Locomotive Recalibration and Prism Adaptation of Children and Teens in Immersive Virtual Environments

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Abstract— As virtual reality expands in popularity, an increasingly diverse audience is gaining exposure to immersive virtual environments (IVEs). A significant body of research has demonstrated how perception and action work in such environments, but most of this work has been done studying adults. Less is known about how physical and cognitive development affect perception and action in IVEs, particularly as applied to preteen and teenage children. Accordingly, in the current study we assess how preteens (children aged 8-12 years) and teenagers (children aged 15-18 years) respond to mismatches between their motor behavior and the visual information presented by an IVE. Over two experiments, we evaluate how these individuals recalibrate their actions across functionally distinct systems of movement. The first experiment analyzed forward walking recalibration after exposure to an IVE with either increased or decreased visual flow. Visual flow during normal bipedal locomotion was manipulated to be either twice or half as fast as the physical gait. The second experiment leveraged a prism throwing adaptation paradigm to test the effect of recalibration on throwing movement. In the first experiment, our results show no differences across age groups, although subjects generally experienced a post-exposure effect of shortened distance estimation after experiencing visually faster flow and longer distance estimation after experiencing visually slower flow. In the second experiment, subjects generally showed the typical prism adaptation behavior of a throwing after-effect error. The error lasted longer for preteens than older children. Our results have implications for the design of virtual systems with children as a target audience.

Index Terms—Virtual environments, perceptual-motor recalibration, perception, children.

1 Introduction

Commodity-level virtual reality (VR) equipment represents an incredible expansion of the reach and scope of immersive virtual environments (IVEs). Included in this expansion, children will begin to experience immersive virtual worlds more frequently. Children are avid adopters of technology, and they will undoubtedly be exposed to virtual reality technologies for both learning and entertainment. Because quality commodity-level head-mounted displays (HMDs) were not available for children previously for reasons of both expense and weight (the Nvis SX 60 weighed 1.45kg, while the HTC Vive weighs 540g — a more direct comparison can be found in Young et al. [80]), immersive technology was not accessible to children for widespread use and adoption. However, that is now changing.

Unfortunately, little is known about how children perceive and act in immersive virtual environments. Although children have been studied previously in immersive virtual reality, the scope of these studies is limited. For example, a significant body of work has been done with children's judgment of gap affordances in pedestrian crossing situations in CAVEs [2, 9, 10, 20, 51, 54–56, 74], HMDs [45–48], and desktop VR [70]. This work has primarily examined 7-12 year-old children and compared their gap judgments to that of adults. Although this investigation is extensive, it primarily focuses on evaluating a specific type of dynamic affordance in virtual environments, namely gap judgments. CAVEs have also been employed as learning environments for second grade children [67] and as virtual theaters [68]. A review of these types of applications can be found in Roussou et al. [66], which focuses on CAVE environments but does not deal directly with either affordances or developmental learning. A body of work in developmental spatial cognition has been performed in desktop virtual environments (e.g., Jansen-Osmann & Wiedenbauer [27], Schmelter et al. [69]), which generally finds that spatial cognition is well developed by the age of 12. In addition, Southgate et al. [72] has discussed ethical issues in research associated with having children and youth in immersive virtual environments. However, when looking at the larger areas of perception and action judgments, there is little work on how children behave outside of the field of pedestrian behavior and gap judgments.

Therefore, it is unknown whether successful immersion for children, even in compelling environments, will require additional hardware and software extensions. A defining feature of such virtual spaces is the ability to act naturally within the space [71], so perceptual elements that adversely affect natural interactions may hinder children's experiences. For example, interpupillary distance adjustments on most current commodity-level HMDs (e.g., the Oculus Rift provides 59-70mm) would not be sufficient for a large proportion of young teenagers and preteens [8, 18]. Likewise, children's spatial cognition and reasoning may not be as developed as that of an adult [12, 49, 50] or they may combine spatial cues differently than adults [53].

In this study we examine how two groups, children aged 8-12 years and teens aged 15-18 years, behave in immersive virtual environments presented by commodity-level HMDs. We examine how they adapt their motor actions to intentional distortions of the visual virtual environment, a process called recalibration [44, 64], and then re-adapt to the normal or baseline environment. We examine this process for two different motor systems, the locomotor system involving walking, and the throwing system that involves hand and arm coordination. In walking, visual information about the rate of self-motion through the environment typically matches the proprioceptive and biomechanical markers of gait. A considerable body of work has shown that if this match is perturbed, then adult participants will adapt to the perturbation, and this mismatch can be measured [15, 36, 37, 44, 64]. An interesting note is that prior work has all been carried out using treadmills or long hallways in which locomotion can be well established. The limited tracking area of commodity-level systems may impose constraints on the ability of participants (be they adults or children) to adapt to locomotion in spaces in which natural walking is tightly constrained.

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For throwing, we adopt the classic method of prism adaptation to recalibrate subjects' hand-arm motor systems [41]. This test involves measuring baseline throwing accuracy, adapting a thrower under prism exposure to an environment that is displaced, and then measuring the post-exposure response to the adaptation. Prism adaptation has been studied previously in virtual environments for adults [4, 22]. In the real world, prism adaptation has been studied for children by Colvin et al. [11], who in a study examining the act of reaching under prism adaptation found that adaptation effects in children aged 8-15 years did not differ. This is perhaps unsurprising since healthy children are generally well-coordinated. However, given the known distortions in visual space of virtual environments as demonstrated by locomotor judgments [5, 21, 26, 30, 31, 34, 43, 62, 77, 79], it seems reasonable to examine children's performance under a different motor system, as well.

