Error Augmentation in Immersive Virtual Reality for Bimanual Upper-Limb Rehabilitation in Individuals with and without Hemiplegic Cerebral Palsy

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***Abstract*—(WC:200/200)**

With more readily available commercial immersive virtual reality (VR) technologies, the potential of new feedback strategies as tools to facilitate motor rehabilitation should be investigated. Augmented feedback or error augmentation (EA) can easily be shown in a virtual environment. Here, visual EA provided via immersive VR was tested for its effectiveness to improve bimanual symmetry in a reaching task. A single-session crossover design was used to test two training cases, with or without EA. With EA, the distance between hands in the forward direction was augmented. Participants were recruited from typically developing (TD) populations (n = 12, ages 13-21) and performed in an adapted environment with an initial asymmetry between limbs. Also, five participants with hemiplegic cerebral palsy (CP) (ages 14-21, MACS I-III) completed the study. Among TD participants, a significantly larger change in symmetry in the adapted environment was shown after EA than training without EA ($F(1,10) = 9.64, p = 0.01$). Each participant in the CP group also improved more after EA training (8.8-103.7)%, such that they achieved lower symmetry error after training with EA. As participants in both groups adapted more symmetrically with EA, beneficial changes from this training method could be evaluated in future studies for longer-term functional changes.

***Index Terms*—Error Augmentation, Virtual Reality, Bilateral Upper-Limb Rehabilitation, Hemiplegic Cerebral Palsy**

I. Introduction

Bimanual task training in rehabilitation involves the use of the less and more affected upper limbs together to promote continued use of especially the more affected limb. Bimanual task training, in comparison to unimanual training, has been suggested to engage neuroplastic growth mechanisms by exciting more cortical networks and encouraging cross-hemispheric activity and cortical reorganization [1]–[3]. Transfer of motor learning in bimanual task training to other practiced and unpracticed functional tasks used for self-care and daily living has been shown in children with neurologic motor disabilities, such as CP [4] [5].

Bimanual task training is especially important for people with hemiplegia due to asymmetries in motor execution. Hemiplegia, defined as weakness on one side of the body causing lateral asymmetry in upper and lower limb mobility [6], is among the most common motor syndromes, presenting in about 25% of the CP population [7]. In addition to practicing daily bimanual activities, such as moving trays, folding laundry, and pushing chairs, which require bimanual symmetrical interactions, having a mirror comparison to follow during bimanual upper-limb reaching could improve position sense in the impaired arms of children with spastic hemiplegia [8] and provide better functional gain over non-bimanual practice [9]. As such, this type of dual-limb training is an important component for new rehabilitation techniques to consider.

Motor rehabilitation programs based on at-home, low-cost, commercial gaming devices have been shown to improve upper-limb performance [10]–[13]. A usability study on the Functional Engagement in Assisted Therapy Through Exercise Robotics (FEATHERS) system [14], a platform adapted from commercially available gaming technology, demonstrated that the majority of participants enjoyed playing games with motion tracked controls [15]. Custom-developed systems for exergaming specific to motor rehabilitation for paediatric populations have also been employed effectively in clinical and at-home programs [16], [17], and active gaming during a rehabilitative session can lead to an increase in the number of repetitions performed within at-home training sessions [18].

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. Movements made in VR have been shown to promote better transfer to functional motor tasks than non-immersive VR practiced movements [19], and in a review of VR as a tool for upper-limb rehabilitation, immersive 3D VR systems were shown to match movements made in physical environments more closely than 2D screen-based game platforms [20], [21]. Immersive VR technologies with 3D display capabilities, forward depth, first-person views or avatars, and large fields of view offer considerable task variation and 3D open learning environments. By limiting the amount of cognitive load required to translate physical movement to the desired in-game movement, 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 [22].

One key advantage of immersive VR technology is the ability to quantitatively adjust the real-time feedback given to the user. Head-mounted display (HMD) VR technology also allows for full occlusion of true visual positioning when augmented visual

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feedback is used while still giving veridical, first-person, 3D movement experiences. For example, error augmentation (EA) is a feedback technique that has been used to adjust feedback based on the amount of error, typically amplifying error based on the user's rehabilitative goals [23]. This type of adaptive error feedback keeps the user engaged in the task goal by accentuating error to elicit large, compensatory or corrective responses [24], motivating the user to reduce movement errors [25]. Correction of error, through error augmentation, was shown to be a more effective method to adapt to a rotated upper-limb reach task than non-augmented feedback [26]. People with neuromotor disabilities may not be as sensitive to small errors, and EA aims to make errors in movement more noticeable [27].

