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Investigating Embodied Interaction in Near-Field Perception-Action Re-Calibration on Performance in Immersive Virtual Environments

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Abstract

Immersive Virtual Environments (IVEs) are becoming more accessible and more widely utilized for training. Previous research has shown that the matching of visual and proprioceptive information is important for calibration. Many state-of-the art *Virtual Reality* (VR) systems, commonly known as *Immersive Virtual Environments* (IVE), are created for training users in tasks that require accurate manual dexterity. Unfortunately, these systems can suffer from technical limitations that may force de-coupling of visual and proprioceptive information due to interference, latency, and tracking error. It has also been suggested that closed-loop feedback of travel and locomotion in an IVE can overcome compression of visually perceived depth in medium field distances in the virtual world [33, 47]. Very few experiments have examined the carryover effects of multi-sensory feedback in IVEs during manual dexterous 3D user interaction in overcoming distortions in near-field or interaction space depth perception, and the relative importance of visual and proprioceptive information in calibrating users distance judgments. In the first part of this work, we examined the recalibration of movements when the visually reached distance is scaled differently than the physically reached distance. We present an empirical evaluation of how visually distorted movements affects users' reach to near field targets in an IVE.

In a between subjects design, participants provided manual reaching distance estimates during three sessions; a baseline measure without feedback (open-loop distance estimation), a calibration session with visual and proprioceptive feedback (closed-loop distance estimation), and a post-interaction session without feedback (open-loop distance estimation). Subjects were randomly assigned to one of three visual feedbacks in the closed-loop condition during which they reached to target while holding a tracked stylus: i) Minus condition (-20% gain condition) in which the visual stylus appeared at 80% of the distance of the physical stylus, ii) Neutral condition (0% or no gain condition) in which the visual stylus was co-located with the physical stylus, and iii) Plus condition

(+20% gain condition) in which the visual stylus appeared at 120% of the distance of the physical stylus. In all the conditions, there is evidence of visuo-motor calibration in that users' accuracy in physically reaching to the target locations improved over trials. Scaled visual feedback was shown to calibrate distance judgments within an IVE, with estimates being farthest in the post-interaction session after calibrating to visual information appearing nearer (Minus condition), and nearest after calibrating to visual information appearing further (Plus condition). The same pattern was observed during closed-loop physical reach responses, participants generally tended to physically reach farther in Minus condition and closer in Plus condition to the perceived location of the targets, as compared to Neutral condition in which participants' physical reach was more accurate to the perceived location of the target.

We then characterized the properties of human reach motion in the presence or absence of visuo-haptic feedback in real and IVEs within a participant's maximum arm reach. Our goal is to understand how physical reaching actions to the perceived location of targets in the presence or absence of visuo-haptic feedback are different between real and virtual viewing conditions. Typically, participants reach to the perceived location of objects in the 3D environment to perform selection and manipulation actions during 3D interaction in applications such as virtual assembly or rehabilitation. In these tasks, participants typically have distorted perceptual information in the IVE as compared to the real world, in part due to technological limitations such as minimal visual field of view, resolution, latency and jitter. In an empirical evaluation, we asked the following questions; i) how do the perceptual differences between virtual and real world affect our ability to accurately reach to the locations of 3D objects, and ii) how do the motor responses of participants differ between the presence or absence of visual and haptic feedback? We examined factors such as velocity and distance of physical reaching behavior between the real world and IVE, both in the presence or absence of visuo-haptic information. The results suggest that physical reach responses vary systematically between real and virtual environments especially in situations involving presence or absence of visuo-haptic feedback. The implications of our study provide a methodological framework for the analysis of reaching motions for selection and manipulation with novel 3D interaction metaphors and to successfully characterize visuo-haptic versus non-visuo-haptic physical reaches in virtual and real world situations.

While research has demonstrated that self-avatars can enhance ones' sense of presence and improve distance perception, the effects of self-avatar fidelity on near field distance estimations

has yet to be investigated. Thus, we investigated the effect of visual fidelity of the self-avatar in enhancing the user's depth judgments, reach boundary perception and properties of physical reach motion. Previous research has demonstrated that self-avatar representation of the user enhances the sense of presence [37] and even a static notion of an avatar can improve distance estimation in far distances [59, 48]. In this study, performance with a virtual avatar was also compared to real-world performance. Three levels of fidelity were tested; 1) an immersive self-avatar with realistic limbs, 2) a low-fidelity self-avatar showing only joint locations, and 3) end-effector only. There were four primary hypotheses; First, we hypothesize that just the existence of self-avatar or end-effector position would calibrate users' interaction space depth perception in an IVE. Therefore, participants' distance judgments would be improved after the calibration phase regardless of self-avatars' visual fidelity. Second, the magnitude of the changes from pre-test to post-test would be significantly different based on the visual details of the self-avatar presented to the participants (self-avatar vs low-fidelity self-avatar and end-effector). Third, we predict distance estimation accuracy would be the highest in immersive self-avatar condition and the lowest in end-effector condition. Forth, we predict that the properties of physical reach responses vary systematically between different visual fidelity conditions. The results suggest that reach estimations become more accurate as the visual fidelity of the avatar increases, with accuracy for high fidelity avatars approaching real-world performance as compared to low-fidelity and end-effector conditions. There was also an effect of the phase where the reach estimate became more accurate after receiving feedback in calibration phase. Overall, in all conditions reach estimations became more accurate after receiving feedback during a calibration phase. Lastly, we examined factors such as path length, time to complete the task, average velocity and acceleration of physical reach motion and compared all the IVEs conditions with real-world. The results suggest that physical reach responses vary systematically between the VR viewing conditions and real-world.