While there is some debate about whether recalibration is limb-specific [14] or not [7, 64], it is clear that recalibration of locomotion does not affect throwing in the real world. Thus, in this paper we study two calibration effects in order to evaluate different motor systems. Examining how adaptation occurs in virtual environments is important for the design of virtual environments if they are to be optimized as learning and training platforms. This optimization may involve special design criteria for specific populations. Our work represents a first effort in this direction with commodity-level equipment and for children.

Our results are interesting on two fronts. First, we show that participants can recalibrate with locomotion and prism adaptation in the relatively small tracked space afforded by commodity-level equipment. Consistent with prior work, we show that this adaptation occurs within a matter of minutes. While there is not a strong difference between age groups shown in this study, we do find a difference that has interesting implications for design. The remainder of this paper is organized as follows. Section 2 places this work in context and reviews prior work relevant to our topic. Section 3 describes the locomotion recalibration experiment and Section 4 describes the prism adaptation experiment. Discussion and conclusions are in Section 5.

2 Background

Interactions with an environment, whether real or virtual, require one to perceive stimuli and to act upon them with precision. These dynamic responses, which involve constant calibrations both physically and perceptually, allow individuals to accomplish feats such as walking across the street, writing an essay, and catching a ball. These adjustments are possible due to a mapping between perception and action, which is referred to as perceptual-motor calibration. As one perceives and interacts with their surroundings, a synthesis of contextual, causal, and ultimately multimodal information informs both the way one perceptually understands and interacts their surroundings [76]. When this information changes, the perceptual-motor mapping changes, a process called recalibration.

2.1 Walking Recalibration

In virtual reality, recalibration has been studied with a number of different types of actions. For example, Ebrahimi et al. [16, 17] evaluated visual and haptic stimuli on calibration in a reaching task. Jones et al. [28, 29] sought to evaluate the affect of field-of-view extensions on walking characteristics. Kuhl et al. [36] evaluated the effect of visual and biomechanical calibration for rotational self-motion. However, one of the most prominent systems of movement to be studied in adults is that of forward walking.

While the process of walking may seem imperceptibly easy to able-bodied human adults, it is a complicated skill upon closer inspection. In order to successfully walk, people must view their surroundings, establish a goal location, and coordinate precise motor movements to travel to this location. Although precise perceptual, cognitive, and motor components underlie our ability to walk, the physical coordination expressed by walking is remarkably adaptable. People can easily respond to the dynamic changes that pervade our external environment, such as changing gait to climb a hill or altering speed to catch a bus. While walking in any scenario, we register both visual information and biomechanical indicators of self-movement which allow us to reason about present and future movements. Typically, these two sources of information match, which allows us to perceive that the world is moving past us at the same speed in which we locomote. The relational mapping between perceptual indicators of self-movement and the biomechanical actions involved in locomotion are likely learned, due in part to the thorough practice obtained throughout life.

Numerous studies have demonstrated that this calibration between perception and biomechanical action is flexible and can be altered. Rieser et al. [64] first demonstrated recalibration of locomotion using a real-world paradigm in which the pairing of visually specified motion and biomechanical information for self-motion was mismatched. This manipulation was accomplished by having an actor walk on a treadmill that was pulled by a tractor at a different speed. For example, in a visually slower condition, the visual flow of the environment was slower than the actor's walking speed; in a visually faster condition, the visual flow was faster than their walking speed. Before this walking intervention, participants demonstrated their current calibration between vision and locomotion by walking to a previously viewed target with eyes closed. This *blind walking* task has been used commonly as an action-based measure thought to represent perceived distance [40], and demonstrates people's ability to dynamically update their perceptual representation of space as they walk [63]. Results showed that people adjusted their walking in a posttest after the intervention period, compared to a pretest. Those who experienced the world as visually slower, overshot the target in the posttest compared to the pretest. Likewise, those who experienced the world as visually faster, undershot the target. This pattern of behavior can be explained by the learning of a new perceptual-motor relationship which was then relied on during the blindwalking task.

Since this seminal study, several labs have replicated and expanded on these findings using virtual reality. These studies have helped to understand how visual-motor feedback changes behavior, both within and outside of an IVE. For example, several studies have shown that receiving visual-motor feedback while walking naturally within an HMD VE improves later distance perception, as revealed by blindwalking. The explanation is that people calibrate to the learned relationship between the dynamically changing computer graphics and their own movement [42, 61]. More recent work has suggested not only that locomotion behavior changes with feedback in the IVE, but that the effect extends to a broader scaling of the space, influencing both distance and size judgments [31–33], but see [38] for an alternative finding. An important question to ask is whether the learning that occurs in the IVE transfers to the real world. This result would suggest that recalibration that occurs is a more generalized mechanism and increases the utility of IVEs for studying basic mechanisms of adaptation. In fact, several studies using both a treadmill-VR system [44, 81] and an immersive HMD [37] demonstrated that the effects of decoupling visual and biomechanical information in the IVE replicate those established in Rieser et al. [64].

An open question, however, is whether children and teens demonstrate similar locomotion recalibration effects as adults. Just as in the previously reviewed work, there have been no studies with children in IVEs that have looked at these types of visual-motor feedback manipulations. However, there is a body of work in the real world demonstrating effects of action-based experience on children's actions. For example, studies on affordances have shown that as young children act and receive feedback from their actions, they become more accurate at judging the possibilities for action [1, 19]. This work suggests that children should be good at calibrating their actions and would show similar or stronger effects of recalibration in our study. Alternatively, multiple factors could reduce effects in children, such as cognitive differences in attention as well as increased variability and less fine tuning of action systems [52]. Our current goal was to adapt the recalibration paradigm used in previous IVE studies to test children. It was necessary both to create a virtual world that was engaging for children, and to create it in a way that could use a smaller tracked space supported by new commodity-level HMDs.

