5.051, 0.001</td>
<td>2.061, 0.073</td>
<td>-2.422, 0.042</td>
</tr>
<tr>
<td>With EA Baseline</td>
<td>39.02 ± 2.40</td>
<td>38.41 ± 2.16</td>
<td>48.35 ± 19.57</td>
</tr>
<tr>
<td>With EA Evaluation</td>
<td>47.43 ± 3.85 *</td>
<td>33.21 ± 3.12 *</td>
<td>49.55 ± 19.39</td>
</tr>
<tr>
<td>$t(11) =$, $p$-significance</td>
<td>-6.402, 0.000</td>
<td>6.093, 0.000</td>
<td>-0.356, 0.731</td>
</tr>
</tbody>
</table>

Multiple paired t-tests found no significant differences in peak velocity, time to peak, or ROM in both the ND/A and D/LA sides at the baseline or evaluation phases between training with or without EA. When comparing ROM in symmetrical baseline to evaluation trials, significant differences in both ND/A and D/LA sides were found, regardless of the training set, except in the
D/LA side without EA. The difference is more likely caused by the application of asymmetry as opposed to EA. It is likely that the D/LA side ROM had the smallest and only non-significant change after training without EA because the training set had the least visual augmentation in which asymmetry was applied to the ND/A side and no EA was applied. A significant change from baseline to post-training evaluation in peak velocity was only found in the training set without EA and significance was found in change in time to peak during the training set with EA. All statistical t-test values for tests run on the secondary outcome measures for the TDP group data can be found in Appendix G.

It was expected that the two baseline values taken before the training sets with and without EA, in which the participants’ natural symmetry was measured, should have been the same. However, as participants were not given specific directions regarding these secondary outcome measures, the high standard deviation found in between-participant averages was seen, leading to slight differences in the baseline secondary metrics in Table 4.4.

The number of peaks in ND/A side velocity during each reach with a minimum peak prominence of 5 cm/s was counted and averaged for the baseline and post-training evaluation phases to test if there were any changes in movement smoothness caused by the application of EA. An average of velocity peaks counted in each TDP participants’ baseline and evaluation trials, averaged between participants, is shown in Table 4.5.

**Table 4.5: Average number of velocity peaks made during both training sets for the TDP group.**

<table>
<thead>
<tr>
<th></th>
<th>Average Between Participants</th>
<th>Average Number of Peaks per Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EA</td>
<td>Baseline</td>
<td>1.47 ± 0.51</td>
</tr>
<tr>
<td></td>
<td>Evaluation</td>
<td>1.44 ± 0.48</td>
</tr>
<tr>
<td>With EA</td>
<td>Baseline</td>
<td>1.40 ± 0.62</td>
</tr>
<tr>
<td></td>
<td>Evaluation</td>
<td>1.49 ± 0.46</td>
</tr>
</tbody>
</table>

Using multiple paired t-tests (statistical values reported in Appendix G), no significant changes in velocity peaks were found for TDP participants from baseline to post-training evaluation in either set and no significant difference was found when comparing sets with and without EA.
For TDP participants, the only visible compensation technique used was trunk flexion, expectedly seen for trials when reaching between 90-100% of the participants reaching ROM occurred. Some trunk compensation was expected to occur at 90% of maximum reach in healthy individuals [116], [117] and the goal with asymmetry applied was set at maximum reach. A significant difference in trunk compensation was found in both sets with EA ($t(11) = -0.2944, p = 0.015$) and without EA ($t(11) = -4.133, p = 0.002$) between baseline trials at less than maximum recorded reach and evaluation trials in which the participants’ ND/A side reached to the full arm length.

It was found that, on average, participants completed the evaluation trials without EA with $0.12 \pm 2.72$ cm less trunk compensation than in evaluation trials with EA. A paired t-test did not find this difference to be statistically significant ($t(11) = 0.779, p = 0.454$). However, when the within-participant difference between the two training sets was split based on training set order, it was found that participants who completed the training set without EA first had $1.92 \pm 3.17$ cm less trunk compensation in their first evaluation set and participants who completed the training set with EA first had $1.38 \pm 1.49$ cm less trunk compensation in their first evaluation set. While statistically non-significant, this larger difference based on the training set order may imply that changes in trunk compensation throughout the experiment correlated more to exercise fatigue over time than whether the participant trained with or without EA.

As an example, differences in ND/A ROM and trunk compensation from initial baseline and both evaluation phases of TDP-7 are shown in Figure 4.6.
Figure 4.6: Example of tracking data from the top-down (X-Z plane) view of reaching movements from TDP-7. TDP-7 started with the training set without EA first. The colour scale (right) represents the velocity of the participant’s hands in cm/s, and the SpineShoulder joint was tracked in solid black to see if there was any trunk compensation.

In addition to the trunk movement tracked by the Kinect, Figure 4.6 also shows that the ND/A side of TDP-7 reached slightly further than required to complete the reaching task after training with EA. This unexpected ‘goal overshooting’ seen was confirmed by checking that the participant’s velocity at the end of the reach was non-zero and in the forward reaching direction. Some participants were observed in video recording to continue to reach past the end goal, particularly with those who employed less vertical movement (y-axis height) during the reaching task; however, goal overshooting was not observed in every participant. Since no significant differences were found in ND/A side ROM between training with and without EA, goal overshooting was likely not significantly affected by the application of EA.
4.2 Clinical Population Response to Error Augmentation

All participants recruited were clinically diagnosed with hemiplegic CP and their motor abilities were classified (Section 3.2.1). Data collected from the CHP participants were analyzed in a similar fashion to the data from TDP participants: primary analysis of symmetry RMSE between training with and without EA and exploration of secondary outcomes.

In addition to changes mentioned in Section 3.1.3, some participants in the CHP group were not able to properly grasp the controller in a manner that allowed them to reach while holding it. To help with weak grasp, 4 of 5 participants (CHP-1, CHP-3, CHP-4, CHP-5) opted to use an adjustable strap that could attach the controller to their hand through a loop around the knuckles and palm.

4.2.1 Average RMSE in Bilateral Symmetry

Symmetry RMSE was calculated for CHP participants in the same manner as for the TDP participants using \( Z_{\frac{N}{DA}} \) as opposed to \( Z_{asy} \) as described in Section 3.1.4. Table 4.6 lists the average symmetry error scores in raw centimetre distance and percent improvement for each participant in the CHP group for the 5 baseline and 5 evaluation trials in both training sets with and without EA.
Table 4.6: Results from the primary outcome measure (symmetry RMSE average over 5 trials) for the CHP participant group.

<table>
<thead>
<tr>
<th>Starting Order</th>
<th>Participant ID #</th>
<th>No EA Set (cm)</th>
<th>With EA Set (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Evaluation</td>
<td>Baseline</td>
</tr>
<tr>
<td>EA First (Group A)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHP-2</td>
<td>3.74 ± 0.73</td>
<td>5.95 ± 1.26</td>
<td>3.69 ± 0.92</td>
</tr>
<tr>
<td>CHP-3</td>
<td>1.70 ± 0.30</td>
<td>1.58 ± 0.57</td>
<td>1.60 ± 0.49</td>
</tr>
<tr>
<td>No EA First (Group B)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHP-1</td>
<td>2.75 ± 1.85</td>
<td>5.15 ± 1.37</td>
<td>2.91 ± 0.52</td>
</tr>
<tr>
<td>CHP-4</td>
<td>7.56 ± 3.08</td>
<td>7.92 ± 0.50</td>
<td>5.80 ± 2.07</td>
</tr>
<tr>
<td>CHP-5</td>
<td>6.10 ± 2.34</td>
<td>4.11 ± 0.44</td>
<td>4.16 ± 1.72</td>
</tr>
<tr>
<td>Average (n = 5)</td>
<td>4.37</td>
<td>4.94</td>
<td>3.63</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.42</td>
<td>2.34</td>
<td>1.55</td>
</tr>
<tr>
<td>Median</td>
<td>3.74</td>
<td>5.15</td>
<td>3.69</td>
</tr>
<tr>
<td>Interquartile Range</td>
<td>3.35</td>
<td>1.84</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Using the average position values for each group of 5 baseline or evaluation trials, improvement after training with or without EA for each participant can be seen in Figure 4.7.

Figure 4.7: Line plots presenting change in symmetry RMSE before and after training with and without EA. Participants in Group A, who started with the training set with EA first, are marked in the legend with an asterisk *.
All participants reached with lower symmetry error after training with EA than after training without EA, as seen by the decreasing slopes in Figure 4.7.

The average difference in percent improvement over the 5 CHP participants was calculated from each individual difference in Table 4.7.

**Table 4.7: Difference in percent improvement from baseline to evaluation RMSE for CHP participants**

<table>
<thead>
<tr>
<th>Starting Order</th>
<th>Participant ID #</th>
<th>Percent Improvement (%)</th>
<th>Difference between Training With or Without EA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No EA Set</td>
<td>With EA Set</td>
</tr>
<tr>
<td>EA First (Group A)</td>
<td>CHP-2</td>
<td>-59.3</td>
<td>36.6</td>
</tr>
<tr>
<td></td>
<td>CHP-3</td>
<td>7.2</td>
<td>16.0</td>
</tr>
<tr>
<td>No EA First (Group B)</td>
<td>CHP-1</td>
<td>-87.4</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>CHP-4</td>
<td>-4.7</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>CHP-5</td>
<td>32.6</td>
<td>44.8</td>
</tr>
<tr>
<td>Average (n = 5)</td>
<td></td>
<td>-22.3</td>
<td>26.6</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td>49.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>-4.7</td>
<td>19.2</td>
</tr>
<tr>
<td>Interquartile Range</td>
<td></td>
<td>66.5</td>
<td>20.4</td>
</tr>
</tbody>
</table>

CHP-4 provided a median difference in percent improvement in which they performed better after training with EA by 23.9%. The sample population of 5 participants had a range in differences between sets of 8.8% to 103.7%.

Visually, a difference between improvement in symmetry error with and without EA, regardless of training set order can be seen in Figure 4.8.
Figure 4.8: Box-plots showing the percent improvement in bilateral symmetry for training with or without EA in CHP participants when divided between the training set order.

Similar to the TDP population, the decrease in sample spread from training without EA to training with EA is more evident than the decrease in average error values. The baselines were expected to have non-significant differences based on order; however, slight differences could be caused by carry-over effects of task learning and fatigue as the sample size did not allow even allocation to starting order groups.

In order to further analyze data from the CHP participants individually, the average error over time was plotted to see if there were any differences in kinematic profile. Figure 4.9 shows a compilation of each participant’s average over time for the 5 evaluation trials.
Figure 4.9: Multiple line plots showing the average reaching error over time for each CHP participant. The shaded area represents the standard deviation over the evaluation trials in training sets with or without EA.
While it was hypothesized that the application of visual EA could cause more small corrective movements and lead to more peaks in the average error profiles, it was found that each of the 5 participants had different methods of adapting to visual EA. CHP-1 was the only one who showed the predicted increase in reaching time and had more peaks in error profile when training with EA. CHP-3 and CHP-5 had average reaching error lines with and without EA that crossed. All participants except CHP-4 had relatively horizontal error profiles when reaching with EA, but when training with no augmented feedback, error profiles were more varied in terms of the direction of change (increasing or decreasing error) and profile smoothness (number of peaks). The only pattern that could be inferred from the error profile was that the overall range of error values throughout the reaching trials was less when training with EA.

4.2.2 Exploration of Secondary Outcomes

The secondary outcomes tested with the CHP participant data mirrored those tested for the TDP population in Section 4.1.2: performance curve parameters, reaching ROM, reaching velocity, and reaching smoothness. Due to the limited sample size of the CHP group, no differences in secondary outcomes between training with and without EA were tested for statistical significance.

An identical procedure for performance curve fitting to TDP RMSE data was used for the CHP participant data and is similarly presented in Figure 4.10.
Figure 4.10: Line and filled area plots of the symmetry RMSE for training trials during sets with and without EA, averaged over all CHP participants. A performance curve equation described in Section 3.3 was fit to the averaged data set.