Most studies examining visual EA for upper-limb motor training have focused on unimanual reaching for achieving path smoothness. For example, studies using the Virtual Reality and Robotic Optical Operations Machine system have shown positive effects on adaptation, learning, and control [28]–[30]. Using the less affected side as an augmented mirror comparison could provide helpful feedback to highlight any maladaptive movement patterns in the more affected side. Studies on mirroring movements from the less affected to the more affected side in stroke survivors show better improvements after training in comparison to unimanual practice [31], [32]. Based on these studies, it was predicted that EA comparing left- and right-hand positions would positively impact motor adaptation and decrease symmetrical reaching errors between the more and less affected upper limbs.

The main purpose of the study was to explore the viability of an immersive VR environment that manipulated visual feedback (i.e., EA) during bimanual movements that could be implemented in engaging home-based rehabilitative systems. Hence, only commercially available hardware was used to simulate accessible options for rehabilitation technology. The main objective of this study was to test the effectiveness of visual EA in which the asymmetry between the upper limbs during a bilateral forward reach was manipulated in typically developing (TD) adolescents and young adults. The system viability and effectiveness of adaptation to symmetry EA was further explored in 5 cases with young individuals with hemiplegic cerebral palsy (CP). To the authors' knowledge, this is the first study to investigate the use of EA in immersive VR for improving bimanual reaching symmetry.

II. Methods

A. Participants

A total of 17 participants were recruited: 12 typically developing adolescents and young adults aged 13-21 (17 ± 3 years, 3 female, 0 left-handed) and 5 participants clinically diagnosed with unilateral or hemiplegic Cerebral Palsy aged 14-21 (17 ± 3 years, 2 female, 3 left-handed). The Manual Ability Classification System (MACS) and Bimanual Fine Motor Function (BFMF) tests provided further information on the extent of disability for the participants in the CP group. Additional participants' baseline demographics and clinical characteristics were summarized from [33] in Table 1.

The study was conducted under the University of the British Columbia Clinical Research Ethics Board (H17-01126) and informed consent was received from all participants before completing any component of the study. Preliminary results from the first 2 participants in the CP group have been presented previously [34].

TABLE I
Clinical Description of Participants in CP Group

ID	Age	Affected UL*	MACS Score	BFMF Score	Time of Injury	Clinical Notes
CP-1	14	Left	II	II	Perinatal	Intraventricular Hemorrhage; Synkinesis, Stereognosis
CP-2	19	Right	I	II	Perinatal	Periventricular Hemorrhage
CP-3	16	Left	III	I	Age 2	Hemolytic Uremic Syndrome resulting in Cerebral Ischemia
CP-4	21	Right	II	II	Perinatal	Hypoxia from Nuchal Cord
CP-5	17	Right	III	III	Neonatal	Encephalopathy with microcephaly

All participants were first screened for any predisposed sensitivity to screen-based visuals and potential susceptibility to cybersickness.
*UL – upper limb; designated by the more affected side.

B. Experimental Setup

The Oculus Rift system (Oculus VR, LLC, Menlo Park, CA, USA), the Oculus Touch controller pair (accurate up to 10 mm) [35], and two Oculus Sensors were used to facilitate the VR environment. During the experiment, the participants' position, orientation, and the visual representation of their hands were rendered using the OVRAvatar package within a 3D virtual environment developed in Unity 3D 5.0 2017 (Unity Technologies, San Francisco, USA). Kinematic upper body joint positions were recorded via a Kinect v2 (Microsoft Corporation, Redmond, USA) through the same Unity 3D interface. While the Kinect v2 has been successfully employed previously to measure upper limb and trunk movement during forward reaching exercises [36]–[38], joint data from the Kinect were not rendered as part of the real-time upper-limb model in the virtual environment due to the low positional accuracy (1-5 cm [34], [35]), high latency, and noticeable jitter. Positional data were recorded at 90Hz, the Oculus system's inherent sampling frequency, and resampled at 30Hz prior to further calculation, to resolve any artifacts caused by the 30Hz temporal resolution of the Kinect.