2.2 Prism Adaptation

Prism adaptation is another way to assess the effect of visual feedback on human perception and motor control in both the real world and VR. To induce this adaptation, wedge prism goggles are worn that shift one's visual field either laterally or vertically. The effect itself can be observed in two different phases: the prism adaptation phase and the post-adaptation phase. In the prism adaptation phase, the participants don the prism goggles, and in the case of a pointing task, they first show a systematic pointing error, which is displaced in the direction of the visual distortion. In other words, if a lateral displacement of the visual field is induced towards the left via the goggles, then the pointing error will also be expressed towards the left. However, over repeated trials, individuals adapt to the new visual information by accommodating for the error of their previous pointing attempts. This reduction in error is referred to as the prismatic adaptation. In the the post-adaptation phase, the prism goggles are removed. Immediate pointing shows pointing error in the reverse direction of the distortion until the actor readjusts to the new visual input. Multiple studies have demonstrated that participants can recalibrate to these visual perturbations in a short duration of time by adjusting their actions with their motor systems [13, 23, 57, 59, 60, 65].

The prism adaptation paradigm has also been leveraged to evaluate human visuomotor responses within and outside of IVEs. In one such instance, Groen and Werkoven [22], manipulated a VE to study the effect of a deliberately misaligned virtual hand position on hand-eye coordination in a posttest in the real world, which revealed a small but significant aftereffect of the prismatic adaptation. More recently, Bodenheimer et al. [4] analyzed the effect of first-person self-avatars on calibration using a prism adaptation throwing paradigm. Participants tossed an object into a target rather than pointing to a designated target as in some of the prior work. All phases of prism adaptation (pre-exposure throwing, adaptation phase for throwing, and post-exposure throwing) were conducted within an IVE. Some participants viewed a first-person self-avatar while throwing and others did not. Significant throwing error occurred during the prism exposure phase for all conditions. However, there was a reduced aftereffect with the presence of an avatar. Similar results have been observed in real world studies for prism throwing where a limb was visible during the adaptation phase [58]. These results are encouraging in that they reinforce both the idea that a throwing motion may be recalibrated through a lateral prism effect and that an IVE can reliably induce a prism adaptation.

3 Experiment 1

Experiment 1 investigated whether visual-motor recalibration effects would be observed using commodity-level equipment in children (aged 8-12) and teens (aged 15-18). Using commodity-level equipment currently necessitates inducing walking recalibration in a small (4 x 4m) tracked space. Whether children would recalibrate similarly to adults was also an open question. Thus, we had two hypotheses for this experiment. The first hypothesis is to test if commodity-level equipment will allow participants to recalibrate walking locomotion. Because of the small tracking space our design, described below, is a departure from prior designs for recalibration in virtual environments [37, 44], and involves short distances of walking followed by turns. The hypothesis is that this type of virtual environment is sufficient to induce recalibration in locomotion. The second hypothesis was that we would find an age-related difference in recalibration effects with this experiment. We did not have an *a priori* conjecture as to the direction of the difference. As discussed previously, children's periods of rapid physical growth (see Lampl et al. [39] for infant patterns) necessitate taking into account their changing body size on a regular basis, but we know little about this recalibration. On the one hand, children are recalibrating constantly to compensate for physical growth in the real world, and therefore they should be expert at recalibrating. They may adjust their calibrations to fit with the demands of HMDs more rapidly and accurately than adults. On the other hand, their capacity to recalibrate may be limited by an immature system that is either noisier or weaker than it will be in its mature state. Either of these limitations could make children less able to adjust to the calibration demands of an HMD. Thus, the second hypothesis is to determine whether there is an age difference in recalibration of walking and in which direction it lies.

We altered the optic flow information in the IVE by making the visual flow either double (2.0) or half (0.5) of the participant's actual walking speed. The design was between-participants, so participants experienced only one of the flow speeds. Recalibration was evaluated via a blindwalking task carried out both pre- and post- IVE exposure.

3.1 Method

3.1.1 Ethics Statement

All experiments were approved by the Institutional Review Board. Prior to participation, written consent was obtained from all participants and from their parents or legal guardians, if they were minors.

3.1.2 Participants

Forty-five children and adolescents participated in two between-subject experimental conditions (n = 20 in the visually faster condition and n = 25 in the visually slower condition). Within each condition, participants were organized into child and teen subgroups. Children were represented by 8-12 year old participants (M age = 10.2) and teens were represented by 15-18 year old participants (M age = 16.7). For the visually faster condition, the teen group consisted of 10 participants (5 male, 5 female) and the child group consisted of 10 participants (8 male, 2 female). For the visually slower condition, the teen group consisted of 14 participants (6 male, 8 female), and the child group consisted of 11 participants (5 male, 6 female). Teenage participants were recruited via email and younger subjects were recruited with direct permission from a legal guardian. All participants were kept naive as to the purpose of the experiment until after completion and were financially compensated for their time with $ 5. In addition to the compensation, participants were invited to experience other games on the Samsung Gear and HTC Vive after they completed the experiment.

3.1.3 Technical Setup

The immersive virtual environment was rendered in Unity, a multi-platform game engine, and viewed through the HTC Vive with a resolution of 1080×1200 per eye. Additional Velcro was added to the straps of the HMD in order to secure the view of the display for younger participants' heads. The field-of-view of the Vive consists of approximately 110 degrees diagonally. All assets in the virtual environment were obtained from free and open source libraries, such as the Unity Assets Store and Google 3D Warehouse, and textures were manipulated in Adobe Photoshop. In addition, position and orientation tracking were entirely supported by the HTC Vive's Lighthouse tracking system, which allowed us to create a compact, mobile setup by placing our computer, the Vive, and additional experimental equipment on a large trolley cart with two shelves. The experiment was conducted on a computer with an Intel Core i7-6700K processor, 32GB of RAM, and a NVIDIA GTX 1080 video card.