Correlation of data to $y = Ae^{-t/B} + C$ was found to be lower in the CHP group than in the TDP population with r-squared values of 0.06 and 0.03 for training with and without EA respectively. While the final performance value, $C$, appeared within a sensible range, $A$ and $B$ values could not be fit to values that were meaningful. It was expected that the overall change and rate of change would be minimal when training without EA for CHP participants as no changes to their natural reaching asymmetry were applied. Immediate adaptation could be inferred from the overall decrease in average error and standard deviation throughout the training trials with EA. A large variation between consecutive trials was seen, as in the TDP group results.

Table 4.8 presents results from the secondary metrics of reaching ROM, peak velocity, time to peak velocity, and number of peaks greater than 5 cm/s.
Table 4.8: Secondary metrics range of motion, peak velocity, time to peak, total reach time, and number of peaks in velocity for the CHP participant group.

<table>
<thead>
<tr>
<th>Average ± STD and Median (IQR) Between Participants</th>
<th>Reaching Range of Motion (cm)</th>
<th>Peak Velocity (cm/s)</th>
<th>Time to Peak (s)</th>
<th>Velocity Peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ND/A (Left)</td>
<td>D/LA (Right)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline Without EA</td>
<td>27.31 ± 14.91</td>
<td>28.67 ± 14.78</td>
<td>25.95 ± 5.67</td>
<td>1.07 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>25.80 (0.81)</td>
<td>22.35 (11.58)</td>
<td>27.17 (5.02)</td>
<td>1.05 (0.11)</td>
</tr>
<tr>
<td>Evaluation</td>
<td>27.83 ± 18.08</td>
<td>29.88 ± 17.88</td>
<td>26.22 ± 15.08</td>
<td>0.73 ± 0.49</td>
</tr>
<tr>
<td></td>
<td>22.81 (20.28)</td>
<td>22.40 (19.94)</td>
<td>27.20 (18.70)</td>
<td>0.65 (0.32)</td>
</tr>
<tr>
<td>Baseline With EA</td>
<td>29.74 ± 15.91</td>
<td>28.99 ± 15.21</td>
<td>34.82 ± 19.03</td>
<td>1.77 ± 1.19</td>
</tr>
<tr>
<td></td>
<td>26.72 (5.96)</td>
<td>23.14 (7.39)</td>
<td>31.00 (13.66)</td>
<td>1.63 (1.16)</td>
</tr>
<tr>
<td>Evaluation</td>
<td>28.40 ± 20.30</td>
<td>27.65 ± 18.83</td>
<td>30.22 ± 17.04</td>
<td>1.52 ± 0.61</td>
</tr>
<tr>
<td></td>
<td>23.65 (12.38)</td>
<td>22.32 (11.37)</td>
<td>30.26 (13.24)</td>
<td>1.67 (0.51)</td>
</tr>
</tbody>
</table>

While no discernable pattern was found in the error profiles presented in Figure 4.9, Section 4.2.1, a difference in reaching smoothness was seen in the evaluation trials between training with and without EA, as shown by a slight increase in velocity peaks. Average peak velocity was also higher after training with EA. However, there is a wider difference in peak velocity averages between the two baseline sets, in which no augmentation was applied which may indicate that the difference in peak velocity during the post-training evaluation was caused by high variation in trial values throughout the session and fatigue effects that were unbalanced between training sets due to the uneven randomized allocation. Similarly, any slight changes in reaching ROM in both sides between sets with and without EA were overshadowed by the large standard deviations of 15-20 cm.

Compensation in the CHP participant group was quantitatively evaluated for trunk compensation in a similar fashion to the TDP participant group. Because CHP-5 required a chest strap attached to a wheelchair during the session, trunk compensation was considered negligible throughout the reaching trials and trunk compensation was measured with a sample size of 4. The average and median difference of trunk compensation after training sets with and without EA was
0.33 ± 7.41 cm and 2.99 (7.15) cm, respectively, such that more trunk compensation was found after training with EA. The average and median difference between the first and second training set, regardless of whether EA was applied, was 2.95 ± 6.60 cm and 3.26 (7.43) cm such that more trunk compensation was used in the second set. These larger increases in error based on training set order are similar to those seen with the TDP group and were likely an effect of exercise fatigue as opposed to the application of augmented feedback.

Additional compensation techniques were observed based on individual motor patterns. An example of another compensation technique visible from recorded kinematic data is shown in Figure 4.11 in which CHP-1 used more compensatory shoulder abduction in the set with EA (Set B). The elbow joint was used to visualize shoulder abduction during the reaching exercises.

**Figure 4.11:** Top-down (x-z plane) plot of the initial baseline and two evaluation phase reaching trials for participant CHP-1. The participant training without EA first and trained with EA second. The colour indicator (right) denotes the instantaneous velocity in cm/s of the recorded point of the participant’s hand. The solid tracked line denotes the position of the participant’s trunk at shoulder level and the dotted grey points represent the position recorded from the elbow joint kinematic data.
Like trunk compensation, individual motor compensation techniques may emerge from exercise fatigue as opposed to emerging from the application of visual EA. From Figure 4.11, some reaching asymmetry was seen around the end distance in Set A (without EA) at approximately 50 cm in the Z-axis. A wider gap between the elbow and hand points in the ND/A side compared to the D/LA side was seen in both evaluation sets. This fact that this difference is discernable determines that the system may be capable of detecting meaningful kinematic changes in compensation in a clinical therapy. Suspected compensation techniques found through qualitative observation of kinematic data were confirmed using the video recordings captured during the sessions.

Another compensation technique that was found only with CHP-5 was the use of their D/LA side to push their ND/A hand forward physically. As the system was designed without a minimum lateral distance between upper limbs at the end goal of the reach, CHP-5 was not restricted from using this technique to complete their reaching trials without consistent verbal reminder by the experimenter and study team. Both participants who required wheelchair seating were also asked to adjust their seating posture multiple times throughout the study as they began to drift towards leaning on their more affected side.

4.2.3 Comparison of Clinical Characterization to Training Responsiveness

The classification of clinical participants in Section 3.2.1 was used in conjunction with the primary findings from Section 4.2.1 to look for any indication of differences in susceptibility to visual EA based on the pre-existing level of motor disfunction. Figure 4.12 compares the MACS and BFMF scores received by the 5 CHP participants to the amount of improvement in bilateral symmetry from baseline after each of the two training sets.
Figure 4.12: Training improvement in comparison to MACS (left) and BFMF (right) scores. MACS – Manual Ability Classification System. BFMF – Bimanual Fine Motor Function. The improvement differences between the two sets for each participant are displayed in parentheses. The values along the x-axis represent the ordinal MACS or BFMF scores given to each individual participant. The average for each classification score when there was more than one participant in the same ability group is shown in a transparent dashed bar.

The participant with the highest bimanual ability (CHP-3, BFMF I) improved the least, while the lowest bimanual ability (CHP-5, BFMF III) improved the most in both training sessions. All three participants with minimal limitations in one hand and larger impairments in the other (BFMF II) improved during the training set with EA but were not able to meet their baseline symmetry after training without EA. No participants were recruited with MACS IV/V and/or BFMF IV/V. No correlation was found between the two assessment scales used.

4.3 Post-Session Questionnaire Results

Qualitative metrics for the post-questionnaire results are presented in Section 4.3 for both TDP and CHP participants. Since the two participant groups were age-matched, any cognitive differences were not expected to significantly affect questionnaire results. The full post-session questionnaire results can be found in Appendix F.

4.3.1 General Information on Use of Technology

The first portion of the post-session questionnaire recorded general sample population characteristics on the frequency of exposure to gaming and computer technology. Figure 4.13a
and Figure 4.13b show data on weekly computer usage and frequency of popular gaming platforms for TDP and CHP participants.

Figure 4.13: Pie-charts (top) and a bar chart (bottom) describing participant use of technology through a week of regular activities.
It was found that computers were the most popular gaming platform for TDP participants. Nintendo was the most popular platform amongst CHP participants; however, all three participants who listed Nintendo specified different consoles (Nintendo DS, Wii, and Switch). The two participants who listed using gaming technology with motion-tracking controllers (Nintendo Wii, Xbox 360 Kinect) were from the CHP group. CHP participants reported more computer usage and use of gaming technology than the TDP participants in general. All CHP participants reported using at least one type of gaming technology at home.

4.3.2 System Usability Survey Results

The average SUS score was 71.25 ± 11.34 for the TDP group and 57.50 ± 17.08 for the CHP group, which is below the average score of 68 reported from 500 studies collected by Sauro [138]. CHP-5 did not complete the SUS survey due to mental fatigue after some questions. Full SUS results can be found in Appendix H. A comparison between TDP and CHP participants’ SUS scores is shown in Figure 4.14, in which TDP participants found the system more usable.

![SUS Results for TDP and CHP Populations](image)

Figure 4.14: Bar chart showing the distribution of SUS scores for the TDP and CHP participant groups.

The question with the average score furthest from positive agreement and highest standard deviation in ratings was “I think that I would need the support of a technical person to be able to
use this system.” This question and “I needed to learn a lot of things before I could get going with this system” were the only two questions with answers selected in both “Strongly Disagree” and “Strongly Agree”. Both questions relate to difficulty in setting up the system independently, which can be a major limiting factor for using commercial technology in a rehabilitative setting [63].

### 4.3.3 Engagement, Immersion, and Fidelity of the Developed Virtual Environment

A summary of additional qualitative survey questions can be found in Appendix H. It is noted that CHP-5 did not answer some questions due to uncertainty, lack of comprehension, and mental fatigue. The survey found overall positive results showing self-reported engagement, comfort, and immersion. A small portion of TDP participants noticed some rendering artifacts and did not feel as if their interactions matched a real-world environment. No participants chose to withdraw or not complete their study session due to cybersickness, and 2 of the 12 TDP participants and 2 of the 5 CHP participants experienced minor symptoms during or after the session. The two specific symptoms exhibited were eye-strain and temporary dizziness. CHP-3 experienced slight physical fatigue upon completion of the session.

While all but one of the TDP participants were capable of noticing the applied asymmetry factor of 70% reach impairment without prior explanation, 9 of 12 (75%) of TDP participants and 3 of 5 (60%) of CHP participants did not notice whether the training set included the use of visual error augmentation. A qualitative observation noted was that TDP participants frequently checked for differences in symmetry by touching their hands together.

A list of additional free-form qualitative comments by all TDP and CHP participants can be found in Appendix H.
4.4 Summary of Results

Study results from the primary and secondary measures mostly matched the hypothesized outcomes. In the TDP participant group, a significant difference ($t(11) = 2.883, p = 0.015$) of 86.4% was found in symmetry RMSE such that training with EA increased improvement in symmetry during the reaching task from baseline to evaluation trials. Statistical significance could not be found in the CHP group, likely due to the limited sample size; however, participants increased in percent improvement when training with EA between 8.8% to 103.7%. Participants adapted within the first 5 reaches and there were slight immediate retention effects found after a single training session. The order in which participants completed the training sets did not seem to affect the primary outcome in either group but may have affected the use of compensation techniques. Specifically, it was found that the difference in trunk compensation during the reaching task was larger between first and second training sets than between training sets with and without EA. Only small differences were found in reaching ROM, peak velocity, and time to peak between training sets with and without EA. It was difficult to make definitive conclusions from the averaged results as a high variation in between-participant results was seen in all metrics evaluated.

From analysis using the clinical classifications MACS and BFMF, a correlation more likely exists between improving from training with symmetry EA and participant BFMF scores. Results suggest that participants that scored BFMF-II were most likely to have room for improvement but were not too impaired to comprehend or adapt to the task. Qualitative survey results found that the majority of participants were engaged and had no adverse effects of cybersickness. The most common participant feedback in terms of usability was a concern about setting up and running the system independently in an at-home rehabilitation setting.
Chapter 5: Discussion

Chapter 5 discusses the implication of the study results from Chapter 4 in terms of the study objectives, summarised in Section 5.1. Some observations and predictions are made about the effects of visual EA on the secondary outcome results in Section 5.2. Section 5.3 presents similarities and differences in results from the TDP and CHP participant groups. Limitations on project scope and setup design are discussed in Section 5.4.