Fig. 1 shows the motion tracking device placement within the 2x2 m physical "play-space", which was defined as the area in which the user could move to interact with the virtual environment without any physical obstructions.

C. Task Design

Participants were asked to perform a reaching task with different bimanually interactable object models. They were required to pick up and move the virtual objects to a specified location with both hands simultaneously. The scenery and tasks were designed to reflect food preparation (i.e. a hotdog onto a bun, meat into a dumpling, rice onto nori, and shrimp into a sushi roll), as seen in Fig. 2. The objects were randomly varied at every 5^{th}, 7^{th}, and 8^{th} trial to mitigate boredom due to the repetitive nature of the task. When the participant hovered over the food item with both hands, two "interaction spheres" were

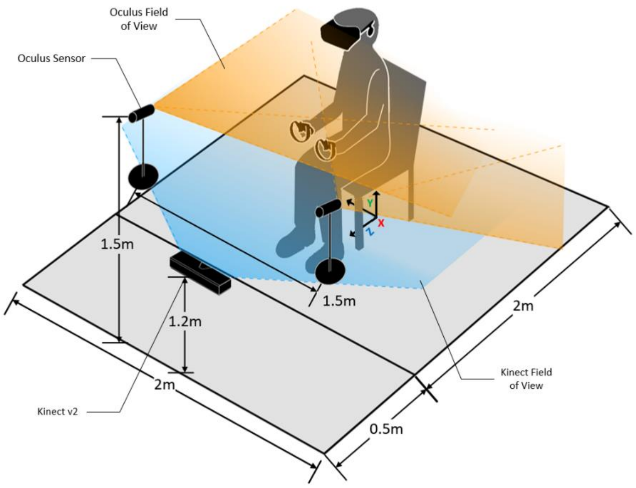

Fig. 1. Experimental setup, sensor layout, and tracking area. The coordinate system of the virtual environment is shown such that the origin was placed on the floor approximately in the centre of the participant's seated location. The Oculus Sensors and Kinect v2 were placed 1.5 m from the play-space origin to maximize the field of view. Angles and distances are not to scale.

Fig. 2. Orthographic view of the virtual scene as seen in the development environment. A picture-in-picture view shows the virtual environment from the user's perspective (with a bun and hotdog as the reaching goal and interactable object respectively). The axes origin shown behind the hotdog cart matches the axes in the physical space marked in Fig. 1.

highlighted, which represented the area in which their virtual hands could pick up the object using the controller's gripper buttons, as shown in the online supplementary material. Since a large portion of the clinical population with hemiplegia also suffers from loss of grasp control [39], for participants in the CP group, a grasp action for each hand was automatically detected when the space of the virtual hand coincided with the interaction sphere of the object, and the object was not released until both hands reached the end goal position.

The 'forward' position of the hands was determined in reference to a global orientation axis that remained static throughout the entire study. The location of the end goal was customized by measuring each participant's baseline maximum reach distance before any recorded study trials. Participants were asked to reach as far as comfortably possible and this distance was recorded. Only augmentation in the Z (reaching) direction was implemented. This augmentation was based on the global axes since the reaching direction and orientation of the starting and end goal position did not change.

D. *Visual Error Augmentation*

Visual EA was used to exaggerate the participant's forward reaching asymmetry between the end location of the hands during experimental trials. As in Fig. 3, the instantaneous position difference between the dominant or less affected (D/LA) side and non-dominant or more affected (ND/A) side in the forward direction was used to visually amplify symmetrical error by adjusting the rendered position of the ND/A hand.

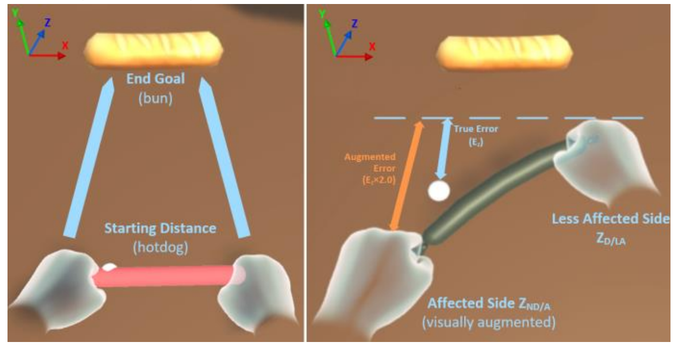

Fig. 3. Diagram of the reaching task (left) and visual error augmentation effect (right). The white sphere above the ND/A side denotes the true position of the participant's hand in the real world. During the experiment, the sphere was hidden from the user and they only saw the rendered augmented hand 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.