We used a red hockey puck to indicate the target walking location. Small strips of tape were placed on the ground near the outer periphery of the walking path at 2m, 4m, and 6m distances for the experimenter to use as reference when placing the puck at desired targets. These markings were not noticeable to participants and participants did not see the experimenter place the targets. An additional long strip of tape was used to indicate the starting line at 0m. Distance walked was measured using a handheld Spectra Precision Laser HD150, which allowed for quick and accurate distance measurements from the starting line to the participant's back after walking. For the visually slower test condition, we required a linear pathway of at least 10 meters to accommodate for a possible overestimation of distance during the blind walking task (as has been observed in prior recalibration experiments). Therefore, the location of the blind walking tests alternated depending on availability of rooms for this condition, but every room was required to provide a bare minimum of a 10 meter linear distance for forward walking. Note that although two environmental contexts were used, our evaluation focused on within-subjects pre-post differences, and each subject was tested in a single environment. Any effect of the physical

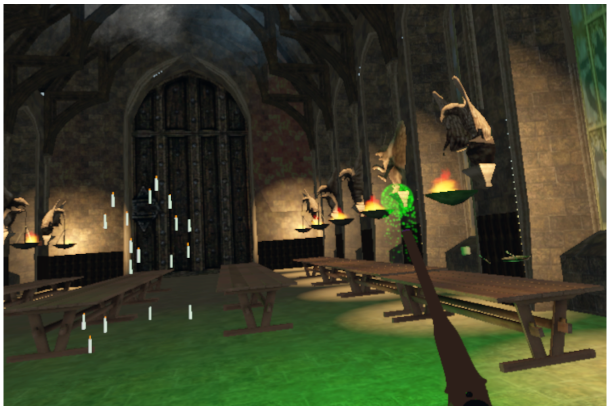

Fig. 1. The virtual walking recalibration environment.

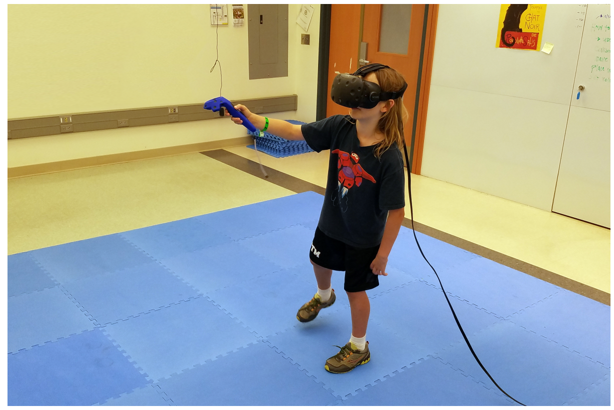

Fig. 2. A 10-year-old participant navigates through the Hogwarts virtual environment.

environment context would have been consistent across the pretest and posttest measures.

3.1.4 Procedure

Before beginning the experiment, each participant was debriefed on the protocol for the blind walking task. The participant was given a blindfold and asked to walk independently around the room in order to ensure that they were comfortable with walking while blindfolded. To prevent participants from gaining biomechanical cues of room dimensions, they were steered away from walls by the experimenter's voice. This was accomplished with a Marco Polo type voice guidance.

After the participants expressed that they were comfortable, they performed one practice trial, in which the experimenter placed the target at a distance of about 4 meters. The participants practiced viewing the target location and then attempted walking to it while blindfolded. After, participants performed the pre-exposure blind walking task, which consisted of 9 total trials with three rounds of unique combinations of the three walking distances at 2, 4, and 6 meters. The order of distances was controlled so that no target distance was repeated consecutively. In addition, the first distance was varied between participants to prevent an effect of order. The same set of distances was used for the pre- and post-exposure trials.

Two experimenters were required to execute the protocol. One stood at the starting line with the precision laser to take distance measurements while the second placed the hockey puck and steered the participant back to start. After placing the puck, the experimenter stood above it, and their back was used as a target for the laser to check distance placement. After the measurement was obtained and the path was cleared of people, the participant was instructed to look at the puck. If the participant stared for more than three seconds, they were instructed to place the blindfold back over their eyes. The puck was then removed by the experimenter (as quietly as possible) and the participant was asked to walk to the puck's location. When the participant stopped, the precision laser was once again used to obtain a distance measurement to their back. They were then directed back to the starting line by the experimenter in paths that somewhat varied from trial to trial. The participant remained blindfolded throughout the experiment to avoid feedback. Accordingly, the participant was only permitted to remove the blindfold to view the targets and then after completion of the last trial once they had been returned to the starting position.

Between the pre-exposure blind walking task and the post-exposure blind walking task, participants were exposed to the virtual reality recalibration environment, which was loosely based on the Hogwarts dining hall from Harry Potter (see Figure 1). Before commencing the exposure trial, participants were instructed in how to adjust the inner pupilary distance of the HMD using the HTC Vive's native method until they could see clearly. Recalibration was achieved through a simulation in which participants would follow a glowing, green orb on a designated path with four equidistant waypoints. While only periodically switching directions, the orb navigated around the perimeter in a cyclical pattern. However, the orb would not proceed to the next waypoint until a participant stepped near it. In addition, the participant was given a Vive Controller, which appeared as a magic wand in the virtual environment. The participant was instructed to tap the orb when it turned red and stopped. The orb would not move again until the participant touched it with the wand (see Figure 2). Participants followed the orb for five minutes and were asked questions about the virtual environment intermittently in order to encourage rich environmental feedback. After completing the recalibration stage of the experiment, participants were immediately blindfolded to prevent acclimation to the real world before the post-exposure trials began. Finally, post-exposure blind walking trials were performed in the same manner as the pre-exposure trials and then participants were debriefed about the experiment.