Dedication

To my Mom and Dad

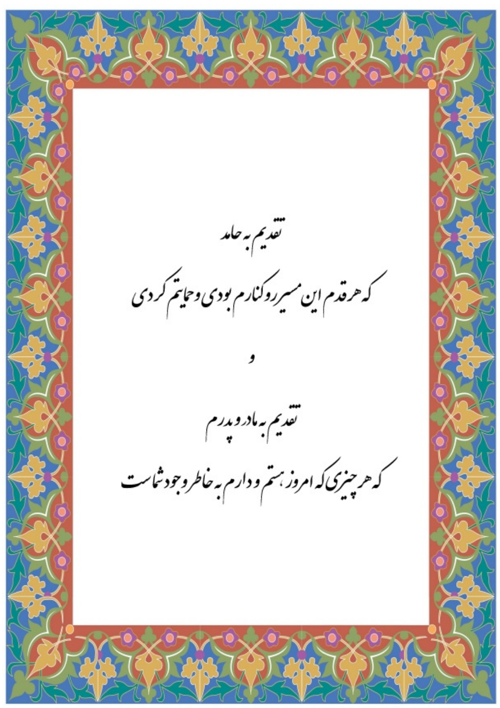
Mrs. Narges Rajabzadeh and Mr. Shirviyeh Ebrahimi - For making me who I am today and for your unconditional support in the hardest of time.

To my husband

Hamed - Because of your continued support and unconditional love. You inspired and encouraged me every step of the way.

To my son

Parsa - My life is much more meaningful just because of you.



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Chapter 1

Introduction and Motivation

There are several promising near field applications in *Immersive Virtual Environments* (IVEs) that allow users to perform fine motor tasks in users' interaction space towards rehabilitation [16], therapy [27], and surgery training [68]. State-of-the-art *Virtual Reality* (VR) systems provide substantial advantages in facilitating repeatable and safe user interactions with the environment in simulating situations that are potentially dangerous, expensive or rare. Although a large amount of effort has been put into creating IVEs and user interaction metaphors to closely replicate the real world situations for the purpose of training and education, many studies have demonstrated that distance perception is distorted and erroneous in VEs [45, 57] which has the potential to adversely affect task performance, training effectiveness, and cause ocular-motor discomfort and simulator sickness. These kinds of distortions are problematic especially when VR is used to train skills involving fine motor activities geared towards transferring to the real world. In order to better understand how near field distance estimation operates in IVE on users, we took some measurements under different circumstances to illustrate that the depth mis-perception could be remedied via visuo-motor re-calibration and formulating methods to enhance spatial perception in IVE:

1. *Explore to what extent users are able to calibrate their depth judgments during visually guided actions in IVEs, when given congruent or dissonant visual and proprioceptive information while performing manual tasks, during 3D interactions in near-field VR.* One way to overcome the distortions in IVE is to allow users to interact with the VE in a natural manner utilizing

3D user interface metaphors that facilitate actions such as reaching and grasping for selection and manipulation [1, 39, 7]. However, feedback representing the users' actions in VR may consist of missing or maligned information in different visuo-motor sensory channels [10]. This may be due to technological limitations such as latency, tracker drift, registration errors, or intentional offsets between visual and proprioceptive information in the performance of near-field 3D interaction. These kinds of distortions could potentially alter users' perception of the environment and could degrade training outcomes, experience and performance. In the real world visuo-motor calibration rapidly alters one's actions to accommodate new circumstances [4, 6]. It has been shown that our physical action is actually influenced by the presence of information from multiple sensory inputs such as visual, proprioceptive, auditory, and tactile channels [22]. Additionally, previous work indicates that the visual and proprioceptive sensory channels are highly tied together and constantly calibrated based on sensory inputs from the real world [4]. However, it is not well understood to what extent users' distance estimation in near field in IVEs is affected by the linkage between the visual and proprioceptive information and how distance judgments will be altered in the presence of a mismatch between the two sensory channels.