As the main movement 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 for all participants. A constant scaling EA factor G of 2.0 was used to amplify the visual error between the D/LA and ND/A sides. As such, the position of the ND/A side appeared as double the true distance away from the D/LA side's forward reaching position. The EA factor was chosen based on estimations of the numerical values used in previous visual EA studies [40] [23]. The augmented visual position Z_{aug} was calculated as follows:

$$Z_{aug} = Z_{ND/A} - (G \times E_z) \quad (1)$$

where the instantaneous reaching symmetry error E_z was:

$$E_z = Z_{D/LA} - Z_{asy} \quad \text{for TD} \quad (2)$$

$$E_z = Z_{D/LA} - Z_{ND/A} \quad \text{for CP} \quad (3)$$

For the group of typically developing (TD) adolescents and young adults (matched in age to the targeted CP group), a 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. This strategy was implemented as the TD group did not have asymmetry as a result of a motor impairment, as in the CP group. Instead of augmenting the true error (as seen in Fig. 3), instantaneous symmetry error E_z was calculated as the difference between the true position of the D/LA side and the intermediate value Z_{asy}, in which Z_{asy} was $0.7Z_{ND/A}$ (see Eq. 2). This forced the TD participants to adapt their ND/A side movement to produce a reach that appeared visually symmetric but was in actuality (and proprioceptively) asymmetric. This resulted in a final reaching position in which the participant's ND/A side was further than the D/LA side in the + Z-direction.

E. *Study Design*

The study was a single-session experiment that used a crossover counterbalanced design with two conditions. Participants were randomized to start training with or without EA in the first set and then switched to the alternate condition in the second set. The order of trials and general chronology of procedures over the two training sets are shown in Fig. 4.

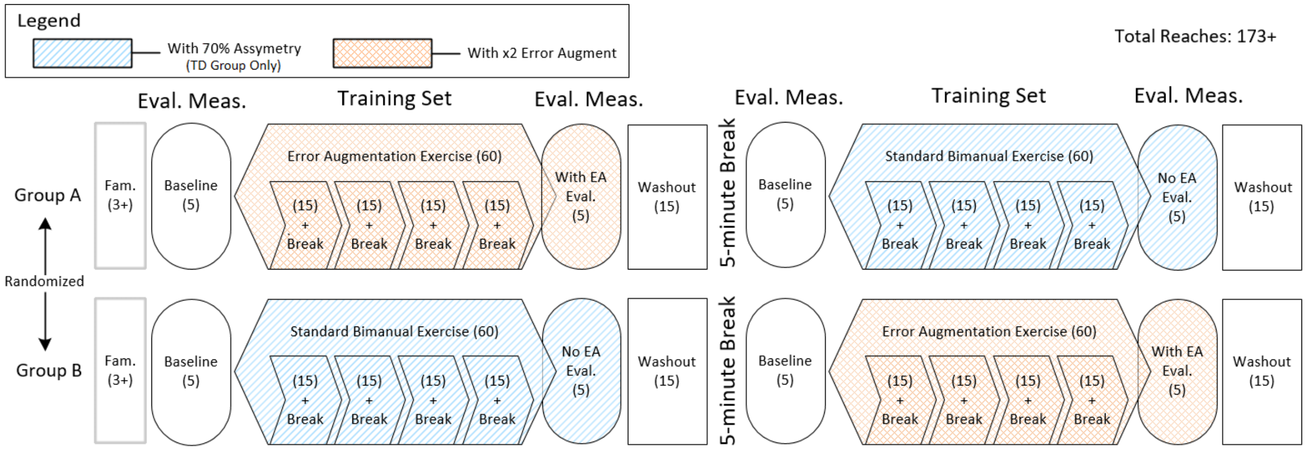

Fig. 4. Diagram of the order of different trial types used in the experiment protocol. Participants would be assigned to either Group A (top line) or Group B (bottom line) randomly. Group A would train with EA in their first set and Group B would train with EA in their second set. The 70% asymmetry, shown for training and evaluation trial types with blue single line hatch, was only applied for TD participants in both training sets as a visual manipulation. Orange cross-hatched trial types were sections in which EA was applied for participants in the CP group, and both EA and 70% asymmetry were applied for TD participants. In Familiarization (Fam), Baseline, and Washout trials, visual positioning matched physical movement and no visual manipulation was applied. The numbers in brackets represent the number of trials in each section; breaks within the training set were taken as requested by the participants.