5.1 Reflection on Study Objectives

To address the research question, “Does visual amplification of hand position asymmetry in an immersive VR environment during bimanual task training increase movement quality in the more affected upper limb?”, it was determined that amplifying visual asymmetry in an HMD VR environment increased the amount of reaching symmetry for adolescent and young adult participants with hemiplegia and for an age-matched, typically developing participant group. The movement quality in the ND/A side was found to improve such that the difference in reaching distance between the ND/A and D/LA sides decreased and participants were able to better mirror the position of their D/LA side during the reaching task when EA was applied. The range of motion of the ND/A side in the direction of the forward reach was not significantly affected by the application of EA in either participant population. The use of EA did not consistently decrease movement speed or smoothness or cause an increase in the use of compensation techniques.

High variation in the kinematic metrics measured is likely to have decreased the significance of any differences between training sets. An attempt was made to normalize the data before comparison using percentage change from individual participant baseline measurements; however, this normalized value was also found to have high standard deviations when averaged between participants. Even with a larger sample size, children with hemiplegic CP will likely show a large variation in kinematic measurements in their more impaired upper limb [139]. In the CHP group, several metrics including the primary outcome symmetry RMSE had baseline values that differed between training sets, though no augmentation was applied in either baseline
before training with or without EA. This also made the evaluation trial averages that were normalized against the baseline averages difficult to interpret as a percentage change.

For the TDP group, only one participant (TDP-2) improved more during the training set without EA in comparison to the training set with EA and was found to be have completed the training set with EA first. Upon further inspection, it was found that the improvement in symmetry error from the first to the second baseline for this participant was comparably large, corroborating the hypothesis that practice effects may have affected outcomes from TDP-2.

Changes in symmetry RMSE were found to be similar to previous studies involving error augmentation. Results in Chapter 4 were reported within 2-5 cm in change in symmetry after training. Valdés [103] found only millimetre differences when measuring forward reaching bimanual symmetry during a study that provided visual and force feedback to reduce trunk compensation. Differences in symmetry after training with or without EA found from this thesis study were expectedly larger as the feedback was directly affected by bimanual asymmetry as opposed to trunk compensation. Changes in secondary outcomes like trunk compensation in this study may have had similarly small differences because the amount of feedback was not affected by this measurement. Sharp [95] reported changes in perpendicular distances of between 0.5-4.5 cm and at maximum 76% improvement when testing visual EA of path deviation during a rotated reaching task. This difference in improvement after training with or without EA is similar to the average 86.4% improvement difference found in the primary outcome. This may be attributed to the matching use of an augmentation factor $G$ of 2.0. The centimetre range of symmetry RMSE found in the results may also be correlated to the value of the augmentation factor.

The use of a single pre-set factor of augmentation may be constraining participants to reach a certain set tolerance of symmetry within this centimetre range. When Wei [118] and Shirzad [19] tested different factors of visual error augmentation, both found a gain factor closer to 2.0 to be better in facilitating motor adaptation on average (Wei reported 2.0 was better than 3.1, and Shirzad reported 1.65 was better than 1.30, with a maximum error improvement of 4.5 cm); however, neither reported analysis on any differences in between-groups variation when training with or without EA. In the primary outcome and performance curve analysis presented in this
study, the standard deviation of symmetry error between participants decreased during and after training with EA in comparison to training without EA, resulting in an average overall decrease in symmetry error. However, if a participant had a starting symmetry error of 2-5 cm or the augmentation factor chosen was less restrictive, the augmentation feedback may be less effective and a change in symmetry might not have been seen. A stricter augmentation factor could have further decreased the spread of sample population outcome values.

To compare the quantitative kinematic change in symmetry found in this study to differences required to see functional changes in motor ability, a transformation from positional difference to angular difference was calculated. The average raw positional differences found from training with EA compared to training without EA were within 2-5 cm. Using a 50th percentile female arm length of 76.0 cm and a reaching distance of 57.8 cm (upper leg length) as an average [140], the positional differences found would generate a change of about 3.5-8.7% in forward reaching distance and a change in rotation about the shoulder of 1.5-3.8°. The just noticeable difference (JND) of proprioceptive changes in shoulder ROM was reported as 0.8° [141], and so the differences are large enough to notice in immediate changes. However, the differences do not translate to any motor changes required to complete daily functional tasks, which can require up to 108° of shoulder rotation [142], even if the changes can be retained after multiple training sessions. Additionally, shoulder angles during goniometric measurements have an error of about 7.4° [143], which is still larger than the noticeable change from using symmetry EA. Changes in positional symmetry would not be apparent in a clinical therapy setting in which range of motion is measured using goniometry, and it is uncertain whether larger changes would be detected over a long-term study.

The effect size of improvement difference in the TDP group in this study’s primary outcome ($\eta^2_{\text{partial}} = 0.438$) was used in comparison to longer term studies in which hemiplegic post-stroke participants trained with EA over multiple sessions. Using force and visual error augmentation at a factor of 2.0, Abdollahi [96] found a small effect size in differences in improvement in clinical measures over 2 weeks of practice ($F(1, 24) = 4.261, p < .050, \eta^2_{\text{partial}} = 0.15$) while Majeed [97] found no significant difference when training with EA after a 2-week training and 1-week rest period using the same technical setup in a subsequent study. The experimental tasks of the two aforementioned studies were similar to the task in this
study, but the Fugl-Meyer clinical scale was used to measure changes in functional ability. It is predicted that effects caused by EA based on differences in symmetry will similarly decrease if clinical scales rating upper-limb motor ability are used instead of kinematic measurements as outcomes. Additionally, it is expected that the value of $\eta^2_{partial}$ calculated for this study may be inflated by the low sample size [144]. Majeed [97] also presents an interesting result in which participants training with EA improved significantly during the 1-week rest period while those training without EA did not. The differences in improvement between training with or without EA may not be significant after a long-term training program; however, this observation may indicate that there is a higher retention rate when using EA, as was found in this study when testing immediate retention during the washout trials.

The effect size ($\eta^2_{partial} = 0.438$) of the primary outcome was also used to compare the effect of symmetry EA to other studies comparing different feedback modalities. In a study comparing cyclic Lissajous, colour, and tone feedback to improve out-of-phase bimanual movements, Chiou [145] found a small effect size between different feedback modalities ($F(2,19) = 26.25, p < 0.001, \eta^2_{partial} = 0.05$) and non-significant differences when compared over multiple sessions. Valdés [103] found no significant difference in bilateral symmetry when comparing force and visual feedback to reduce trunk compensation. The larger effect size found in this study may be attributed to the direct amplification of visual positioning such that the feedback is noticeable but does not require any translation from colour to position or vertical position to horizontal position. It is also predicted that the smaller effect sizes may have been influenced by the number of feedback modalities being compared throughout each study. In both related studies, a difference between two types of feedback was evaluated in which every condition had at least one feedback mode, whereas this thesis study compared one type of feedback to a no-feedback control case.

The TDP participants trained to complete a task in which they were reaching symmetrically visually but felt asymmetry proprioceptively. By evaluating the blind and washout trials, it was found that without any visual feedback, symmetry based on proprioceptive sensing is worse regardless of whether training with or without EA was used. When visual feedback was returned in the washout trials some asymmetry was retained, but participants immediately re-adapted to
their natural symmetry within the first 5 washout trials on average. This reinforces Judkins’ findings [89] that visual feedback quickly overrides conflicting proprioceptive sensing.

5.2 Notable Observations Related to Secondary Outcomes

The maximum correlation ($r^2 = 0.89$) for all training and washout trials fitted to motor adaptation performance curves was found in the TDP group washout trials after training without EA. Curves generated from the training trials in the TDP group reached within 10% of the final performance value, $C$, within the first 5 trials. This immediate adaptation to the asymmetrical task may explain the higher overall learning, $A$, and rate of learning, $B$, in training sets without EA, as the participants might have adjusted to the asymmetry with EA within the first trial. With less error in the first trial, there may be less change in error and a lower rate of learning overall. Celik [101] similarly reported a smaller variance between participants and a lower final performance value in error with the use of visual EA when testing rotated reaching patterns. In contrast, Shirzad [19] found higher final performance error when visual EA was implemented. Both studies report a similarly small number of trials to reaching values close to $C$, but also had higher r-squared correlation ($> 0.9$) to a fitted curve and less variation over subsequent trials than presented in Sections 4.1.2 and 4.2.2.

No significant differences in the TDP group were found in reaching ROM in the D/LA limb between trials in which error augmentation was applied, despite Sleimen-Malkoun reporting decreased ROM of the unaffected side to match the paretic side in coupled symmetric tasks [58]. A slight decrease in D/LA reaching ROM was found in the CHP group from training without EA to training with EA; however, this difference is much smaller than the interquartile range of errors in either set. The application of visual asymmetry and augmentation simultaneously resulted in a significant decrease in D/LA reaching ROM in the TDP group after training with EA. This may mean that to create a physically asymmetric reach, TDP participants were adjusting both their ND/A and D/LA sides together and adjusted more when error augmentation made the lateral differences more noticeable.

Results from this study found a slight decrease in the time to peak velocity but overall lower peak velocities for both participant groups after training with EA in comparison to after training without EA. This is similar to findings in a study on upper-limb error augmentation in a rotated
visual field [95], in which trials after training with EA were performed more quickly and with fewer stops, such that participants were reaching peak velocity earlier; however, with a overall lower peak velocity, participants may be taking more time to rely on EA feedback. This difference could indicate that the use of EA may require more cognitive processing once engaged. Visual EA in this study also did not negatively impact movement smoothness.

The low number of participants that noticed the application of EA may indicate the suitability of using immersive VR technology. Participants were able to better adapt by seeing a more noticeable gap in symmetry but did not notice the augmentation as a separate disturbance in their movement patterns. In a study on haptic retargeting in non-rehabilitative use cases, it was found that even for a large discrepancy in distance, participants did not notice any differences in reaching direction in immersive VR through an HMD until notified [146]. Brewer [147] also found that participants were susceptible to visual feedback distortion during a unimanual motor task without noticing a change. However, the TDP participants’ ability to notice EA may have been compromised as more attention may have been given to the application of the asymmetry factor changing visuomotor behaviour than the superimposed EA factor. In cases when the feedback modality needs to be clearly noticeable, such as when using haptic feedback [105], a larger scaling factor may be necessary. The augmentation factor was easy to adapt to in a short term, but it may be natural for participants to quickly resume movement with their previous amount of asymmetry and for CHP participants to return to any learned non-use of their ND/A side without continued practice.

There was slight correlation between differences in training improvement and participants’ clinical motor classification scores. While those with better MACS scores (I-II) did not improve symmetry when training without EA, all participants improved from their baseline asymmetry during the training set with EA. The MACS scores seemed less correlated to improvement in symmetry than BFMF scores such that there may be a certain middle level of BFMF score (BFMF-II) that is best suited for improvement in bilateral reaching using EA. This may signify that the group with a larger difference in upper-limb mobility between their more and less affected sides may benefit from bilateral visual EA more than those with more balanced capabilities. Those with lower function, in general, will benefit equally from practice with and without EA. It was expected that the mobility limitations of groups in the lower motor ability
(MACS / BFMF IV and V) would prevent them from completing the task either due to lack of capability to hold and move the controllers without adaptation or assistance, or due to comorbid impairments that would have prevented verbal communication while wearing the HMD.

5.3 Comparison of Effects in Control and Clinical Populations

Participants in both the TDP and CHP groups were able to decrease the positional difference between the ND/A and D/LA upper limbs more when training with EA than when training without EA. TDP participants were, on average, not able to return to their baseline visual positional difference level after the application of visual asymmetry. This could imply that the 2.0 EA factor may have matched or surpassed the limit of healthy human perception of visual symmetry. Improvement for TDP participants was limited to returning to baseline symmetry (minimum error) whereas CHP participants were able to show positive percent improvement beyond their original baseline. All CHP participants were able to decrease their asymmetry after training with visual EA. As no additional asymmetry was applied, the visual amplification of error allowed them to increase their symmetry more than in their normal bilateral reaching pattern, even after training.

Trends in secondary outcome measures between training with or without EA were found to be similar between TDP and CHP participants. A larger number of velocity peaks was found in CHP participants, likely due to the lack of motor control caused by their motor disability. CHP participants also had lower peak velocities, longer times to peak velocity, and a higher variation in all results. These findings are similar to Robert’s findings when observing differences in reaching between typically developing children and children with CP [76].