3.2 Results

Recalibration is the change that occurs when the pairing of visual flow information for motion is mismatched from the biomechanical information for self-motion. We tested for recalibration of walking in children and teens in both the visually faster and visually slower conditions by examining their post-exposure blindwalked distances to their pre-exposure blindwalked distances. If children and teens show a recalibration effect similar to adults, then we would expect those in the visually slower condition to walk farther on the post-exposure trials as compared to the pre-exposure and those in the visually faster condition to walk shorter distances in the post-exposure as compared to pre-exposure.

Because there may be individual differences in blindwalked estimates of distance and because we are interested in within-subjects change to assess recalibration after exposure, we calculated ratios to compare pre-exposure distances to post-exposure distances. First, we scaled the walked estimates to the actual distance by dividing estimate by actual. Then we obtained an estimate of each subject's pre-exposure walking judgment at each of the distances measured by taking the mean of those scaled estimates and using that mean as the average pre-exposure walked distance. Next, we employed two methods of creating ratios for walking recalibration, following Rieser et al. [64], to assess whether the effect of recalibration was reasonably long-lived or short-lived. In the first calculation of ratios, we took the mean of all the post-exposure walking judgments at each distance, and calculated the ratio of the post-exposure mean minus the pre-exposure mean to the pre-exposure mean, giving us a Weber-like fraction. If the effect of recalibration is reasonably long-lived, then we should see an effect over all trials as reflected in this calculated set of ratios. However, the effect may be short-lived, and so, like Rieser and colleagues, we also computed ratios using the same fraction, but using only the first posttest trial at each distance. Note that by design, the first block of trials for each participant consisted of each distance (2m, 4m, 6m) in a randomized order.

The first analysis, which examined whether there was a long-lived

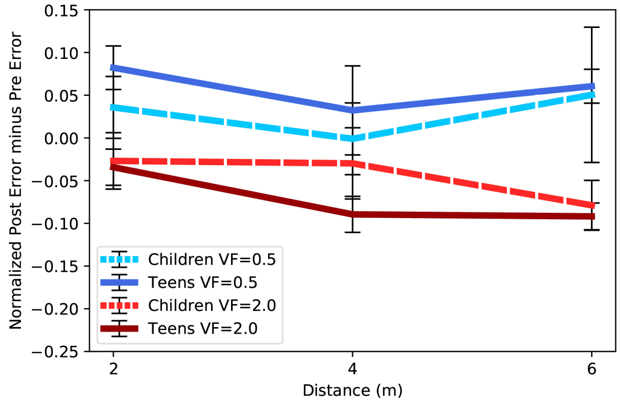

Fig. 3. The overall results of walking recalibration expressed as a ratio of distance using the mean of all post-exposure trials subtracted from the mean of the pre-exposure trials. Results are shown by visual flow (VF) condition (faster, slower) and age group of participants. Error bars are standard errors of the mean.

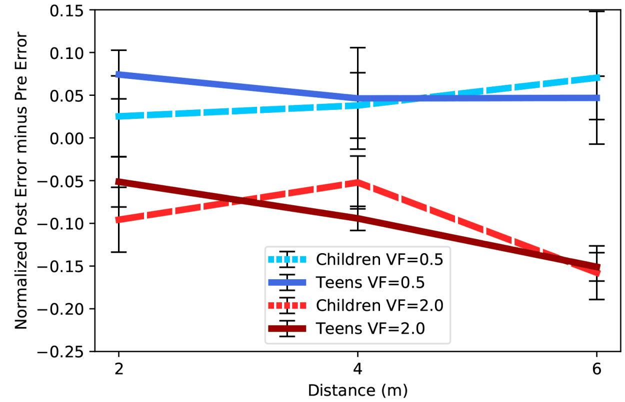

Fig. 4. The results of walking recalibration expressed as a ratio of distance using only the first post-exposure trial subtracted from the mean of the pre-exposure trials. Results are shown by visual flow (VF) condition (faster, slower) and age group of participants. Error bars are standard errors of the mean.

effect, was a 2 (exposure condition: visually faster or visually slower) x 2 (age: children or teenager) x 3 (distance) repeated measures mixed ANOVA that was performed on the ratios with mean distance calculations over all trials. The only significant effect was the predicted effect of exposure condition $F(1,41) = 12.48, p = .001, \eta_p^2 = .23, \text{power} = 0.93$, showing an average of 4.3% overshoot of distance walked in the visually slower condition and an average 5.9% undershoot of distance walked in the visually faster condition. This effect demonstrates that participants recalibrated their actions differentially as a function of the direction of the decoupled visual and biomechanical information for self-motion. There was no evidence of an effect of age on the recalibration effect ($p = .96$). Given the relatively small sample size for each age group, we also conducted a follow-up 2 (exposure condition) x 3 (distance) ANOVA on the same ratios, removing age group as a categorical factor but including age in years as a continuous covariate. The results were replicated, finding only an effect of exposure condition.

For the second method of analysis, which tested for a short-lived effect, we conducted the same type of ANOVA but using the ratios consisting of only the first posttest trial minus the pretest mean. This revealed a significant effect of exposure condition, $F(1,41) = 25.84, p < 0.001, \eta_p^2 = .38, \text{power} = 0.99$, showing an average 5% overshoot in the visually slower condition and an average 10% undershoot in the visually faster condition, and no other significant effects. Notably, this analysis provides evidence of a stronger effect size, suggesting that the recalibration effect is strongest on the initial trial, but then reduces somewhat over time. Again, the lack of significant age effect ($p = .81$) suggests there is not a difference between younger and older children in the magnitude or timescale of the recalibration effect, at least for this paradigm. This lack of age effect was also confirmed with an additional ANOVA removing the age group, but adding age in years as a continuous covariate. The same strong effect of exposure condition occurred. The data for this method of analysis is shown in Figure 4.