2. *Characterize the physical reach motion for 3D interaction, and study how the reaches are different in real versus virtual worlds, and in the presence or absence of visuo-haptic information.* Understanding the properties of reach motion has applications not only in VR but also in areas such as animation, robotics, biomechanics, neuroscience, and ergonomics. Most often, human hand movements during spatial interaction to perform selection and manipulation tasks are executed via reach and are ballistic in nature [73]. Rapid reaches to targets are characterized by a fast ballistic phase and then a much smaller and slower corrective phase. Past work has shown that the most accurate way to measure distance perception via rapid reaches is to use the end point of the fast ballistic phase [4]. In such scenarios, users most often reach guided by visual information, and at other times using peripheral vision or no vision while reaching [67]. Therefore, a comparative investigation of reach motions, examining the properties and characteristics of reaches, in the Real World (RW) as well as the IVE and in the presence or absence of vision and/or haptic feedback is important in understanding the characteristics of human motions under different interaction circumstances. As shown by many studies, the

visual perceptual characteristics in VR are limited compared to the real world [40]. It is not well understood how these limitations affect reaching motions during 3D interaction in the IVE.

3. *Study the impact of anthropometric fidelity of self-avatar on spatial perception in action space in IVEs.* Recent perception research suggests the presence of avatars influence how users perceive and interact with their surroundings [24, 70, 81]. Virtual self-avatars are life-size visual representations of the user, seen from a first-person perspective and co-located with users' actual body. Presence of a self-avatar has been shown to have an effect on users' spatial perception in medium field in IVEs [48, 37, 79]. Furthermore, visual fidelity of self-avatar could also alter the users' spatial perception in IVEs [60]. Previous studies found the present of even a static self-avatar in the environment improved distance judgment via blind walking [59, 48]. A less informative representation of the body, such as displaying the joint positions only in real world, shown to be sufficient on perceiving different human activities and also estimating distance [28, 63]. However, it is not well understood how the visual fidelity of self-avatars affects the perception of ones' environment in VR. In these previous studies, the self-avatar is mainly used to provide a sense of presence and was not involved in the calibration phase or the user's responses. Also, the perception of self-representation is only studied in medium distance and less is known about the impact of animation fidelity on spatial perception in action space in IVE. Thus, we explore how the anthropometric characteristics of the arm and hand during 3D interaction affect users' near-field depth perception in IVEs.

Chapter 2

Related Work

The space around us can be categorized into three main regions: personal space (near field), action space (medium field), and vista space (far field) [14]. In general, personal space is the area within a typical user's arm reach, action space is beyond personal space up to roughly 30m, and vista space is considered all further distances. Previous research in action space has shown that distances can be quite accurately estimated in the *Real World* (RW) at up to 20m, while these are mostly underestimated in *Virtual Environments* (VEs) [40, 80, 57, 74]. Similarly, distance estimation is distorted but overestimated in personal space (or near field) in VEs as compared to the real world [17, 62] which may have implications on physical reaching behavior of participants in the near field. Willemsen et al. [77] illustrated that the mechanical properties of the HMD can potentially contribute to distance underestimation as measured using blind walking. However, Grechkin et al. [23] pointed out that mechanical properties of the HMD cannot be the only reason for the distance underestimation in VE. Grechkin et al. [23] compared RW viewing, both with and without an HMD, to four VR presentations; i) virtual world in HMD, ii) *Augmented Reality* (AR) in HMD, iii) virtual world in *Large Screen Immersive Display* (LSID) and iv) photorealistic virtual world in LSID. They also found that underestimation occurred in all VE conditions, although the magnitude of the errors varied substantially. In another study, Witmer and Kline [80] demonstrated that users underestimated distances in both the RW and a VE with underestimation in VE being more pronounced. They also pointed out that traversing distances in VE reduced the overall underestimation which could be due to the fact of taking an action in VE.

Ongoing perception is an inherent component of the normal action-perception cycle. Actions

influences perception which then effects how we interact with the world or change our view of it [76]. Generally, action impacts the way we perceive the third-dimension or depth perception. Some previous work studied the effect of the potential effort required to complete a task and its effect on perceiving the environment. Proffitt et al. [54] showed that wearing a heavy backpack caused distance overestimation. In another study Willemsen et al. [77] found distance underestimation that could partially be explained by the weight and forces from the HMD during the walking task. Also, the perceived distance is affected by action capabilities of the body [36]. For instance, Linkenauger et al. [36] showed that the tool orientation and its easiness to grasp had influenced the perceived closeness and reachability of the tool. The removal of perceptual feedback is a perturbation that adversely effects the performance of actions [4].

The action-perception cycle also has an effect on overcoming the perturbations of visual distance and direction through continuous calibration [3, 6, 82]. The rate of calibration (aka adaptation) has been shown to be constant despite the immediate calibration wearing displacement prisms [3]. Ziemer et al. [82] showed that participants calibrate to a perturbed visual information or walking speed in either real world or IVE using blindfolded walking technique. Additionally, their results indicate that with imagined walking technique, calibration has an effect only when visual information was distorted. In contrary, Nguyen et al. [50] found distance judgments were unaffected even by a significant scaling of the surrounding environment in IVE in action space. Similar to Bingham and Pagano [4], Bourgeois and Coello [6] showed that the calibration occurred in the first few trials when a new shift to visual feedback was introduced in near-field space. Their results indicates that spatial perception can be modified by motor experience with a few interactions with perturbed environment, which cause adaptation to the new visuo-motor constraints in the real world.