Any carry-over effects seen from completing both sets within a single session should have been counteracted by the cross-over study design; however, slight differences in the training sets without EA were found based on the order in which participants trained on the two sets. With CHP participants, cognitive or physical fatigue effects may have caused lower percent improvement in the group that trained without EA second, as opposed to those who trained without EA first. In the TDP participant group, the opposite was found such that participants performed with more improvement in symmetry when training without EA in their second set. TDP participants were more susceptible to learning or practice effects as they trained on an
asymmetric task for the first time, whereas CHP participants were more fatigued after practicing with their natural asymmetry. This difference between populations may limit further use of a TDP group parallel to make predictions about symmetric bilateral reaching with hemiplegia.

5.4 Study Limitations

A major limitation of this study was the use of a single-session experiment design. Without a longer washout period or training over multiple days, neuroplastic differences in bimanual upper motor control could not be seen from including symmetry error augmentation in a reaching exercise therapy regimen. Retention of motor adaptation and eventual learning needs to be tested through a long-term study. Other projects using error augmentation have extended their investigation to determine possible long-term motor learning gains from their rehabilitative protocols. Following protocol from a bimanual practice study by Majeed [97], a longer-term study of the effects of bilateral training could be performed to investigate the retention of movement quality over time. Other studies also included weekly training sessions to measure motor gains in clinical functional scales over an extensive rehabilitation training period [148], [149] and a comparison of kinematic measurement tools against changes in clinical scales could be conducted. Wadden [150] was able to predict motor learning ability in stroke survivors with longer-term protocols and both kinematic and clinical scales could be applied similarly. In order to provide a suitable comparison to these studies and directly test learning retention, it is recommended that a future study is conducted in which motor learning is examined beyond single-session motor adaptation changes with a follow-up phase greater than 24 hours afterward.

Randomized allocation of training set order was used to avoid any carry-over effects of task learning and no significant difference in symmetry RMSE was found to be based on training set order. However, it could not be determined if possible carry-over effects of within-subjects testing from task practice [151] were balanced by effects of boredom or attention fatigue over both training sets. Task training could decrease error in the second training set, but attention fatigue may increase error in the second set. Some differences in trunk compensation were found to exist based on training set order. While randomized allocation should prevent carry-over effects, a study in which only one training set with two larger groups of participants training either with or without EA would eliminate carry-over effects entirely.
While a constant gain factor of 2.0 was used in this study, the exact gain factor for optimal susceptibility to visual error augmentation in symmetric error comparisons should be investigated. In a study using fMRI to measure neural activation during a locomotor exercise, it was found that force augmentation was less effective when provided consistently [90]. An optimal gain factor could have been tested by finding an average ‘just noticeable difference’ [147] for when augmentation is applied or by finding a point of subjective equality [102] for which error with and without EA is the same after a set number of trials. Modulation of the error augmentation factor could be explored such that a changing difficulty may keep the participant more engaged. A ‘challenge point’ [152] could have been established based on the participant’s skill level to maintain increased cortical activation and promote neuroplastic motor learning. Comparisons to augmentation of other dimensions (i.e. stretch, lateral path deviation, and lifting upwards during reach) should be investigated in the future to test susceptibility to scaling factors based on movement direction.

Objects that stretch infinitely without resistance are not reflective of object constraints that exist when working with some physical objects requiring two-handed synchrony. In this experiment, all bimanual interactable objects were able to stretch an infinite amount and provided no force restriction in a manner that physical objects would provide tension between two hands. Force or haptic feedback could have been used to augment physical properties of virtual objects to provide tasks that are more functional or comparable to activities in daily living. This addition of feedback present when handling physical bimanual objects could have provided more intuitive cues for more symmetric reaching and better transfer of motor learning to functional activities.

Of the CHP participants, only CHP-2 was able to wear the headset for the first time without assistance and did not need to add straps to ensure the controller was securely grasped. While the controllers were chosen for their ergonomic shape and size, they still may not be sufficiently designed for players with limited hand mobility or grasp control. All of the CHP participants were successful in holding the controller independently after some adaptation, but the use of different grasping techniques resulted in some controller orientations on the ND/A side that did not match the orientation of the D/LA side controller. This orientation difference may have added a slight discrepancy in the asymmetry measured by the controller and the asymmetry of
the participants’ wrist or hand. The technical setup also did not provide any compensation for asymmetry in physical arm length.

Some issues with signal noise from the Kinect v2 occurred in some cases when the participants were not able to move outside their wheelchair for the session. Some atypical jumps in joint positions in the elbow, shoulder, and head points were found before and after filtering, possibly caused by the proximity of the wheelchair back to the participants’ body. Eckert highlights this detection issue with Kinect tracking as a reoccurring unaddressed issue with past exergaming studies [153]. Future iterations of similar studies could implement a filtering system to ensure that less signal noise and better upper body tracking occurs for wheelchair users.

As reported in Section 4.3, a major concern from participants regarding the system was the ability of the participant or future user to set up and run the system independently without extensive training. Since an experimenter was always present to set up and run the system prior to the arrival of each participant, the SUS scores listed may not be comprehensively indicative of the system usability.
Chapter 6: Conclusion

The chapter and thesis are concluded with a final summary of presented material in Section 6.1. Section 6.2 presents suggestions for future work in analyzing the effects of bimanual practice and testing long-term effects of immersive VR and visual EA based on lateral upper-limb symmetry.

6.1 Summary

Hemiplegia causes a lateral asymmetry in motor ability hindering activities of daily living and ultimately affecting quality of life. Repetitive practice in a clinical physiotherapy setting is the leading form of treatment for neurological injuries that result in motor dysfunction. Recent work in improving the quality of movement and control from repetitive practice looks towards using game design and exergaming tools to encourage active engagement and increase participant retention through extensive long-term exercise regimens. With improved human movement tracking technology in commercial gaming systems over recent years, new research is essential to investigate the potential of new rehabilitation methods using these tools.

The thesis study combines immersive VR for engagement and fidelity to real-life movement and bimanual task training for its researched improvements to neuroplastic qualities found in repeated practice. The main research question was grounded in existing literature findings in which systems with dynamic feedback found positive outcomes. The feedback modality of error augmentation was chosen as a direction aligned with techniques used for upper-limb reaching exercises. Bilateral symmetry was tested as a novel measurement to which visual augmentation was applied.

A system testing error augmentation of bilateral symmetry during two-handed upper-limb reaching was developed using the Oculus Rift VR system. The virtual environment developed presented a 3D space in which a food preparation task was used to create a repeated bimanual exercise task. The error between the forward reaching position of the two hands was recorded as the primary metric for evaluating if movement quality improved with the application of error augmentation. A single-session study was conducted in which participants with hemiplegic cerebral palsy and age-matched typically developing youth were recruited.
Key results include the following: the research found that improvement in symmetry was significantly higher with the application of visual EA in the typically developing population participants when training to complete an asymmetrical task. Maximum velocity per reach or total reach time were not significantly affected by training with EA with either population. The reaching range of motion only changed in the non-augmented side of typically developing participants with the application of asymmetry. A high variation in averaged between-participant results was seen in all metrics evaluated and this greatly impacted being able to make definitive conclusions.

In general, participants adapted well to the error augmentation tested, and they were able to decrease symmetry error more after training with amplified bilateral symmetry error. It was found that the range of position differences and level of improvement caused by visual EA were similar to studies using the same augmentation factor. The use of error augmentation did not cause any adverse effects on kinematic reaching patterns.

Conclusions from this thesis project could be used as a reference for or against using bilateral symmetry error augmentation as a feedback method for at-home exergaming tool or programs designed for upper-limb rehabilitation. While this study presents positive outcomes from using visual symmetry EA, EA may only be useful for a smaller sub-population and some drawbacks found from using HMD VR systems with participants with lower motor function may provide a means of identifying this subgroup.

Application of this type of error augmentation in immersive VR gaming can be implemented directly in games specifically designed for rehabilitation. Intermediate software suites that port commercial games to motion controlled gaming for rehabilitation, such as FEATHERS [154], may also be able to implement similar augmentation algorithms. Sports training applications could also benefit from the development of new dynamic feedback using bilateral error augmentation techniques in virtual environment simulators.

Further research is required to test if error augmentation in immersive virtual reality in an upper-limb rehabilitative setting presents long-term retention of higher symmetry movement qualities acquired in this thesis study.
6.2 Future Work Recommendations

The most crucial recommendation for future work would be to conduct a similar study with a larger clinical population sample size. To validate the differences found in Section 4.2, a larger sample size can be used to confirm statistical significant of the effects of visual symmetry EA. This significance would allow more concrete and generalizable predictions to be made about CHP behaviour. A sample set with even starting-order groups should be procured, with a large enough sample size to confirm or reject significant differences with sufficient test power.

Additional data collection could be performed with a more diverse population, such as participants of other ages and different neural injury times or mechanisms. Adults with CP or stroke in the ageing population could be tested to observe if there are any differences in motor adaptation and symmetry that occur after the developing age. Differences in comfort and ease of use of the HMD may also differ between the ageing and developing population. The ageing population may find more difficulty adapting to the EA training due to differences in neuroplastic potential [33]. Participants with ABI or Stroke may also have different levels of learned non-use or compensation techniques as they would be re-learning motor patterns that were previously unimpaired. Protocol for a longer-term immersive VR-based rehabilitation program for older adult stroke survivors was proposed by Huang [155] and future comparison could be made if the experimental setup is sufficiently similar.

The combination of feedback modalities such as visual, haptic, and audio feedback could be applied to augmentation of bilateral symmetry to observe feedback modality interactions and to optimize levels of their application [156]. The Oculus Touch controllers provide single-point haptic feedback that could be used to augment or amplify feedback based on symmetry error. By comparing the use of haptic or force feedback in addition to using visual EA, an optimal combination that provides intuitive responses to error could be used to increase immersion in the virtual environment.

Further testing into other bimanual feedback and movement templates could be explored. In this study, EA was only applied to symmetry error in the forward-reaching direction. Movement mapping techniques such as Lissajous feedback, in which bimanual movement is coupled in two perpendicular spatial axes to form a single cursor point, has been shown to be successful in
increasing learning speed in complex asymmetric tasks [157]. This mapping could be further augmented to encourage movement in the more affected side and provides alternative tasks for participants to practice in VR. Mirrored movements would also be more easily facilitated in immersive VR, where a goal position could be displayed directly on top of the current position of the more affected hand.

Integration of other brain-based biometric data such as EEG or fNIRS into the headset could be used to more directly measure cognitive engagement during the rehabilitative exercise. It was observed qualitatively from experimenter comments that during training sets without EA, participants who reached with better symmetry engaged with more of the elements in the virtual environment that were not directly related to the task goal. Measuring brain activity could provide an indication for the number of elements or types of feedback that provide optimal engagement without cognitive overload or distraction. If recorded in real time, these measurements may also to provide another modality of augmented feedback such that brain signal could determine resistive feedback given.

Further exploration of the Oculus Touch controllers should be conducted to determine what other capabilities could be harnessed from the controller design. The quantifiable grasp size and capacitive touch sensors could be used in a fine motor control exercise task. However, some adaptation to commercial motion tracking controllers may be required. In this study, a simple strap was used when the CHP participant couldn’t properly grasp the controller. An adapted attachment or silicone non-slip cover made need to be designed to allow more ease of use. Designs for more modular game controllers such as the Xbox Adaptive Controller (Microsoft Corporation, Redmond, USA) could also be used for future iterations of studies involving gaming technology for upper-limb rehabilitation.

Finally, a larger variety of tasks and game types will need to be developed to conduct a long-term study or for use in a continuing rehabilitative program to prevent participant withdrawal from boredom or fatigue. With the use of commercial gaming technology for rehabilitative goals, one may consider the use of commercial games for rehabilitation as well. The development of a library of useable games on each motion-tracked gaming platform including VR systems may be helpful to clinics who may have the technology available but no programs to run.
References


Appendices

Appendix A - Oculus Touch Positional Tracking Accuracy

The following results are presented from the abstract of an investigation pending publication as a journal article in the Journal of Medical Internet Research (JMIR) Biomedical Engineering. Preprint available online at: http://preprints.jmir.org/preprint/12291

Background: As commercial position tracking technology becomes more readily available, it is necessary to evaluate the accuracy of these systems prior to using them for biomechanical and/or motor rehabilitation applications.