Thus, participants recalibrated in this experiment, in the directions that we theoretically expected. Although the recalibration effect was strongest on the first trial suggesting it is somewhat shortlived, it was still noticeable at the distances in our tracked space during our posttest trials. This suggests that a longer exposure time may be needed for a longer recalibration effect. Our first hypothesis is thus confirmed. We did not find any age-related effects of recalibration, and thus our second hypothesis is not confirmed. We discuss these findings further in Section 5.

4 Experiment 2

In Experiment 2, we tested for a recalibration effect in a functionally different motor task that utilizes a different effector in the human body: throwing. We used a traditional prism throwing adaptation paradigm in order to determine the effect of lateral displacement on throwing adaptation in adolescents. Prior work has demonstrated this effect in adults both in the real world and in an IVE [4, 22]. For this task, participants must throw an object to a target, which lies directly in front of them at a short distance. The paradigm includes three different phases: the pre-exposure phase, the prism exposure phase, and the post-exposure phase. The pre-exposure phase provides the participant's baseline performance prior to any visual manipulations in the IVE. The prism exposure phase induces the prism effect, which offsets the participant's view counterclockwise about their vertical axis by 17 degrees. Finally, the post-exposure phase returns the participant to the default viewpoint without any visual manipulations. In adult subjects, a positive error is expressed initially during the prism exposure phase in the direction of the displacement until the participant gradually recalibrates to the new viewpoint. Conversely, in the post-exposure phase a negative aftereffect is expressed until the participant adapts back to the baseline viewpoint. Discrepancies in performance across children and teens may indicate that differences in perceptual and physical development affect an individuals ability to act during and after exposure to an environment with different visual feedback. Consistent with Experiment 1, we have two hypotheses about this experiment. The first hypothesis is that we will find an age-related difference in prism adaptation, although, again we do not have an *a priori* expectation about which age group may prove more adept at adapting. The second hypothesis is, again, that the prism adaptation effect will occur for both age groups in our virtual environment.

4.1 Method

4.1.1 Ethics Statement

All experiments were approved by the Institutional Review Board. Written consent was obtained from all participants, and from their parents or legal guardians if they were minors, prior to participation.

4.1.2 Participants

Twenty-five children and adolescents participated in a single within-subject experimental condition. Again, participants were grouped into either a child or teen subgroup based on age. Children were represented by 8-12 year old participants (*M* age = 10.45) and teens were represented by 15-18 year old participants (*M* age = 16.7). The teen group consisted of 14 participants (6 male, 8 female), and the child group consisted of 11 participants (5 male, 6 female). Recruitment and compensation were the same as in Experiment 1. All participants were kept naive as to the purpose of the experiment until after completion.

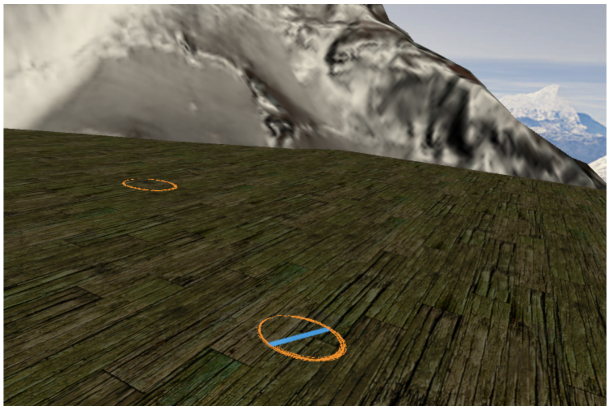

Fig. 5. The prism adaptation virtual environment.

4.1.3 Technical Setup

The same technical setup was used as in Experiment 1. However, all participants were run in the same experimental room for the prism adaptation task in this experiment, because extended room for walking was not needed as in Experiment 1. In this task, additional safety precautions were put in place to protect the Vive Controller, which was tossed both virtually and in reality into the target space. In order to protect the controller, the floor was covered with 0.5 inch thick foam puzzle squares and a full size inflatable mattress was placed over the squares in the same longitudinal direction as the target was displayed in the IVE. In addition, one of the experimenters acted as catcher to ensure no collisions would damage the controller. These extra preventative measures were put in place under the assumption that younger participants may be prone to more inaccurate or variable tosses due to lack of fine motor control.

4.1.4 Procedure

The procedure for the second experiment generally adheres to the procedure described by Bodenheimer et al. [4], with the addition of some safeguards to account for the fact that children were tossing Vive controllers instead of the soft ball that adults tossed in the previous work. The starting position for throwing and the target location markers were both represented by orange circles within the IVE. The starting circle was placed at origin on the ground plane. It also circumscribed a blue starting line for the participant to stand on throughout the experimental procedure. For accurate positioning at the starting point, participants were instructed to trace their real feet (virtual feet were not portrayed) with the controller to ensure that they stood directly on the line both virtually and in reality. The target was placed directly in front of the participant at a two meter distance. To improve perception of its location, it was slightly elevated above the ground. The IVE was a large, open space with a mountain view and wooden flooring (see Figure 5).

Two experimenters were also needed for this experiment. One stood near the target to catch the controller and the other between the participant and the catcher to return the controller. Participants were instructed to give a gentle, underhanded toss to the target 12 times (see Figure 6). These 12 throwing trials were repeated in each of the three phases of the experiment: the pre-exposure phase, the prism exposure phase, and the post-exposure phase. Between each phase, participants were asked to close their eyes while the experimenter initiated the next phase of the experiment. The prism adaptation was identical to that in [4], except that it induced the virtual prism effect by rotating counter-clockwise the participant's visual field by 17 degrees along the virtual camera's vertical axis (instead of clockwise as in the previous paper).