Overall, there is a large amount of work that focuses on visuo-motor recalibration through closed-loop interactions in real world [61, 4] as well as in VE's [47, 33]. To overcome the problem of seeing the world as compressed in VR, some suggested that users' interactions with the environment could potentially change distance estimation in relatively short amount of time [57, 1, 30, 29]. In another study, Kelly et al. [30] showed that only five closed-loop interactions with an IVE significantly improved participants' distance estimates. The result of their study also indicated that the improvements plateaued after a small number of interactions over a fixed range of distances. Much of the work investigating visuo-motor calibration has used open-loop distance judgments with no vision of the target, such as blind walking and blind reaching. Some other techniques such as

imagined timed-walking, bean bag throwing, triangulated walking, and verbal report were also used to measure the egocentric distance judgments in IVEs [56]. For instance, Kunz et al. [34] compared blind-walking and verbal report. They showed there was no significant difference between a low and high quality VE using blind-walking whereas there was a significant difference using verbal report. Similar to Milner and Goodale [46], they suggested that verbal report and action-based responses use different neurological streams and may involve two distinct perceptual processes [49, 52, 20]. Overall, all these studies found that verbal judgments were more variable, less accurate, and subject to systematic distortions that were not evident in action responses [53, 51]. For instance, Pagano and Isenhower [53] compared verbal report and reaching responses for egocentric distance judgments. They characterized the verbal reports to be more indicative of relative distance perception whereas reaching responses were more indicative of a absolute distance perception. Thus an immediate, action based response that uses physical reach is mainly employed in investigating distance perception via visuo-motor calibration.

The kinesthetic and proprioceptive cues are a part of visuo-motor system that enhance our awareness of our end effectors (hand and feet) to walk, reach or grab objects even without vision. However, sometimes the link between the kinesthetic and visual information is broken in IVEs. Consequently, performance is affected by this mismatch [64]. Hence, many studies have examined users' performance in action space by studying the time and speed of the motion trajectories of the participants' movements to better characterize their behaviors in IVEs [64, 11, 9]. Similarly, in VR applications, such as rehabilitation [16] and surgical training simulations [68], the physical movements play an important role in the user experience and the user interaction with the IVEs. However, in some of these areas, an accurate visual representation of the hand movements in IVEs is crucial and could influence the educational and training outcomes of the simulation. This visual representation of hand movement can be through use of a stylus or an avatar. Altenhoff et al. [1] studied the effect of visual and tactile feedback on depth perception in IVE via a stylus representation of the hand movements. Ries et al. [59] and Mohler et al. [48] showed that even a static self-avatar in the environment improved distance judgment via blind walking.

Generally, self-avatars are used to give the sense of presence to the users in IVE. Previous work has demonstrated the body ownership illusion in the presence of specific types of synchronous multi-sensory and sensorimotor simulation [72, 71]. For instance, by having a visual-tactile synchrony, Slater et al. showed that the rubber hand illusion could be replicated in virtual reality

[71]. In their experiment, they hid the real arm and showed a virtual arm to the participants in a large screen display. Then they either provided a synchronous or asynchronous visual and tactile stimulus to the participants. Their results indicate that the visual-tactile synchrony is important in virtual reality application especially for those which require some kind of interaction with the virtual environment. Embodiment could also be induced through first-person viewpoint of the virtual body where there is a visuo-motor synchrony between the real body and virtual representation [2, 42].

Despite the importance of self-avatars in IVE, only a few studies have looked at its effect on user's spatial perception. Mohler et al. [48] explored the effect of articulated self-avatar on absolute egocentric distances in medium space in an IVE. They found participants made more accurate judgments in tracked self-avatar condition as compared to static and no avatar conditions. In another study, Lok et al. [37] compared object handling in read world, virtual world and a hybrid environment via a self-avatar. They found no effect on the sense of presence between different self-avatar conditions. Williams et al. [79] also looked at the presence of self-avatar on distance judgments in medium distance in IVE. They found that participants' distance judgment became more accurate when the self-avatar was present for distances smaller than 3m. They observed an significant underestimation for distance greater than 7.5m. Overall, the presence of self-avatar has been shown to have an effect on user's spatial perception. However, to what extent it affects the user's spatial perception in near field in IVE is not well understood.

Another body of research has looked at the visual fidelity of avatars in IVE. Volante et al. [75] investigated the effect of the visual fidelity of the avatar on users' behavioral and emotional responses. They showed that users in visually realistic avatar condition expressed more of the expected emotion towards the avatar as compare to non-photo-realistic conditions. In another study, Lok et al. [37] compared the real world avatar hand with the virtual and a hybrid representation of it and found no significant effect between the conditions. Regarding virtual humans in IVE, McDonnel et al. [43] found that more realistic avatars can be even more disturbing to the users as compared to less realistic avatars due to the uncanny valley effect. However, there has been no evidence of this phenomenon regarding self-avatars. In another study, Lin and Jörg [35] showed participants responded to threats in all the conditions from realistic hand to non-anthropomorphic block model. However, the users' responses were strongest in the realistic hand condition and weakest in the wooden block model condition. They concluded that synchronize movements of the avatar hand with the real hand was one of the main factors on inducing the sense of presence and the ownership of the virtual hand.