Objective: A study was performed to evaluate the relative position accuracy of the Oculus Touch controllers in a 2.4 x 2.4 m play-space.

Methods: Static data samples (n=180) were acquired from the Oculus Touch controllers at step sizes ranging from 5-500 mm along 16 different points on the play-space floor with graph paper in the X (width), Y (height), and Z (depth) directions. The data was compared to reference values using measurements from digital calipers, accurate to 0.01mm; physical blocks, for which heights were confirmed with digital calipers; and for larger step sizes (300 and 500 mm), a ruler with hatch marks to millimeter units.

Results: It was found that the maximum position accuracy error of the system was 3.5 ± 2.5 mm at the largest step size of 500 mm along the z-axis. When normalized to step size, the largest error found was 12.7 ± 9.9% at the smallest step size in the y-axis at 6.23 mm. When the step size was <10 mm in any direction, the relative position accuracy increased considerably to above 2% (~2 mm at maximum). An average noise value of 0.036 mm was determined. A comparison of these values to cited visual, goniometric, and proprioceptive resolutions concludes that this system is viable for tracking upper-limb movements for biomechanical and rehabilitation applications. The accuracy of the system was also compared to accuracy values from previous studies using other commercially available devices and a multi-camera marker-based professional motion tracking system.

Conclusions: The study found that the linear position accuracy of the Oculus Touch controllers was within an agreeable range for measuring human kinematics in rehabilitative upper-limb exercise protocols. Further testing is required to ascertain acceptable repeatability in multiple sessions and rotational accuracy.
Interested in **Virtual Reality**?
Have weakness on one side of your body?
**Consider joining our study!**

**About:** The FEATHERS project uses video games as therapy for people with hemiplegia. We are currently looking at how VR can change visual feedback to better help people reach therapy goals.

**Who:** Teens and young adults (Ages 13-21)

**What:** Play a two-handed target-reaching game for between 90-120 minutes while wearing the Oculus Rift headset.

**FEATHERS**

**Sign up:**

[Email]
[Personal Information Redacted]

[UBC Logo]

[Personal Information Redacted]
Interested in **Virtual Reality**?

Want to help people with stroke or cerebral palsy?

**Join our study!**

About: The FEATHERS project uses video games as therapy for people with hemiplegia. We are currently looking at how healthy individuals react to new therapy techniques that involve VR.

Who: Healthy teens and young adults (Ages 13-21)

What: Play a two-handed target-reaching game for between 60-90 minutes while wearing the Oculus Rift headset.

Sign up:

[Personal Information Redacted]
Informed Consent Form: Teens or Young Adults with Hemiplegia

FEATHERS 2.0:
Functional Engagement in Assisted Therapy through Exercise Robotics
(Exploring Error Augmentation for Symmetric Bimanual Tasks)

Principal Investigator
Name: Hendrik F. Machiel (Mike) Van der Loos
Position title: Associate Professor
Organization: UBC Department of Mechanical Engineering

Co-Applicants
Name: Elizabeth Croft
Position title: Professor
Organization: UBC Department of Mechanical Engineering

Name: Lara Boyd
Position title: Associate Professor
Organization: UBC, Faculty of Medicine, Department of Physical Therapy

Name: Naznin Virji-Babul
Position title: Assistant Professor
Organization: UBC, Faculty of Medicine, Department of Physical Therapy

Name: Nicola Hodges
Position title: Assistant Professor
Organization: UBC Faculty of Education, School of Human Kinetics
Co-Applicants who are Community Partner Representatives
Name: Heather Branscombe
Position title: Director
Organization: Abilities Neurological Rehabilitation, Inc.

Name: Judit Spence
Position title: Director of Physical Therapy
Organization: BC Centre for Ability Association

Name: Alec Black
Position title: Director of Shriners Gait Lab
Organization: Sunny Hill Health Centre for Children

Contact Person:
Please contact Hendrik F. Machiel (Mike) Van der Loos

in the event of any unusual occurrences or difficulties related to this research.

Funding Agency
This project is currently funded by Kids Brain Health Network (KBHN) – Networks of Centres of Excellence (NCE) as a project for Tottech: Tangible, organizing and therapeutic technologies to engage children.
Introduction

We invite you to take part in a research study being conducted by Mike Van der Loos, who is a professor at the University of British Columbia, and his colleagues. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. By participating in the study, we might learn things about our technology that can be used to help you and others like you. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

Purpose of the Study

The overall goal of the FEATHERS project is to improve user engagement in physical therapy by using social media and online games to do exercises. We propose to combine low-cost robotic devices, a therapeutic exercise program, social media such as Facebook, and on-line performance sharing between therapy clients and their therapists. We believe that these approaches will help in creating motivating exercise programs for adults with stroke and teenagers with hemiparetic cerebral palsy, which could significantly improve their function and ultimately lead to a higher quality of life.

The purpose of this study is to develop an engaging arm exercise environment to promote the increase in function of the weak arm of teens and adults with hemiplegia, beyond current therapy approaches. By building the exercise sessions into immersive gaming environments, users will be more motivated to continue with their therapy day after day, rather than resisting doing exercises that may be boring.

Researchers in Mechanical Engineering, Physical Therapy, and Kinesiology at the University of British Columbia collaborate with three Vancouver-area rehabilitation services organizations in conducting this usability study. This study focuses on testing the use of a new motion tracking technology (Oculus Rift VR System and Oculus Touch controllers) for upper limb rehabilitation. This study aims to gain more insight into the ease of use and functionality of the developed software and hardware and evaluation human susceptibility to changes in visual symmetry.

Study Design

If you choose to participate, this study will involve interacting with an immersive VR environment using a motion tracking system by playing a simple game. A short motor ability assessment may be done, and then we will ask you to perform a set of activities using the Oculus Rift head-mounted display and a set of Oculus Touch motion controllers. With the system, you will be able to interact with virtual objects using the controller buttons and motion tracking and will be asked to use two-handed reaching motions. By performing these tasks, you will be asked to play a simple food preparation game that scores reaching motion quality based on the symmetry between your hands.
Motion tracking video data from the systems will be recorded. We will collect basic demographic data (age, gender, diagnosis) in the beginning of the study session as well as a clinically validated motor ability assessment score. Audio-visual recording of a pre-study assessment may be taken to classify motor ability and audio-visual data or photography of the study set up in use may be taken during the session for publication purposes. You will be notified before any recordings occur. At the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the systems.

All data and analyses will keep the identity of all participants, both the participant and the caregiver/parent/guardian, entirely confidential. (Please refer to “Will my Taking Part in this Study be Kept Confidential?” section of this document, for more details about the collected data).

**Who can participate in this study?**

We are seeking interested clients of rehabilitation clinics, aged 13+, who present with hemiplegia as a result of a neurological impairment (CP, ABI, paediatric stroke, etc.) and are willing to test the motion tracking systems.

Also, they should be able to:

i. Verbally communicate by speaking and understanding basic English
ii. Use both eyes and visually interact using a stereoscopic device that allows a minimum interpupillary distance of 58mm
iii. Comfortably support a 470g head-mounted display
iv. Move both arms away from their body at least some distance such that their affected hand reaches the middle length of their thigh around waist level without any help from the strong hand
v. Stand or sit independently for 15 minutes at a time in a chair without arm supports for a total of up to 120 minutes

**Who Should not Participate in this Study?**

If the participant’s English language is not sufficient to provide informed consent or have had orthopedic surgery in the past 6 months, they will be excluded.

**How Many Participants Will Take Part in this Study?**

We are aiming to recruit a total of 20 teens or young adults with CP or other acquired brain injuries to participate in this study.
Who is conducting the research?

The study is being conducted by Dr. Van der Loos and colleagues listed on the title page of this form. Dr. Van der Loos or one of his colleagues, and a research assistant, may be present in the room in addition to your or another rehabilitation professional.

What will this Study Cost Me?

This study will be no cost to you.

What will you be asked to do?

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one session, conducted by Dr. Van der Loos or one of his colleagues, and assisted by a research assistant and a physical therapist. It will be a maximum of 120 minutes (2 hours) in duration. We may make one phone call to you outside of this session if you feel it this would be the easiest way to participate in the motor ability assessment. This call will not be recorded unless you give us verbal permission during the call. The study may be videotaped with audio, a note taker will document important events as they occur, and the motion tracking data will be recorded. This is a requirement of the study. For more details about the confidentiality and use of the collected data, please refer to the Confidentiality and Anonymity section of this consent form.

What are the risks by participating in this study?

You could become mentally or physically tired during the study. Cybersickness could occur after using the technology for more than 30 minutes. We will provide you more information about this prior to the study. You will take short breaks every 30 minutes or as soon as you ask to have one if you feel tired. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos, the therapist, or one of the other researchers will also be available to answer your questions during and after the session.

What are the benefits to your participation in this study?

There are no direct benefits to your participation. However, you may benefit from the knowledge that a new arm movement therapy is being developed that could potentially be used by persons with hemiplegia and you may feel satisfied to know that you have contributed to the development of evidence-based practice in rehabilitation.
What Happens if Something Goes Wrong?

Signing this consent form in no way limits your legal rights against the sponsor, investigators, or anyone else, and you do not release the study doctors or participating institutions from their legal and professional responsibilities.

Do you have to participate?

Your participation is completely voluntary. There are no penalties if you do not want to participate. There is no financial reward for participating. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. If you do not wish to participate, you do not have to provide any reason for the decision nor will you lose the benefit of any medical care to which you are entitled or presently receiving.

You have the right to request the withdrawal of your information collected during the study. This request will be respected to the extent possible. Please note however that there may be exceptions where the data will not be able to be withdrawn for example where the data is no longer identifiable (meaning it cannot be linked in any way back to your identity) or where the data has been merged with other data. If you would like to request the withdrawal of your data, please let your study doctor know.

Similarly, the researchers have the right to terminate this research project at any time. The study investigators may decide to discontinue the study or withdraw the participant from the study at any time, if they feel that it is in the best interest of the person under your care. Data collected up to the point of their withdrawal from the study must be kept for data analysis purposes under strict provisions of confidentiality.

After the Study is Finished

With your permission, you may be contacted in the future to ask to clarify any information given to the study team during the study or, separately, regarding your participation in other studies or phases of this project. At that time, you can refuse to participate, and your name and contact will be removed from future correspondence. If you would be interested in receiving more information about these future studies, please check the appropriate box at the end of this form. If you are interested in the results of the study, you can contact the researchers and they will provide you with information about the results from this study.

Confidentiality and Anonymity

According to the UBC Policy on Scholarly Integrity, the notes, motion tracking data, assessment scores, and the videotaped and/or audio recordings from the sessions will be used for the purposes of analysis and then destroyed after 5 years of the end of this study. All collected data will be kept in a secure, locked room and/or secure UBC-based server at UBC for five years after the end of this study. We will blur identifying features in video and
photographs presented in publications and only transcriptions of audio may be presented. Access to the photographs, audio-visual data will be restricted to the investigators.

We will use the collected data only in relation to this particular study. Also, manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report. Your de-identified research data, which means your name, birthdate, and other identifiers have been removed, may/will be published or deposited into a publically accessible location at the time of publication. This enhances the transparency of the research but also allows others to access the data. This should not increase risks to you, but it does mean that other researchers may analyze the data for different reasons other than those described in this consent form. Once data is made publically available, you will not be able to withdraw your data.

Your confidentiality will be respected. However, research records and health or other source records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives of UBC Clinical Research Ethics Board for the purpose of monitoring the research. No information or records that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law.

You will be assigned a unique study number as a subject in this study. This number will not include any personal information that could identify you (e.g., it will not include your Personal Health Number, SIN, or your initials, etc.). Only this number will be used on any research-related information collected about you during this study, so that your identity as a subject in this study will be kept confidential. Information that contains your identity will remain only with the Principal Investigator and/or designate. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to ensure that your privacy is respected and also give you the right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information. Further details about these laws are available on request through the above contacts listed.