4.2 Results

Horizontal displacement from the target was measured for each participant for each throwing trial in the pre-exposure, prism exposure, and post-exposure phases. Average signed displacement error across

Fig. 6. A 10 year-old participant tosses the controller into the target space.

12 participants for the pre-exposure condition for children and teens is presented in Figure 7. To test the adaptation during the prism-exposure phase, we calculated the mean signed error across the 12 pre-exposure trials for each participant and subtracted it from the error on each prism-exposure trial for that participant. This gives a within-participant measure of the difference in error between each prism trial and the pre-exposure baseline. Similarly, we subtracted this mean pre-exposure error from each post-exposure trial to assess the magnitude of the aftereffect on each trial. Outliers were tested for by checking if any data was greater than 3SD above the mean. Two outliers in the pre-exposure condition and two outliers in the post-exposure condition were found and replaced with the means of their respective condition. We ran a 2 (age group) x 12 (trial) mixed analysis of variance (ANOVA) separately for all three phases (pre-exposure, prism-exposure difference, and post-exposure difference). The analysis on the pre-exposure trials showed no effect of trial, $F(11,253) = .326$, $p = .98$, nor age group, $F(1,23) = 2.17$, $p = .15$. As seen in Figure 7, the means across trials hovered around zero, suggesting that both younger and older children are able to throw relatively accurately within the IVE.

A 2 (age group) x 12 (trial) ANOVA on prism exposure assessed the pattern of throwing error as a function of the prism manipulation. As predicted, there was a significant effect of trial, showing a large signed error on the initial trials, which decreased as trials progressed, $F(11,253) = 20.06$, $p < .001$, $\eta_p^2 = .466$. There was, however, no difference between age groups, $F(1,23) = 1.31$, $p < .264$, $\eta_p^2 = .054$, and there was no age x trial interaction, $F(11,253) = .99$, $p < .452$, $\eta_p^2 = .041$. A 2 (age group) x 12 (trial) ANOVA on post-exposure error assessed the aftereffect, or the strength of the adaptation effect over time. Here again, there was the predicted effect of trial, $F(11,253) = 14.38$, $p < .001$, $\eta_p^2 = .38$, showing an initial increase in error in the opposite direction, that reduced over the first several trials. Notably, there was a trial x age group interaction, $F(11,253) = 1.95$, $p < .04$, $\eta_p^2 = .078$, indicating a different pattern of change in error in the younger and older groups. As seen in Figure 9, while both groups decreased in error similarly for the first four trials, at trial 5, the younger children continued to show more error than the older group. This difference was confirmed by independent t-tests at each trial, showing no significant differences for the first 4 trials ($ps < .2$), but a difference in error at trial 5, $t(23) = -2.96$, $p < .001$ (Mean error $= -.125, -.039$ for children and teens, respectively).

Given that this effect is based on analyses of single trials, we also ran a second set of ANOVAs on the prism exposure and post-exposure data after averaging the trials into 3 bins (4 trials in each bin). The effects were replicated. For the prism exposure trials, a 2 (age group) x 3 (trial bin) mixed ANOVA showed a significant effect of bin, with decreasing error as bins of trials progress, $F(2,46) = 55.50 p < .001$, $\eta_p^2 = .71$, but no difference between age groups ($p = .26$) and no age x bin interaction ($p = .62$). For the post-exposure trials, we replicated the predicted effect of decreasing error with trial bin, $F(2,46) = 58.28$, $p < .001$, $\eta_p^2 = .72$, as well as the trial bin x age group interaction, $F(2,46) = 4.41$, $p < .02$, $\eta_p^2 = .16$, suggesting a difference in adaptation between age groups as trials progress. This difference was confirmed by independent t-tests at each bin, showing that initially younger children and teens showed the same magnitude of error in the first bin, $t(23) = -.089$, $p = .93$, but that the younger children showed larger error in the second bin of trials compared to the teens, $t(23) = -2.95$, $p < .007$ (Mean error = -.099, -.041 for children and teens, respectively). The error at the third bin did not differ between groups ($p = .34$).

This difference at the second bin of trials is consistent with the single-trial analysis and suggests that the aftereffect lasts longer for younger versus older children and has implications for understanding different mechanisms of recalibration. Thus, in this experiment, both our first hypothesis and our second hypothesis were confirmed. We discuss this further in Section 5.

5 Discussion And Conclusion

This paper examined recalibration using current, commodity-level HMD-based VR systems for a previously unstudied population — children aged 8-12 and teens aged 15-18. We examined recalibration in locomotion using a visual flow manipulation and recalibration in throwing using prism adaptation. Both our visual flow manipulation and prism adaptation technique followed from previous experiments run on adults in VR (Mohler et al. [44] for locomotion, Bodenheimer et al. [4] for throwing). Slight modifications were required to move the recalibration methods to commodity-level systems. For the locomotion recalibration system, continuous walking involved a shorter path before a turn, and many more turns, than had ever previously been attempted. It was not clear *a priori* that turning, or pausing to turn, would not interrupt the locomotion adaption process that occurs during recalibration. For prism adaptation, instead of tossing a ball, which cannot be tracked by default in an off-the-shelf commodity-level system, the Vive controller was tossed instead.