Similarly, Ma and Hommel [41] evaluated the hand ownership illusion in situations involving an active operation of the end effector. They found an enhancement on the impression of the hand ownership when coupled with the real hand movements. Similarly, Ries et al. [60] investigated the effect of self-avatar visual fidelity on users' spatial perception via direct blind walking. They provided users with either a fully tracked, high-fidelity self-avatar or a fully tracked but simplified self-avatar (only the tracking marker locations were presented using small spheres). They then compared their results with no avatar condition and found that participants with low-fidelity avatars showed greater improvement on medium field distance estimation as compared to no avatar. However, participants' distance estimation with a high-fidelity avatar was significantly more accurate than the low-fidelity and no avatar conditions. They concluded that a minimal level of avatar visual fidelity may be required to improve users' distance judgments. Overall, the visual fidelity or the rendering style of the avatar and the active operation of the self-avatars have been extensively studied over the last few year in IVE. However, it is less known about the effect of the visual fidelity of the self-avatar on user's spatial perception in near field in IVE.

Runeson and Frykholm [63] studied the effect of the real-world joint position representation on medium field distance estimation. They attached retroreflective material to the ankles, knees, wrists, elbows, hips, shoulders, and forehead of two actors. They then recorded the throwing action of those actors towards 6 target distances at various locations from 1.75 m to 8 m. Runeson and Frykholm demonstrated that by showing the joint positions only to the participants, the participants could accurately estimate the distance from the actor to the targets. Based on Runeson [63], we created a low-fidelity self-avatar viewing condition in which the main joints[1] were illustrated using blue spheres. The radius of each of the spheres representing the joints was extracted from the Anthropometric source book [12] to create custom low-fidelity self-avatars. The use of this low-fidelity self-avatar was compared to two other conditions; the use of a faithful high-fidelity self-avatar and the rendering of only the end-effector at the hand. The same inverse kinematic system was employed in all three conditions to calculate the position of the joints with HTC Vive trackers to accurately track user's upper body and arm motion (figure 5.2).

Most of the previous research investigating the effect of self-avatars in distance perception was conducted in medium field, where distance is estimated via blind walking. The main visual contributors during walking are the eye level and a fixation point on the ground which is approxi-

[1]Illustrated joints are: ankles, knees, wrists, elbows, hips, shoulders, neck and forehead

mately two steps ahead [21]. Unlike medium field, the primary distance perception task in near field is reaching, which has different affordances. The two main visual contributors in on-line control of hand movements while reaching are a) the position of the hand and b) the hand motion [65]. Generally, walking and reaching use two distinct mechanisms which can affect distance estimation quite differently in the presence of the self-avatars. It has been shown that reaches become more accurate when users can see their arm while reaching in the real-world [55, 25]. McManus et al. [44] showed that the users' performance in terms of accuracy and time to complete was improved in the presence of self-avatars when users could interact with the environment. Moreover, it is not well understood if the anthropometric similarity of self-avatar with its real-world representation has any effect on users' distance estimation via reaching tasks in IVE. Additionally, the presence of self-avatar and its visual fidelity may have a greater impact on users' distance estimation in reaching activities when the fixation point is at the end-effector (hand) as compared to walking tasks as the fixation point is somewhere in front of legs [21, 65]. Data regarding the alteration of depth perception measured via pre- and post-test phases straddling a calibration phase in which users receive information from their self-avatar regarding their activates in VR is missing. Also, the perception of self-representation is mostly studied in medium field distance and less is known about the impact of visual fidelity of self-avatar on space perception in near-field in IVEs.

Chapter 3

Effects of Visual and Proprioceptive Information in Visuo-Motor Calibration

It has been suggested that closed-loop feedback of travel and locomotion in an *Immersive Virtual Environment* (IVE) can overcome compression of visually perceived depth in medium field distances in the virtual world [33, 47]. However, very few experiments have examined in IVEs the carryover effects of multisensory feedback during manual dexterous 3D user interaction in overcoming distortions in near-field or interaction space depth perception, and the relative importance of visual and proprioceptive information in calibrating users distance judgments. In the following experiment, we investigated carryover effects of calibration to inaccurate visual feedback, with participants making reach estimates to near-field targets in the IVE. There were three conditions of perturbed visual feedback in an IVE. These perturbations were such that the participants' reach estimates were scaled to appear 20% closer to the viewer than the actual physical location of the estimate (*Minus condition*), veridical with no scaling (*Neutral condition*), or 20% farther from the participant reaches (*Plus condition*). To test for calibration, a baseline measure in an IVE in which participants complete distance estimates without feedback will be compared to IVE estimates made after visual feedback was provided. *It is hypothesized that participants whose reach appeared 20% closer during the calibration session will believe they are under-reaching, and thus will reach farther*