While participants will be asked to respect the confidentiality of others, we cannot guarantee that this will happen. In cases in which recruitment is collected from community locations or social media groups, community members who have participated in the experiment may converse amongst themselves.
What if you still have some questions?

If you have any questions or desire further information about this study before or during participation, please feel free to contact:

Leia Shum

[Personal Information Redacted]

You may also contact Dr. Van der Loos at the phone or e-mail addresses listed on the title page of this document if you have questions about this study.

Problems or Concerns

If you have any concerns about your rights as a research subject or your experience while participating in this study, contact the Research Participant Complaint Line in the University of British Columbia Office of Research Services at email:

[Contact Information Redacted]

Please reference the study number H17-01126 when calling so the Complaint Line staff can better assist you.
FEATHERS 2.0:
Functional Engagement in Assisted Therapy through Exercise Robotics
(Exploring Error Augmentation for Symmetric Bimanual Tasks)

Informed Consent Form: Capable Teens and Young Adults with Hemiplegia

I have read the document entitled: “Informed Consent Form: Capable Teens and Young Adults with Hemiplegia” and understand its content.

I understand that my participation in this study is strictly voluntary and that I may withdraw at any time, for any reason, without penalty, and that this will not change the quality of care that I receive. I understand that there is no monetary reward for participating in this study. I have been given the opportunity to discuss the study and my questions have been answered to my satisfaction. I understand that I will not be identified by name in any written or verbal report that results from this study. I also understand that I will receive a copy of the study’s Cyber-sickness Information Sheet in addition to this Informed Consent Form. I understand that I am not waiving any of my legal rights as a result of signing this consent form.

In agreeing to participate in this study, I understand that I am consenting to participate in a one-on-one session led by Dr. Van der Loos and a co-investigator and acknowledge that this includes that the discussions will be recorded.

________________________  ____________________  ____________________  
Participant Name     Signature     Date

In the case that I cannot physically provide a signature to consent to my participation in this study, the below witness signature of my parent/legal guardian will stand for record of my verbal consent:

[ ] required  [ ] not required

________________________  ____________________  ____________________  
Witness Name     Signature     Date
In addition, and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

Participant Name  Signature  Date

In the case in which the research team needs to clarify any information I had given them during the session, I agree to allow my contact information to be used to contact me to ask to verify or correct my given data.

Participant Name  Signature  Date

[ ] Yes, I can be contacted for future studies
   Phone:  Email:

[ ] No, I do not want to be contacted for future studies

Printed Name,  Signature,  Date
Principal Investigator  Principal Investigator

My signature above signifies that the study has been reviewed with the study participant by me and/or by my delegated staff. My signature may have been added at a later date, as I may not have been present at the time the participant’s signature was obtained.
FEATHERS 2.0:
Functional Engagement in Assisted Therapy through Exercise Robotics
(Exploring Error Augmentation for Symmetric Bimanual Tasks)

Principal Investigator
Name: Hendrik F. Machiel (Mike) Van der Loos
Position title: Associate Professor
Organization: UBC Department of Mechanical Engineering

Co-Applicants
Name: Elizabeth Croft
Position title: Professor
Organization: UBC Department of Mechanical Engineering

Name: Lara Boyd
Position title: Associate Professor
Organization: UBC, Faculty of Medicine, Department of Physical Therapy

Name: Naznin Virji-Babul
Position title: Assistant Professor
Organization: UBC, Faculty of Medicine, Department of Physical Therapy

Name: Nicola Hodges
Position title: Assistant Professor
Organization: UBC Faculty of Education, School of Human Kinetics
Co-Applicants who are Community Partner Representatives
Name: Heather Branscombe  
Position title: Director  
Organization: Abilities Neurological Rehabilitation, Inc.  
[Personal Information Redacted]

Name: Judit Spence  
Position title: Director of Physical Therapy  
Organization: BC Centre for Ability Association  
[Personal Information Redacted]

Name: Alec Black  
Position title: Director of Shriners Gait Lab  
Organization: Sunny Hill Health Centre for Children  
[Personal Information Redacted]

Contact Person:  
Please contact Hendrik F. Machiel (Mike) Van der Loos  
[Personal Information Redacted]

Funding Agency  
This project is currently funded by Kids Brain Health Network (KBHN) – Networks of Centres of Excellence (NCE) as a project for Tottech: Tangible, organizing and therapeutic technologies to engage children.
Introduction

We invite you to take part in a research study being conducted by Mike Van der Loos, who is a professor at the University of British Columbia, and his colleagues. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study will likely not benefit you directly, but we might learn things that will benefit others. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

Purpose of the Study

The overall goal of the FEATHERS project is to improve user engagement in physical therapy by using social media and online games to do exercises. We propose to combine low-cost robotic devices, a therapeutic exercise program, social media such as Facebook, and on-line performance sharing between therapy clients and their therapists. We believe that these approaches will help in creating motivating exercise programs for adults with stroke and teenagers with hemiparetic cerebral palsy, which could significantly improve their function and ultimately lead to a higher quality of life.

Researchers in Mechanical Engineering, Physical Therapy, and Kinesiology at the University of British Columbia collaborate with three Vancouver-area rehabilitation services organizations in conducting this usability study. This study focuses on testing virtual reality (VR) and motion tracking technology (Oculus Rift VR System and Oculus Touch controllers) for upper limb rehabilitation. This study aims to gain more insight into the ease of use and functionality of the developed software and hardware and evaluation human susceptibility to changes in visual symmetry.

Study Design

In this phase of the project, we will ask you to perform a set of activities that involve interacting with a virtual reality environment using the Oculus Rift head-mounted display and a set of Oculus Touch motion controllers. During this interaction you will be able to interact with virtual objects using the controller buttons and motion tracking that require two-handed reaching motions to complete given tasks. By performing these tasks, you will be asked to play a simple food preparation game that scores reaching motion quality based on the symmetry between your hands.

Motion tracking video data from the systems will be recorded. We will collect basic demographic data (age, gender, handedness) in the beginning of the study session. Audio-visual recording or photography of the study set up in use may be taken during the session for publication purposes and will be notified before the recording occurs. At the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the systems. Using your feedback from this study, we will redesign the interfaces to make them more appropriate to our final targeted populations.
All data and analyses will keep the identity of all participants, both the participant and the caregiver/parent/guardian, entirely confidential. (Please refer to “Will my Taking Part in this Study be Kept Confidential?” section of this document, for more details about the collected data).

Who can participate in this study?

We are seeking interested healthy teens and young adults above the age of 13 years that have no neurological or physical impairments that affect upper limb movement. They should also be able to:

vi. Verbally communicate by speaking and understanding basic English
vii. Use both eyes and visually interact using a stereoscopic device that allows a minimum interpupillary distance of 58mm
viii. Comfortably support a 470g head-mounted display

Who is conducting the research?

The study is being conducted by Dr. Van der Loos and colleagues listed on the title page of this form.

What will you be asked to do?

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one session, conducted by Dr. Van der Loos or one of his colleagues, and assisted by a research assistant. It will be about 60-90 minutes in duration. The study discussion and motion tracking data will be recorded. This is a requirement of the setup design. For more details about the confidentiality and use of the collected data, please refer to the Confidentiality and Anonymity section of this consent form.

Will there be any negative consequences for you by participating in this study?

Physical or mental fatigue or cybersickness could occur after using the immersive VR technology. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos or one of the other researchers will also be available to answer your questions during and after the session.

What are the benefits to your participation in this study?

There are no financial benefits to your participation. However, you may benefit from the knowledge that a new upper extremity therapy is being developed that could potentially be used, and you may feel satisfied to know that you have contributed to the development of evidence-based practice in rehabilitation for acquired brain injury/stroke and/or cerebral palsy.
What Happens if Something Goes Wrong?

Signing this consent form in no way limits your legal rights against the sponsor, investigators, or anyone else, and you do not release the study doctors or participating institutions from their legal and professional responsibilities.

Do you have to participate?

Your participation is completely on a volunteer basis. There are no penalties if you do not wish to participate. There is no financial reward for participating. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. Similarly, the researchers have the right to terminate this research project at any time. Data collected up to the point of withdrawal from the study will be kept for data analysis purposes under strict provisions of confidentiality.

You have the right to request the withdrawal of your information collected during the study. This request will be respected to the extent possible. Please note however that there may be exceptions where the data will not be able to be withdrawn for example where the data is no longer identifiable (meaning it cannot be linked in any way back to your identity) or where the data has been merged with other data. If you would like to request the withdrawal of your data, please consult the contact information provided in this informed consent form.

After the Study is Finished

With your permission, you may be contacted in the future to ask to clarify any information given to the study team during the study or, separately, regarding your participation in other studies or phases of this project. At that time, you can refuse to participate, and your name and contact will be removed from future correspondence.

If you would be interested in receiving more information about these future studies, please check the appropriate box at the end of this form.

If you are interested in the results of the study, you can contact the researchers and they will provide you with information about the results from this study.

Confidentiality and Anonymity

According to the UBC Policy on Scholarly Integrity, the notes, motion tracking data, and the videotaped recordings with audio from the sessions will be used for the purposes of analysis and scientific publication and then destroyed after 5 years of the end of this study. All collected data will be kept in a secure, locked room and/or secure UBC-based server at UBC for five years after the end of this study. We will blur identifying features in video and photographs presented in publications and only transcriptions of audio may be presented. Access to the photographs, audio-visual data, and motion tracking data will be restricted to the investigators.
We will use the collected data only in relation to this particular study. Information from these sessions may be used to design future robot-based social-media and game interface. Also, manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report. Your de-identified research data, which means your name, birthdate, and other identifiers have been removed, may/will be published or deposited into a publicly accessible location at the time of publication. This enhances the transparency of the research but also allows others to access the data. This should not increase risks to you, but it does mean that other researchers may analyze the data for different reasons other than those described in this consent form. Once data is made publically available, you will not be able to withdraw your data.

Your confidentiality will be respected. However, research records and health or other source records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives of the FEATHERS team or by representatives of UBC Clinical Research Ethics Board for the purpose of monitoring the research. No information or records that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law.

You will be assigned a unique study number as a subject in this study. This number will not include any personal information that could identify you (e.g., it will not include your name, SIN, or your initials, etc.). Only this number will be used on any research-related information collected about you during this study, so that your identity as a subject in this study will be kept confidential. Information that contains your identity will remain only with the Principal Investigator and/or designate. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to insure that your privacy is respected and also give you the right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information. Further details about these laws are available on request to your study correspondent.

While participants will be asked to respect the confidentiality of others, we cannot guarantee that this will happen. In cases in which recruitment is collected from community locations or social media groups, community members who have participated in the experiment may converse amongst themselves.
What if you still have some questions?

If you have any questions or desire further information about this study before or during participation, please feel free to contact:

Leia Shum @

[Personal Information Redacted]

You may also contact Dr. Van der Loos at the phone or e-mail addresses listed on the title page of this document if you have questions about this study.

Problems or Concerns

If you have any concerns about your rights as a research subject or your experience while participating in this study, contact the Research Participant Complaint Line in the University of British Columbia Office of Research Services at email:

[Contact Information Redacted]

Please reference the study number H17-01126 when calling so the Complaint Line staff can better assist you.
Informed Consent Form: Healthy Pilot Usability Testing

I have read the document entitled: “Informed Consent Form: Healthy Pilot Usability Testing” and understand its content. I understand that my participation in this study is strictly voluntary and that I may withdraw at any time, for any reason, without penalty. I understand that there is no monetary reward for participating in this study. I have been given the opportunity to discuss the study and my questions have been answered to my satisfaction. I understand that I will not be identified by name in any written or verbal report that results from this study. I also understand that I will receive a copy of the study’s Cyber-sickness Information Sheet in addition to this Consent Form. I understand that I am not waiving any of my legal rights as a result of signing this consent form.

In agreeing to participate in this study, I understand that I am consenting to participate in a VR system usability test led by Dr. Van der Loos and a co-investigator and acknowledge that this includes that sessions will be recorded.

__________________________  __________________________  __________________________
Participant Name                      Signature                      Date

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

__________________________  __________________________  __________________________
Participant Name                      Signature                      Date
In the case in which the research team needs to clarify any information I had given them during the session, I agree to allow my contact information to be used to contact me to ask to verify or correct my given data.