The study session was broken into two sets with a mandatory 5-minute rest period between sessions, during which the HMD was removed to prevent potential cybersickness or fatigue from overuse of a HMD system. At least three reaches were performed before any recording to allow the participant to gain an understanding of the task and setup, with no visual augmentation applied. In the baseline and washout trials, participants performed forward reaching trials without any EA, or for the TD group, without any EA and without 70% asymmetry applied. These trials allowed for collection of pre- and post-training test data. A set of 15 trials was used to washout out adapted visual effects from training with 70% asymmetry for TD participants and EA for both groups. The main training trials consisted of 60 training and 5 evaluation trials. The evaluation trials were used to compare to the baseline to measure change in symmetry between training with or without EA. After completing one set of these trials, participants performed a second set, in which EA was applied or removed, depending on the order of conditions.

F. *Outcome Measures and Statistical Methods*

The primary outcome was symmetry Root-Mean-Squared Error (RMSE) in cm. This was calculated from the instantaneous distance E_z between the hands, as shown in Eqs. 2 and 3, throughout each trial. Average RMSE from the five evaluation trials in each training set was compared to the 5 baseline trials for each participant. RMSE from the training trials was also fit into a performance curve equation [23] to explore the effect of EA on short-term adaptation parameters.

Secondary outcome measures in movement kinematics were: range of motion in the forward reaching direction (ROM), peak velocity per reach (PV), time to peak velocity (TTP), movement smoothness, measured by the number of velocity peaks per reach (MS) and trunk compensation (TC). Full descriptions of secondary metric definitions can be found in the online supplementary material. Data were also collected pertaining to participant experience using the System Usability Scale (SUS) [41] regarding the system as a whole (the Oculus hardware and VR environment). Additional Likert-type scale questions were asked concerning virtual environment fidelity and immersion and to record any cybersickness effects during or after the session. Finally, participants were asked at the end of the session whether they perceived any differences in trial sections to test whether the visual augmentation was noticed.

Statistical comparisons were conducted using SPSS v25 (IBM, Armonk, USA). A repeated-measures ANOVA was performed on the change in RMSE from baseline to evaluation for the TD group, with training set type (with or without EA) as the within-subjects condition and training set order as a between-subjects factor. Pairwise t-tests were used to test for significant changes between other trial types and in secondary metrics between training conditions. Bonferroni correction was used when multiple t-tests were performed on the same data.

III. Results

The primary outcome measure of symmetry, RMSE, was used to analyze differences between training with or without EA in TD and CP groups. Given the small sample size (n=5) of the CP group, statistical tests were not conducted on the data from this group, but descriptive results are reported to explore the potential of EA on this population.

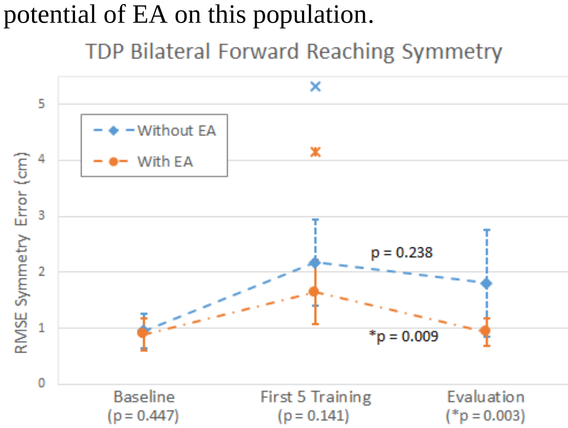

Fig. 5. Average (point) and standard deviation (bar) of RMSE averages for 12 TD participants in the baseline, first 5 trials of training, and evaluation trials for training sets with and without EA. The coloured crosses at ~4 and 5 cm denote outliers excluded from avg. and std. calculation. * denotes statistical significance compared to a corrected $p < 0.01$ using a Bonferroni correction. P-values listed under trial type labels compare differences in trials between EA conditions and p-values listed along the dotted lines show statistical significance between training and evaluation trial types for each condition.