after the calibration. It is also hypothesized that participants who view their reach to be 20% farther during the calibration session will believe they are overreaching, and thus will reach shorter after the calibration. Similarly, during closed-loop physical reach responses, we expect that participants to physically reach farther in Minus condition and closer in Plus condition to the perceived location of the targets, as compared to Neutral condition in which participants' physical reach is expected to be more accurate to the perceived location of the target. These perturbations will be explained in detail in the experiment methodology section. In our experiment, distance judgments were measured using physical reach responses to targets in an IVE. We specifically examined the end of the ballistic reach phase in order to ascertain the perceived depth judgments.

Research Questions:

I Are users' reach responses in post-test (open-loop) affected by the calibration phase in the near field in IVE?

II Do users scale their depth judgments to visual and proprioceptive information during 3D interactions in the near field?

III How do users improve their near field distance judgments during (closed-loop) visual feedback in the IVE?

IV To what extent are users' distance judgments affected by mismatch in visual and proprioceptive information during closed-loop interaction in the IVE?

V Does closed-loop interaction in an IVE cause continuous improvement in distance estimation over time?

3.1 Experiment Methodology

3.1.1 Participants

36 participants (26 female, 10 male) were recruited from the student population of Clemson University and received course credit for their participation. The participants' handedness was recorded. All participants in this experiment were right handed. All participants were tested for visual acuity and performed a stereoacuity using the Titmus Fly Stereotest. All participants provided informed consent.

3.1.2 General Setup

Figure 3.1 shows the experimental apparatus used for this experiment. Participants were asked to sit on a wooden chair to which their shoulders were loosely tied. This was done to serve as a gentle reminder for them to keep their shoulders in the chair during the experiment. Otherwise, they had the full control of their head and arms. Participants reached with a tracked wooden stylus that was 26.5cm long, 0.9cm in diameter, and weighing 65g. All users were asked to hold the stylus in their right hand in such a way that it extended approximately 3cm above and 12cm below their closed fist. Each trial began with the back end of the stylus inserted in a 0.5cm groove on top of the launch platform, which was located next to the participant's right hip.

The target consisted of a groove that was 0.5cm deep, 8.0cm tall, and 1.2cm wide. The groove extended from the center of the base of a 8.0cm wide and 16cm tall white rectangle. The target was enclosed within a 0.5cm border made from thick, black tape. This was added to help participants to distinguish the target from the white background wall. Participants were required to match the stylus tip to the groove of the target during the experiment.

The target was placed at participants' eye level and midway between the participants' eyes and right shoulder in order to keep the distance from the eye to the target as close as possible to the distance from the shoulder to the target. The position of the target was adjusted by the experimenter using a 200cm wooden optical rail. The rail extended in depth along the floor and was parallel to the participants' viewing direction. The target was attached to the optical rail via an adjustable, hinged stand. To prevent any interference with the electromagnetic tracking system, the target, stand, stylus and optical rail were made of wood.

3.1.3 Visual aspects

An NVIS nVisor SX111 HMD weighing about 1.8kg was used for the experiment. The HMD contains two LCOS displays each with a resolution of 1280 x 1024 pixels for viewing a stereoscopic virtual environment. The field of view of the HMD was determined to be 102 degrees horizontal and 64 degrees vertical. The field of view was determined by rendering a carefully registered virtual model of a physical object (similar to [49]). The simulation used here consisted of the virtual model of the training room, experimental room and apparatus created using Blender. The virtual replica of the apparatus included target, stand, chair, tracking system, and stylus. A static virtual body

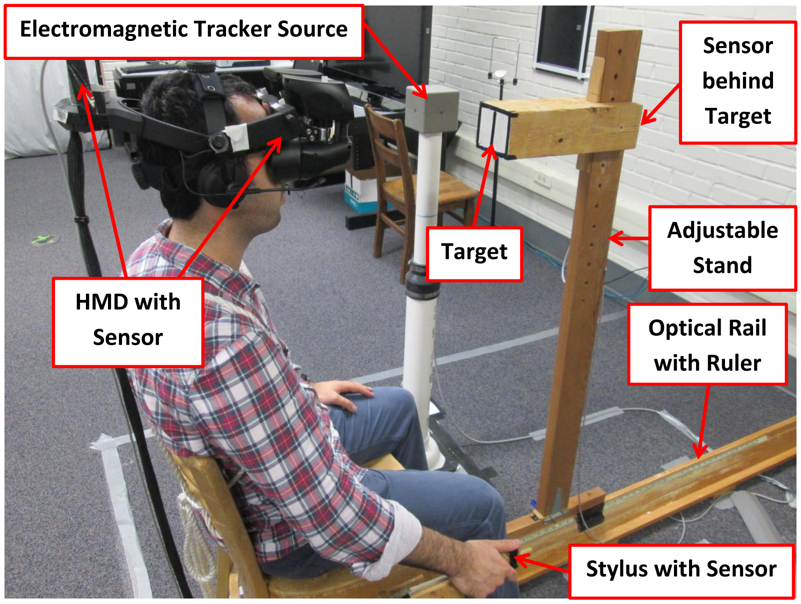

Figure 3.1: Shows the near-field distance estimation apparatus. The target, participant's head, and stylus are tracked in order to record actual and perceived distances of physical reach in the IVE.

seated on the chair was also presented to provide an egocentric representation of self whether the participant looked down [Figure 3.2].