Participant Name  Signature  Date

[ ] Yes, I can be contacted for future studies
Phone:          Email:

[ ] No, I do not want to be contacted for future studies

Printed Name,  Signature,  Date
Principal Investigator  Principal Investigator

My signature above signifies that the study has been reviewed with the study participant by me and/or by my delegated staff. My signature may have been added at a later date, as I may not have been present at the time the participant’s signature was obtained.
Cyber-sickness Information Sheet

This information sheet was developed by Dr. Bernie Garrett in UBC Faculty of Nursing for use with immersive VR technology involving commercial head-mounted displays and adapted for this experiment.

What is cyber-sickness (also called visually induced motion sickness or simulation sickness)?

Cyber-sickness is a type of motion sickness that can be caused by the visual appearance of movement. It is usually associated with digitally rendered environments that simulate self-movement, such as the immersive multimedia environments used in this study. Symptoms of cybersickness are similar to motion sickness and often last minutes to hours, but will generally disappear after a full night’s sleep. Studies show symptoms are more severe if you use the device while standing without holding onto any support, so it is important that participants are sitting while they use the head mounted display (HMD) during this study.

What are the symptoms of cyber-sickness?

- Nausea
- Dizziness
- Eye strain
- Headache
- Pale skin (pallor)
- Sweating
- Dryness of Mouth
- Fullness/Awareness of Stomach
- Dizziness (vertigo)
- Ataxia (disequilibrium/a lack of coordination)
- Vomiting
- Confusion/Difficulty Focusing

What should I do if I feel the effects of cyber-sickness while using the head mounted display?

Immediately express this to the experimenter during the session and remove the head mounted display. Do not attempt to ignore the symptoms and continue as this could increase their severity. If you do experience symptoms, please record this in the questionnaire for that session and indicate the amount of time you were able to complete.

Some amount of cyber-sickness is not unusual on initial use of the HMD, and most people will build up tolerance so that the symptoms disappear. If you experience symptoms, you should not attempt to continue the session without a break and the next session should be for 5 minutes only. After a break of at least 15 minutes you can return and extend your use for 10 minutes and then gradually increase your use time as tolerated. If you experience significant cybersickness (i.e. any of the above symptoms that last more than 15 minutes after discontinuing use of the HMD) more than twice during the testing period please alert the investigators and the session to stop. If you experience any severe symptoms please remove the head mounted display, alert the experimenter and contact your doctor.

If you have any questions about simulator sickness with respect to this study, please contact:

Professor Mike Van der Loos
University of British Columbia

Cyber-sickness Information Sheet – FEATHERS 2.0 v1 (March 26th, 2018) | 1/1
FEATHERS 2.0: Functional Engagement in Assisted Therapy through Exercise Robotics

Exploring Error Augmentation for Symmetric Bimanual Tasks

LEIA SHUM – PROTOCOL DETAILS

Background
The FEATHERS project at the RREACH Lab at UBC focuses on developing and evaluating novel physical exercise technologies for kids with motor disabilities. The study team would like to study how immersive VR technology can be used to benefit upper limb rehabilitation for persons with hemiplegia. The purpose of the experiment is to see how the use of error augmentation (i.e. adding visual or game element feedback to accentuate deviation from the desired exercise motion) might encourage persons with hemiplegia to engage their affected side more effectively by comparing the symmetry between the stronger and weaker limbs. It is also hypothesized that the immersive environment of VR and the ability to provide 1:1 direct visual feedback will increase active engagement to rehabilitative exercises in these populations. The study will address the question of whether error augmentation aids in the rehabilitation of the affected upper limb movement quality in hemiparesis when practicing bilateral reaching tasks.

Inclusion Criteria
Participants must fit the following criteria to be able to be selected for the study:

i. 13 years old and older
ii. The ability to follow instructions and answer questions in English
iii. Ability to visually interact using a stereoscopic device that allows a minimum interpupillary distance of 58mm
iv. Ability to comfortably support regular head motion while wearing a 470g head-mounted display
v. The ability to stand or sit independently for 15 minutes at a time in a chair without arm supports
vi. No known high susceptibility to cyber-sickness effects as reported by the participant

Additional criteria for clinical participants include:

i. Hemiplegia as a result of a neurological impairment (CP, ABI, paediatric stroke, etc.)
ii. Ability to move both arms away from their body at least some distance such that their affected hand reaches the middle length of their thigh around waist level without any help from the strong hand, as reported by participant, consenting guardian, or adjoining therapist (shoulder/elbow flexion and extension)
iii. Have not had orthopedic surgery in the past 6 months

Experimental Setup
Adolescents and young adults with hemiplegia (i.e. due to ABI, CP, etc.) and their adjoining therapists will be recruited for from the community. The study is a single session of about 60-90 minutes of repetitive reaching tasks in an immersive VR environment using an Oculus Rift HMD and the Oculus Touch motion tracking controllers. We will conduct testing at the participant chosen location with an easily transportable system including a standard 2-3 sensor hardware setup and software developed by the research team. Sessions conducted outside the research lab rooms will require a minimum of a 2m x 1.5m space for calibration. The participants will test all augmentation factors in a randomized order.
Appendix C - Consort Flow Diagram for Recruitment of Typically Developing Participants

Locations Posted Information (n = 23)

Participants Assessed for Eligibility (n = 28)

Excluded (n = 4)
a) Inclusion criteria not met
   i) Age Restriction (n=4)

Participants Accepted (n = 24)

Excluded (n = 11)
a) Did not wish to participate (n=1)
b) Did not respond to scheduling (n=9)
c) Other reasons (n=1)

Allocated to intervention (n = 13)

Set A = With EA
Set B = No EA

Received Intervention (n = 7)
Discontinued intervention (n = 0)

Analysis (n = 6)
1 Excluded from analysis from incorrectly inferred joint data

Set A = No EA
Set B = With EA

Received Intervention (n = 6)
Discontinued intervention (n = 0)

Analysis (n = 6)
Excluded from analysis (n = 0)
Appendix D - Verbal Instructions and Study Session Checklist

Pre-experiment Checklist and System Familiarization Instructions

FEATHERS 2.0 – PROJECT PROTOCOL APPENDIX A

System Setup

1. Confirm Kinect is not being run by any external (webcam) processes
2. Restart the computer
3. Run through Oculus calibration & Guardian System setup (required only if sensors moved)
4. Run Unity Program
   a. Headset turns on
   b. Controllers have sufficient battery life
   c. Avatar hands open and close properly
   d. Objects confirm grabbable
   e. Floor height is correct
   f. Make sure all augmentation is off
   g. DO NOT STOP PLAYING program, or re-run without wearing headset (grip issue)

Load up IN HEADSET > Home > Oculus Menu > Show IPD Crosshair visual

Show Participant Physical Hardware

1. Explain camera sensors location and Kinect
2. Show them how to hold the controllers
   a. Show where to put your thumbs – not on the buttons
   b. Show where your other fingers go – trigger and gripper buttons
   c. Have them confirm if they can grip trigger and gripper
3. Show them how to adjust the headset shape
   a. Show three Velcro straps and elastic pull bands
   b. Show moveable earphones
   c. Show them the IPD notch

Confirm that they understand – ask for questions here

4. Get them to try on the headset
   a. Put on and adjust the headset tabs
   b. Set to correct IPD and headset height
      (Press any CONTROLLER key to get started)
5. (Re)start the environment and confirm the two objects they see are the hotdog/bun
   a. Give them the controllers
   b. Ask them to try to close their hands
   c. Ask them to look and move their hands
Take the controllers and take the headset off – ask for questions here

Ask for cybersickness symptoms.

**Explaining the task:**

1. Give them a demo – wear the headset yourself and ask them to look at the screen
   a. Explain reach symmetry is primary goal, making smooth forward movements bimanually
   b. Show them which part of the reach is recorded
   c. Explain the colour gradient and scoring system
      i. Green is moldy and bad, want to keep the hotdog as pink as possible
      ii. Explain hot dog quality and tip jar

**Pre-experiment questions:**

1. Ask about handedness and set dominant to unaffected [K/L]
2. Explain how many reps you’re going to do

Ask for questions here

**Setup Parameters**

1. Ask them to wear the headset again
2. Check and record max and min reach and set bun to a comfortable reach distance [T/Y]
3. Check if chair height is difficult to reach above knees
4. Make sure they’re sitting right up to the table
5. Get them to test feedback showing green hotdog on both right and left ‘forward’
   a. Move only your left hand forward – green? How about right?
6. Ask them to complete one hotdog and check they understand the task – ask about any difficulties:
   a. Reaching?
   b. Hard to make dog touch properly?
   c. Hard to pick up hotdog?

Ask if they feel dizzy or uncapable in any manner

Ask for any final questions here

Let them know we’re going to start on the first set

**PILOT STUDIES ONLY: TURN ASYMETRY ON** – 8 (3 familiarity, 5 baseline)

RUN THE EXPERIMENT

(write down and follow session blocks depending on which group they’re allocated to)
Using Error Augmentation in Immersive Virtual Reality (VR) for Bimanual Upper Limb Rehabilitation

Lea Shum – REACH Lab – July 3, 2018

Diagram showing the setup of error augmentation in VR for bimanual upper limb rehabilitation.
Appendix E - Pilot Data Sample Size Calculation

Pilot Data (3 Healthy Adults – presented at GF Strong Research Day May 2018)

<table>
<thead>
<tr>
<th>Participant ID #</th>
<th>Starting Order</th>
<th>Baseline (cm)</th>
<th>Evaluation (cm)</th>
<th>Percent Improvement (%)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No EA</td>
<td>With EA</td>
<td>No EA Set</td>
</tr>
<tr>
<td>PP-1</td>
<td>No EA First</td>
<td>14.93</td>
<td>7.68</td>
<td>2.49</td>
<td>62.0</td>
</tr>
<tr>
<td>PP-2</td>
<td>EA First</td>
<td>6.39</td>
<td>2.28</td>
<td>1.64</td>
<td>64.3</td>
</tr>
<tr>
<td>PP-3</td>
<td>No EA First</td>
<td>4.33</td>
<td>2.83</td>
<td>1.04</td>
<td>34.6</td>
</tr>
<tr>
<td>Average (n = 3)</td>
<td></td>
<td>9.10</td>
<td>3.62</td>
<td>2.55</td>
<td>-53.6</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td>6.26</td>
<td>2.47</td>
<td>1.66</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Baseline averages in pilot participants were calculated using the first 5 trials in the training set with 70% asymmetry already applied. This resulted in higher percentage improvement overall.
## Appendix F - Post-Session Questionnaire

[Image of System Usability Scale]


### System Usability Scale

<table>
<thead>
<tr>
<th>Statement</th>
<th>Strongly disagree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I think that I would like to use this system frequently</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>2. I found the system unnecessarily complex</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>3. I thought the system was easy to use</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>4. I think that I would need the support of a technical person to use this system</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>5. I found the various functions in this system were well integrated</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>6. I thought there was too much inconsistency in this system</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>7. I would imagine that most people would learn to use this system very quickly</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>8. I found the system very cumbersome to use</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>9. I felt very confident using the system</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>10. I needed to learn a lot of things before I could get going with this system</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
</tbody>
</table>
FEATHERS (Functional Engagement in Assisted Therapy through Exercise Robotics)  
(Symmetry Error Augmentation) Post-Test Questionnaire

Date: ______________________ Sex (please circle): Male Female
Age: ______________________ Diagnosis: ______________________
Weaker side of my body (circle one): Left Right
Therapy services I receive: __________________________________________
How often do you receive therapy? ______________________________________

We would like your feedback about your experience trying the FEATHERS systems.

For each of the following statements, please circle the answer that best represents how you feel:

A. General Information

1. How many hours per week do you spend using computers?

<table>
<thead>
<tr>
<th>None</th>
<th>1-5 hours</th>
<th>6-10 hours</th>
<th>11-15 hours</th>
<th>More than 16 hours</th>
</tr>
</thead>
</table>

2. Which systems do you use to play games at least once per week?

<table>
<thead>
<tr>
<th>None</th>
<th>Xbox</th>
<th>PlayStation</th>
<th>Nintendo Wii</th>
<th>Computer</th>
</tr>
</thead>
</table>

Other systems?