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A. TD Response to an Asymmetric Reaching Task

As the TD group trained to a manipulated, asymmetric task, it was observed that training with EA impacted final symmetry RMSE, as seen in Fig. 5. After training without EA, TD participants were not able to return to their baseline visual asymmetry and maintained a higher level of error compared to their performance after training with EA in the evaluation trials.

The difference between RMSE in either condition was not significant for baseline trials and the first 5 trials of the training set (Fig. 5, based on pairwise t-tests); however, participants performed with significantly lower RMSE after training with EA when comparing the evaluation trials. The decrease in RMSE from the first 5 training trials to the 5 evaluation trials was only significant after training with EA. The majority of participants were able to achieve a level of visual symmetry closer to their baseline as seen in Fig. 6. A decrease in error and return to the baseline represents improvement for this group. Participants that had higher error than baseline represents cases in which training did not allow them to return to a level of visual symmetry similar to that shown during baseline trials without the 70% asymmetry factor after training.

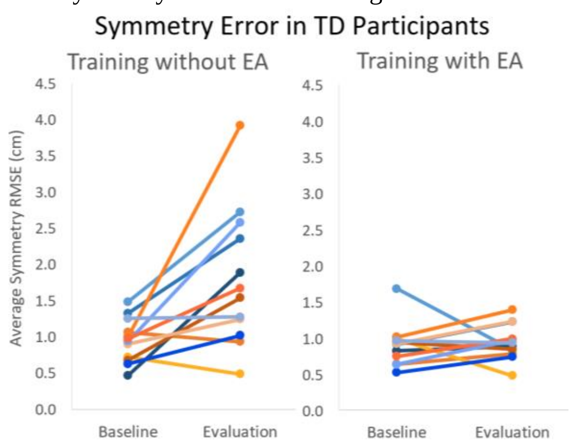

Fig. 6 Line plots presenting change in symmetry RMSE before and after training with (right) and without (left) EA for the 12 TD participants. Participants in Group A, who started with the training set with EA first are marked in orange and those in Group B starting without EA are in blue.

On average, TD participants changed by 0.85 ± 0.89 cm or 98.7 ±109.8% of their baseline RMSE after training without EA in the evaluation trials. Training with EA allowed them to return closer to baseline at a change of 0.04 ± 0.37 cm or 12.3 ± 35.0% (average difference per participant was 86.4% closer with EA). The repeated-measures ANOVA performed on the TD group data determined that there was a significant difference in this change in RMSE ($F(1,10) = 9.64, p = 0.01$, medium effect size, $\eta_p^2 = 0.49$) between the types of training. Training set order (n = 6/order) did not affect the pattern of results: (1,10) $= 0.30, p = 0.60$).

The average symmetry RMSE values throughout the TD training trials were fit to performance curves using the equation $y = Ae^{-t/B} + C$ [23]. Fig. 7 shows the average and standard deviation (filled area) with and without EA. It can be seen that between-participant variability was lower and final performance error, C, was lower with EA. Curves generated from the training trials for the TD group in Fig. 7 reached within 10% of the final performance value, C, within the first 4 trials, and participants adapted or de-adapted quickly to the task regardless of training with or without EA.

Fig. 7. Line and filled area plots illustrating the symmetry RMSE for training sets with and without EA, averaged over all TD 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.

The first 5 washout trials (not shown) after training with EA were higher in average RMSE, but it only took an average of 3 trials to reach 10% of C in comparison to 7 trials after training without EA. A high rate of initial adaptation and faster washout may indicate reliance on real-time strategies for explicit correction when training with EA; however, the non-zero change in the performance curves from washout trials may be evidence of additional short-term skill acquisition.

Secondary kinematic outcome measures were compared across the two training conditions for the evaluation trials using paired t-tests. There were no significant differences in PV, TTP, MS, or ROM in both the ND/A and D/LA sides based on training with or without EA. However, there was a significant difference ($t(11) = 6.09, p = 0.00$) from baseline to evaluation in ROM in the D/LA side only after training with EA, which could indicate some compensation from the D/LA side to maintain symmetry without increasing N/DA ROM.