We had four hypotheses, two for each experiment. Two of our hypotheses were that recalibration and adaptation would occur in our setups and in these commodity-level systems. Both hypotheses were confirmed. In the locomotion condition, participants recalibrated to visual flow, although the recalibration should be characterized as a short-lived event. In comparison to Mohler et al.'s work done with adults [44], two things stand out. First, the adaptation stage in Mohler et al. was 10 minutes instead of five. We only adapted children and teens for 5 minutes because we were concerned that walking a circuitous route in the HMD for too long might induce simulator sickness. Although there was no formal assessment of simulator sickness, no participant expressed sickness during the experiment. Second, our results are roughly consistent. Mohler and colleagues found undershoot by 6% in the visually faster condition; we find undershoot of 10% in this condition. Mohler and colleagues found that adults overshot by 3% in the visually slower condition, we found children and teens overshot by 5% in this experiment. Mohler and colleagues were using different methods and equipment, of course, but the perception-action recalibration for locomotion is similar. Kunz et al. [37] found that adults overshot and undershot about 10% in both conditions when using an HMD. In the prism adaptation condition, we found a prism adaptation effect similar to that observed in adults by Bodenheimer et al. [4].

Two of our hypotheses were that we would see age-related differences in recalibration between children aged 8-12 and teens aged 15-18. The basis for these hypotheses came from the supposition that children undergoing rapid development would potentially have a different experience with recalibration than older teens. In the locomotion recalibration

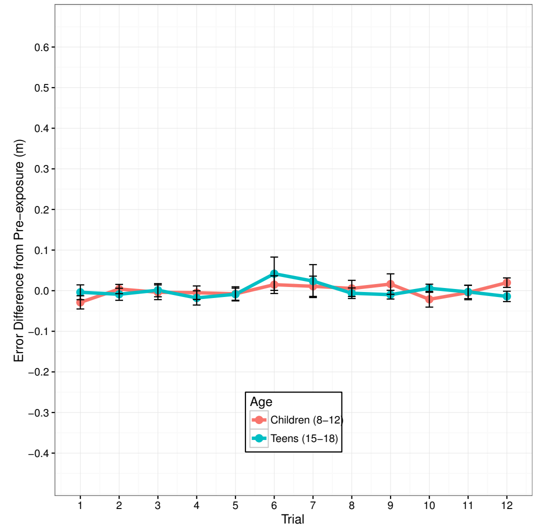

Fig. 7. Average signed displacement error for children and teens in pre-exposure condition. Error bars are standard errors of the mean.

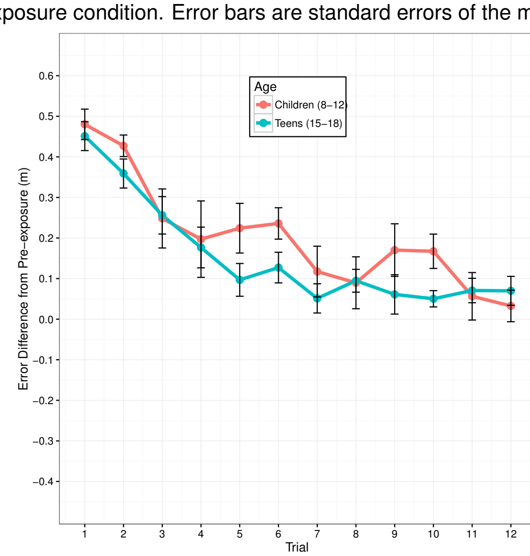

Fig. 8. Error during Prism exposure (Prism error − mean pre-exposure error) during the prism phase.

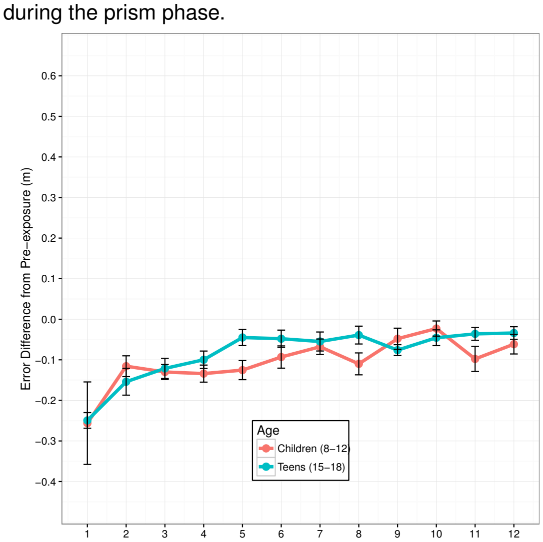

Fig. 9. Error in Post-exposure trials (Post-exposure error − mean pre-exposure error) during the post-exposure trials.

experiment, this hypothesis could not be confirmed, as we found no age-related differences. In the prism adaptation condition, however, we found that children had a significantly slower rate of re-adaptation after exposure to the prism condition. This provides some support for the belief that children's capacity to recalibrate is limited because their visuo-motor system is still immature. Our results suggest that learning and training systems targeted towards younger audiences may want to consider slower adaptation for the design of optimal experiences.

Our study is not without limitations. While the advent of affordable high-end virtual reality has allowed for a larger audience, there are several problems with the current state of technology. One major hurdle is the weight of head-mounted displays. While adults may find the mass of HMDs a minor hindrance, this weight presents a greater obstacle for populations lacking healthy, adult levels of physical strength. As a result, children become fatigued after prolonged VR use. Several younger participants expressed concern over the weight of the Vive's HMD in these experiments.

Nevertheless, these results are promising. A benefit of children showing walking recalibration may lie in the realm of locomotion methods within VR. Methods for navigating in large virtual environments [6, 24, 25, 73, 75, 78] may benefit from recalibration effects by increasing presence or spatial awareness. Also, Bodenheimer et al. [4] found a significant effect of the presence of an avatar in prism adaptation, so it would be interesting to see how that and other body ownership illusions [3, 35] may effect our target audience.

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