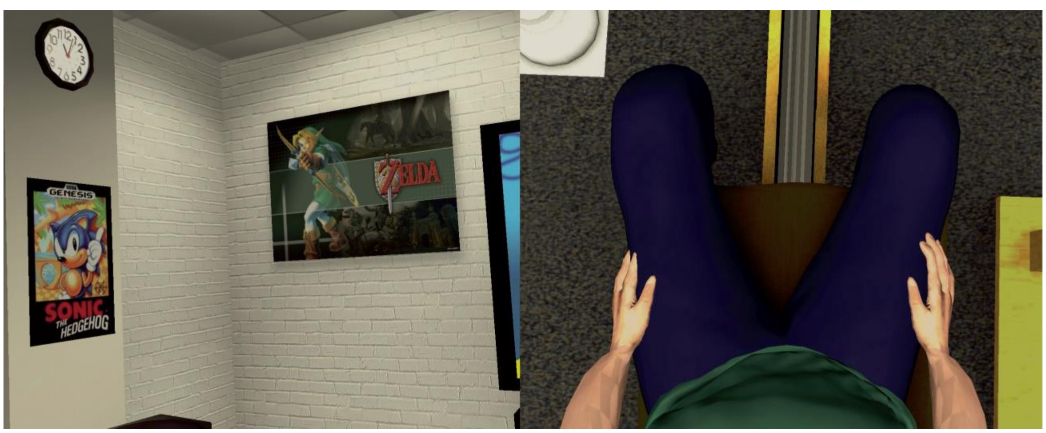

Figure 3.2: The left image shows a screenshot of the training environment from the participants first person perspective with HMD. The right image shows a screenshot of the avatar as seen from the participants perspective.

Since the haptic feedback was removed from the experiment, we designed our simulation so

that the stylus' tip would turn red when it was within a 1cm radius of target's groove. Figure 3.3 shows three screen shots of the virtual target and stylus. Based on the visual information provided to participants, they visually detected when the stylus intersected a groove in the target's face in the IVE.

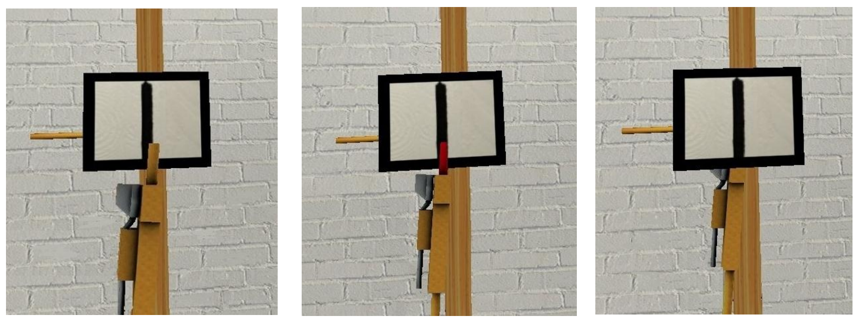

Figure 3.3: Image on the left shows a screen shot of the virtual target as perceived by participants in the IVE with the stylus in front of the target. Image on the middle shows that the tip of the stylus turned red when it was placed in the groove of the target, and on the right shows stylus passed the target. Participants received visual and proprioceptive feedback only when interacting with the target during closed-loop trials.

3.2 Procedure

Upon arrival, all participants completed a standard informed consent form and demographic survey. Participants were provided with documentation describing the experimental procedures after which their informed consent was acquired. All participants were tested for visual acuity of 20/40 or better using the Titmus Fly Stereotest when viewing an image with a disparity of 400 sec of arc. The interpupillary distance (IPD) was then measured using the mirror-based method described by Willemsen et al. [78]. Later, the measured IPD was used as a parameter for the experiment simulation to set the graphical inter-ocular distance, and the HMD was adjusted accordingly for each participant. Participants were instructed to sit straight up in a chair in a comfortable position. Participants' shoulders were then loosely strapped to the back of the chair to serve as a gentle reminder for them to keep their shoulders back in the chair during the experiment. Before measuring the participant's maximum arm reach, the physical target height was set to the participant's eye level. The participant's maximum arm reach was measured by adjusting the physical target so that

the participant could place the stylus in the groove of the target with their arm fully extended. However, this was performed without using the extension of their shoulder [1]. The maximum arm length was then used to generate target distances to be set during the experiment. Participants were instructed on how to make their physical reach judgments before putting on the HMD. They were asked to start each trial with the stylus in the dock next to their hip and reach to the virtual target with a fast, ballistic motion to where they believe the virtual target had been, and then adjust their initial reach by moving back and forth.