B. CP Group Response to Symmetric Training with EA

All 5 participants with CP reached with lower symmetry error (i.e., average over 5 trials in the evaluation compared to the baseline set) after training with EA than without EA (Fig. 8). Similar to results from TD participants, any differences in

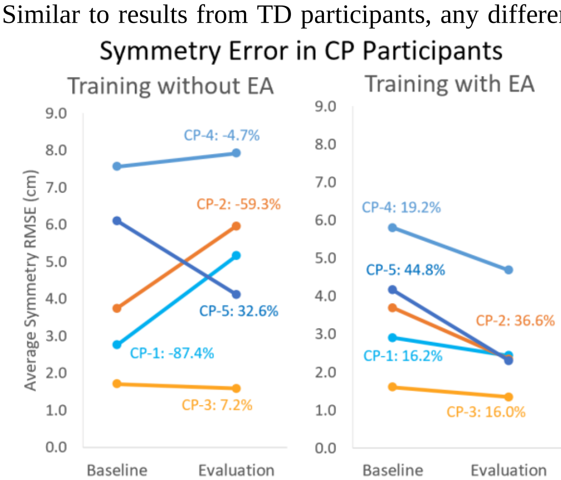

Fig. 8. Line plots showing change in symmetry RMSE before and after training with (right) and without (left) EA for the 5 participants with CP. Participants in Group A, who started with the training set with EA first, are marked in orange and those in Group B, starting without EA, are in blue. Corresponding data labels denote the percent change in error from baseline, in which a positive change represents a decrease in error after training.

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secondary outcomes between training with or without EA were much smaller than their respective standard deviations (e.g. change in reaching ROM in the ND/A side between training sets averaged between 1-3 cm, but standard deviations varied from 15-20 cm). An increased number of velocity peaks, from less than 1 to a maximum of 5, occurred in trajectory profiles of participants with CP, likely due to the lack of motor control. Participants in this group also had lower peak velocities, longer times to peak velocity, and a higher variation in all kinematic measures in comparison to TD group averages.

The participant with the highest bimanual ability (CP-3, BFMF I) improved the least, while the lowest (CP-5, BFMF III) improved the most in both training sessions with and without EA. 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. Participants with MACS I and II scores only surpassed their baseline symmetry error after training with EA and those with MACS III scores improved regardless of training set; however no correlation was found in numeric percent improvement to MACS scores. No correlation was found between the two assessment scales used.

C. *Survey Results*

The average SUS score was 71.25 ± 11.34 for the TD group and 57.50 ± 17.08 for the CP group. Based on 500 studies analyzed by Sauro [42], the average score of a system that is considered usable is 68. The system would be considered "Good" or acceptably usable for the TD group, but for the CP group, the score below the 50th percentile of 500 studies warrants an "OK" descriptor, but is only marginally acceptable [43]. The lower scores in both groups were mostly driven by two questions related to difficulty in setting up the system independently, which could be a major limiting factor for using commercial technology in a rehabilitative setting [14].

The survey found overall positive results showing self-reported engagement, comfort, and immersion. 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. Full Likert scale answers can be found in [33] and in the supplementary online material.

TD participants were also asked about whether they noticed the applied asymmetry factor of 70% at the end of the session. All but one of the participants noticed the asymmetry. With respect to visual error augmentation, 9 of 12 (75%) of TD participants and 3 of 5 (60%) of participants in the CP group did not notice whether the training set included visual error augmentation. The low number of participants who noticed the application of EA may indicate the suitability of using immersive VR technology for visually augmented feedback. 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.

IV. Discussion

Amplifying visual asymmetry in an HMD VR environment for an age-matched, typically developing group significantly improved symmetry error after training with EA in comparison to training without EA. Moreover, the reaching symmetry for all 5 participants with hemiplegic CP also increased after training with EA, in comparison to increases for only 2 participants when EA was not applied during practice. In general, this could indicate that participants were able to better mirror the position of their D/LA side during the reaching task when EA was applied. Mirroring D/LA side movements could be used as a guide to encourage more functional use of N/DA side. The results from this study provide initial positive evidence of the potential of employing visually augmented feedback to existing active gaming and VR systems to promote bimanual symmetry for persons requiring rehabilitation.