____________________________________________________________________________________________

____________________________________________________________________________________________

____________________________________________________________________________________________
B. **Immersive Fidelity**

1. I felt comfortable wearing the headset and moving around during the session.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

2. When moving my head, it felt like the environment was moving in a normal/natural way:

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

3. I did not notice any weird artifacts (blurring, odd lighting, edge effects, pixelated objects, other distracting visual effects) during the session.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

4. The environment felt 3D and had realistic depth.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

5. My interactions within the environment were as if I was in the real world.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

6. It was easy to succeed in the environment.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>
7. Overall, how immersed/engaged did you feel in the VR environment?

<table>
<thead>
<tr>
<th>0 – not at all</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 – very much</th>
</tr>
</thead>
</table>

8. Overall, how present did you feel in the VR environment?

<table>
<thead>
<tr>
<th>0 – not at all</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 – very much</th>
</tr>
</thead>
</table>

C. Cyber Sickness

1. I experienced some motion/cyber sickness during the session.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

2. I experienced some motion/cyber sickness after removing the headset.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

D. Future Uses

1. I would use this technology at home for rehabilitation:

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
</table>

Why? Or why not?

____________________________________________________________________
____________________________________________________________________
____________________________________________________________________

132
### Appendix G - Exploratory Paired T-test Results of Secondary Outcomes

#### Paired Samples Test – Comparing Baseline Trial Averages (With and Without EA)

<table>
<thead>
<tr>
<th>Pair</th>
<th>Paired Differences</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Deviation</td>
<td>Std. Error Mean</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Pair 1</td>
<td>MaxVBN - MaxVBE</td>
<td>-.5889</td>
<td>.11640</td>
<td>.03880</td>
<td>-.14836</td>
</tr>
<tr>
<td>Pair 2</td>
<td>PkTimeBN - PkTimeBE</td>
<td>-.21036</td>
<td>.74287</td>
<td>.24762</td>
<td>-.78138</td>
</tr>
<tr>
<td>Pair 3</td>
<td>PksBN - PksBE</td>
<td>.06667</td>
<td>.44721</td>
<td>.14907</td>
<td>-.27709</td>
</tr>
<tr>
<td>Pair 4</td>
<td>LROMBN - LROMBE</td>
<td>-.01464</td>
<td>.05565</td>
<td>.01855</td>
<td>-.05741</td>
</tr>
<tr>
<td>Pair 5</td>
<td>RROMBN - RROMBE</td>
<td>-.01525</td>
<td>.05255</td>
<td>.01752</td>
<td>-.05565</td>
</tr>
</tbody>
</table>

#### Paired Samples Test - Comparing Evaluation Trial Averages (With and Without EA)

<table>
<thead>
<tr>
<th>Pair</th>
<th>Paired Differences</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Deviation</td>
<td>Std. Error Mean</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Pair 1</td>
<td>MaxVEN - MaxVEE</td>
<td>.00620</td>
<td>.07398</td>
<td>.02466</td>
<td>-.05066</td>
</tr>
<tr>
<td>Pair 2</td>
<td>PkTimeEN - PkTimeEE</td>
<td>-.07556</td>
<td>.16159</td>
<td>.05386</td>
<td>-.19977</td>
</tr>
<tr>
<td>Pair 3</td>
<td>PksEN - PksEE</td>
<td>-.04444</td>
<td>.26034</td>
<td>.08678</td>
<td>-.24456</td>
</tr>
<tr>
<td>Pair 4</td>
<td>LROMEN - LROMEE</td>
<td>-.01388</td>
<td>.03911</td>
<td>.01304</td>
<td>-.04395</td>
</tr>
<tr>
<td>Pair 5</td>
<td>RROMEN - RROMEE</td>
<td>.00482</td>
<td>.03583</td>
<td>.01194</td>
<td>-.02272</td>
</tr>
</tbody>
</table>

MaxV – Maximum Velocity, PkTime – Time to Peak, Pks – Number of Peaks, LROM – ND/A Side ROM, RROM D/LA Side ROM
BN – Baseline trials in training set with no EA, BE – Baseline trials in training set with EA
EN – Evaluation trials in training set with no EA, BE – Evaluation trials in training set with EA
*All raw values are presented in metres.

### Paired Samples Test

<table>
<thead>
<tr>
<th>Pair</th>
<th>Paired Differences</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>MaxVBN - MaxVEN</td>
<td>-.07707</td>
<td>.09545</td>
<td>.03182</td>
<td>-.15044 to -.00371</td>
<td>-2.422</td>
<td>11</td>
<td>.042</td>
</tr>
<tr>
<td>Pair 2</td>
<td>PkTimeBN - PkTimeEN</td>
<td>.36668</td>
<td>.49239</td>
<td>.16413</td>
<td>-.01181 to .74516</td>
<td>2.234</td>
<td>11</td>
<td>.056</td>
</tr>
<tr>
<td>Pair 3</td>
<td>PksBN - PksEN</td>
<td>.02222</td>
<td>.62004</td>
<td>.20668</td>
<td>-.45438 to .49882</td>
<td>1.08</td>
<td>11</td>
<td>.917</td>
</tr>
<tr>
<td>Pair 4</td>
<td>LROMBN - LROMEN</td>
<td>-.08485</td>
<td>.05040</td>
<td>.01680</td>
<td>-.12359 to -.04611</td>
<td>-5.051</td>
<td>11</td>
<td>.001</td>
</tr>
<tr>
<td>Pair 5</td>
<td>RROMBN - RROMEN</td>
<td>.03195</td>
<td>.04652</td>
<td>.01551</td>
<td>-.00381 to .06771</td>
<td>2.061</td>
<td>11</td>
<td>.073</td>
</tr>
<tr>
<td>Pair 6</td>
<td>MaxVBE - MaxVEE</td>
<td>-.01198</td>
<td>.10090</td>
<td>.03363</td>
<td>-.08954 to .06558</td>
<td>-1.356</td>
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<td>.731</td>
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<tr>
<td>Pair 7</td>
<td>PkTimeBE - PkTimeEE</td>
<td>.50148</td>
<td>.49632</td>
<td>.16544</td>
<td>.11997 to .88298</td>
<td>3.031</td>
<td>11</td>
<td>.016</td>
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<tr>
<td>Pair 8</td>
<td>PksBE - PksEE</td>
<td>-.08889</td>
<td>.47022</td>
<td>.15674</td>
<td>-.45034 to .27256</td>
<td>-5.567</td>
<td>11</td>
<td>.586</td>
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<tr>
<td>Pair 9</td>
<td>LROMBE - LROMEEN</td>
<td>-.08410</td>
<td>.03941</td>
<td>.01314</td>
<td>-.11439 to -.05381</td>
<td>-6.402</td>
<td>11</td>
<td>.000</td>
</tr>
<tr>
<td>Pair 10</td>
<td>RROMBE - RROMEEN</td>
<td>.05203</td>
<td>.02562</td>
<td>.00854</td>
<td>.03234 to .07172</td>
<td>6.093</td>
<td>11</td>
<td>.000</td>
</tr>
</tbody>
</table>

### Paired Samples Test

<table>
<thead>
<tr>
<th>Pair</th>
<th>Paired Differences</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
<th>95% Confidence Interval of the Difference</th>
<th>t</th>
<th>df</th>
<th>Sig. (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>TrunkBN - TrunkEN</td>
<td>-.02711</td>
<td>.02176</td>
<td>.00656</td>
<td>-.04173 to -.01249</td>
<td>-4.133</td>
<td>11</td>
<td>.002</td>
</tr>
<tr>
<td>Pair 2</td>
<td>TrunkBE - TrunkEE</td>
<td>-.02416</td>
<td>.02722</td>
<td>.00821</td>
<td>-.04245 to -.00588</td>
<td>-2.944</td>
<td>11</td>
<td>.015</td>
</tr>
<tr>
<td>Pair 3</td>
<td>TrunkBN - TrunkBE</td>
<td>.00469</td>
<td>.03893</td>
<td>.01174</td>
<td>-.02146 to .03084</td>
<td>.400</td>
<td>11</td>
<td>.698</td>
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<tr>
<td>Pair 4</td>
<td>TrunkEN - TrunkEE</td>
<td>.00764</td>
<td>.03249</td>
<td>.00980</td>
<td>-.01419 to .02947</td>
<td>.779</td>
<td>11</td>
<td>.454</td>
</tr>
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</table>
Appendix H - Extended Survey Results and Qualitative Comments

H.1 Table of SUS Survey Results

<table>
<thead>
<tr>
<th>Question</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Score</th>
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</thead>
<tbody>
<tr>
<td>TDP-1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>80</td>
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<tr>
<td>TDP-2</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>TDP-3</td>
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<td>4</td>
<td>2</td>
<td>5</td>
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<td>50</td>
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<td>TDP-4</td>
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<td>5</td>
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<td>4</td>
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<td>1</td>
<td>5</td>
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<td>TDP-5</td>
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<td>5</td>
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<td>4</td>
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<td>1</td>
<td>4</td>
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<td>5</td>
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<td>70</td>
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<td>TDP-7</td>
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<td>85</td>
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<td>5</td>
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<td>1</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>2</td>
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</table>
H.2 Post-Session Survey Results

<table>
<thead>
<tr>
<th>Statement</th>
<th>Agree</th>
<th>Disagree</th>
<th>Neither Agree nor Disagree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I felt comfortable wearing the headset and moving around during the session.</td>
<td>75%</td>
<td>20%</td>
<td>40%</td>
<td>25%</td>
</tr>
<tr>
<td>When moving my head, it felt like the environment was moving in a normal/natural way.</td>
<td>75%</td>
<td>60%</td>
<td>40%</td>
<td>25%</td>
</tr>
<tr>
<td>I did not notice any weird artifacts (blurring, odd lighting, edge effects, pixelated objects, other distracting visual effects) during the session.</td>
<td>25%</td>
<td>42%</td>
<td>40%</td>
<td>33%</td>
</tr>
<tr>
<td>The environment felt 3D and had realistic depth.</td>
<td>33%</td>
<td>40%</td>
<td>40%</td>
<td>67%</td>
</tr>
<tr>
<td>My interactions within the environment were as if I was in the real world.</td>
<td>25%</td>
<td>17%</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>It was easy to succeed in the environment.</td>
<td>8%</td>
<td>58%</td>
<td>40%</td>
<td>25%</td>
</tr>
<tr>
<td>Overall, how immersed/engaged did you feel in the VR environment?</td>
<td>17%</td>
<td>33%</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>Overall, how present did you feel in the VR environment?</td>
<td>17%</td>
<td>50%</td>
<td>20%</td>
<td>33%</td>
</tr>
<tr>
<td>I experienced some motion/cyber sickness during the session.</td>
<td>92%</td>
<td>8%</td>
<td>80%</td>
<td>10%</td>
</tr>
<tr>
<td>I experienced some motion/cyber sickness after removing the headset.</td>
<td>100%</td>
<td>40%</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>I would use this technology at home for rehabilitation.</td>
<td>8%</td>
<td>67%</td>
<td>60%</td>
<td>25%</td>
</tr>
</tbody>
</table>
H.3 List of Qualitative Comments

Comments from TDP Participants:

“If I had to do boring exercises at home, the VR system would make it more fun.”

“It was very fun. Although the task is repetitive, the change in objects and the effects + reward system makes it fun to continue and play.”

“Good user interface, easy to maneuver/interact with; it was useful to practice regaining balance between hands.”

“Because I did feel a difference between the symmetrical and asymmetrical tests and I think I adjusted to it. “

“Can help trick my brain by providing a false/created image and environment.”

“Could modify the environment to make the process more exciting.”

“Not completely monotonous (switching between sushi and hot dog).”

“It is a fun thing to do without really doing anything.”

Comments from CHP Participants:

“I liked having money and selling good food, I liked eating and mostly throwing things off the table.”

“I didn't like glitching when the objects fell through the table.”

“The difference between set A/B was more pressure on my left hand - it was pulling back.”

“Would be nice to have a silicon gripper handle because plastic is slippery.”

“It doesn't give you the choice to ignore the right [ND/A] side.”

“I didn’t like dropping objects or having to stretch or move my hands together to finish.”

“I enjoyed the VR, it was fun.”

'Very fun and motivating.”