A. *Differences between TD and CP Group Participants*

Participants in both the TD and CP groups were able to decrease the (visual) positional difference between the ND/A and D/LA upper limbs more when training with EA than when training without EA. TD participants were able to return closer to baseline symmetry after training with EA whereas all participants in the CP group showed positive improvement in RMSE beyond their original baseline after training with EA. The visual amplification of error allowed them to increase their symmetry more than in their normal bilateral reaching pattern, evidenced in the post-test evaluation trials.

The TD participants' ability to notice EA may have been compromised as more attention may have been given to the application of the 70% asymmetry factor changing visuomotor behaviour than the superimposed EA factor. Moreover, because EA was a scalar factor of the amount of error, a lower error would have produced a lower degree of error augmentation. Thus, TD participants, who on average produced between 1-2 cm of error, would have seen less difference (2-4 cm) than participants in the CP group, who produced up to 8 cm symmetry error and would have seen up to 16 cm visual positioning difference.

The augmentation factor was easy to adapt to in the short term, as demonstrated by both the TD and CP group participants. However, as long-term learning was not evaluated, it is possible that participants would quickly resume "non-trained" movement, which for participants in the CP group could mean a return to any learned non-use [44] of their ND/A side without continued practice. Additionally, in a multi-session study, the system may perform more poorly in terms of viability with individuals with CP, given the marginally usable scores observed when administering the SUS questionnaire.

There may be a certain middle level of BFMF score (BFMF-II) that is best suited for improvement in bilateral reaching using EA. For participants in the CP group, results suggest that participants at BFMF-II were most likely to benefit from the accentuated asymmetry from EA training whilst improving less with standard bimanual training. 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, may benefit equally from practice with and without EA.

B. Comparison to Related Work

Differences in change in error with or without EA were found to be similar to previous studies with EA in different augmentation modalities. When providing healthy individuals with visual EA of path deviation during a rotated reaching task, Sharp [28] reported changes in perpendicular distances of 0.5-4.5 cm resulting in a maximum of 76% difference in error improvement after training without EA in comparison to after training with EA, . This difference in improvement after training with or without EA is similar to the TD participant average 86.4% improvement difference found in our work for 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 the centimetre range found in study results. When Wei [23] and Shirzad [40] 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. Most TD participants were only able to return to their baseline symmetry but were rarely able to achieve greater visual symmetry during the manipulated task, possibly indicating evidence of a ceiling effect caused by an augmentation factor that was less strict than other tested values.

In comparison to the performance curves presented in Fig. 7, Celik [45] 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 [40] found higher final performance error when visual EA was implemented. Both studies reported 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 in this study.

C. Future Work Recommendations

Along with visual manipulations of EA, it is important to test how training in immersive virtual environments compares or transfers to real-world reaching. There are limited studies [46] that have tested the fidelity of 3D VR environments to real-life motions when including EA or intentional visual manipulation. Furthermore, as the majority of participants were not able to distinguish training sets with or without EA, it is likely that using immersive VR allows participants to be susceptible to more drastic manipulations; however, this remains to be tested directly.

Moving forward, it will be necessary to conduct a similar study with a larger sample size of individuals with CP, as it was not possible to statistically conclude the effectiveness of this methodology with only 5 cases. Separation of adolescents and young adults (18+) and inclusion of other age groups, as well as further inclusion of individuals with other neurologic disorders leading to hemiplegia, such as ABI or Stroke, could also be explored in future studies. This would allow more concrete and generalizable predictions to be made about the response of people with hemiplegia to EA in an immersive VR environment.

Retention of motor adaptation and eventual learning should also be tested through a long-term study. Without a longer washout period or training over multiple days, it would be difficult to elicit neuroplastic changes due to improved bimanual motor control and prevent additional carry-over effects between training conditions. A wider set of virtual bimanual tasks, including asymmetric tasks, could also be employed to encourage transfer of improved motor function to real-world functional tasks. Employing faded feedback strategies could also be investigated to potentially reduce long-term reliance on the provided augmented feedback.

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 as in [47], [48]. 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 visual EA, an optimal combination that provides intuitive responses to error could be used to increase immersion in the virtual environment.

While both participant groups expressed interest in using VR as a motivation tool for performing rehabilitation exercises, only TD participant SUS scores ranked the system above "usable". The lack of usability for participants in the CP group requires further exploration into reducing hardware setup up difficulties, as well as adapting commercially-available controllers for the use of people with disabilities [14].

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