All participants started the experiment by viewing a training environment in IVE that was designed to help the participants acclimate to the viewing experience. Next, the participants were presented with a photorealistic virtual representation of the real room within which the experiment took place. The virtual room also included an accurate replica of the experimental apparatus. During testing, the participants performed 2 practice trials followed by 30 trials of blind reaching in the baseline or pretest session. Trials consisted of 5 random permutations of 6 target distances corresponding to 50, 58, 67, 75, 82, and 90 percent of participant's maximum arm length. For each trial, with the HMD display turned off, the target distance was adjusted using the physical target to which the sensor in attached. Then, vision was restored and virtual target was displayed. Once participants notified the experimenter that they were ready, the vision in the HMD was turned off via a key press to eliminate visual feedback in pretest and posttest sessions and stayed on in calibration session. In the open-loop blind reaching (pretest and posttest sessions), the physical target was then immediately retracted to prevent any collision between the participants' stylus and target. The tracked position of the stylus (hand), target, and head was logged over the duration of the experiment.

To reduce auditory cues to the target's position during preparation for the next trial, white noise was played in the participant's headphones. The initiation of the white noise was also used as a signal for the participants to return their hand to the stylus dock in preparation for the next trial. The next trial distance was then adjusted with the HMD display turned off in IVE conditions.

3.3 Tracking of Physical Reach

A 6 degree of freedom Polhemus Liberty electromagnetic tracking system was used to track the position, and orientation of the participants head, stylus, and target. Due to electromagnetic

tracking systems sensitivity to metallic objects in physical environment, the tracking system was calibrated to minimize the interference, which are described in detail in our previous works (See Napieralski et al. [49] and Altenhoff et al. [1]). The calibration step insured the tracking system was accurate to 0.1cm and 0.15 degree. Raw position and orientation values of the tracked sensors were logged in a text file for each participant. This data was later used to analyze the results of the experiment.

3.4 Experiment Design

The experiment consisted of three sessions: a baseline measure without feedback (pretest), a calibration session with visual feedback, and finally a post-interaction session without feedback (posttest). The experiment used a between subjects design where participants were randomly assigned to one of the three viewing conditions in the calibration session (Figure 3.4).

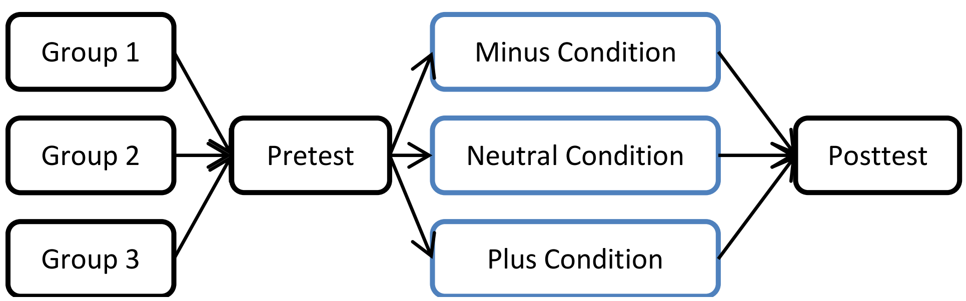

Figure 3.4: Experiment design.

In the pretest, participants performed 2 practice trials followed by 30 trials of blind reaching in the baseline pretest session. Trials consisted of 5 random permutations of 6 target distances corresponding to 50, 58, 67, 75, 82, and 90 percent of participant's maximum arm length. At least two days after the pretest was completed, participants completed 20 physical reaches in the IVE with visual feedback in the calibration session. Participants continued each reach until they successfully placed the virtual stylus into the virtual target's groove. The three viewing conditions for the calibration session were as follow:

- *Minus Condition*: -20% gain where the visual stylus appeared at 80% of the distance of the physical stylus.
- *Neutral Condition*: 0% gain, or no gain, where the visual stylus was co-located with the

physical stylus.

- *Plus Condition*: +20% gain where the visual stylus appeared at 120% of the distance of the physical stylus.

Figure 3.5 depicts the physical and virtual stylus in different conditions. Based on the participants' viewing condition and their maximum arm reach, they were provided with five random permutations of four target distances (a total of 20 trial distances.) For Minus viewing condition four target distances corresponding to 50, 58, 67, and 75 percent of the participant's maximum reach was displayed, for Neutral viewing condition four target distances corresponding to 58, 67, 75, and 82 percent of the participant's maximum reach was displayed, and for Plus viewing condition four target distances corresponding to 67, 75, 82, and 90 percent of the participant's maximum reach. Note that in Minus condition, the virtual stylus appeared to be closer to the participants; therefore, participants were expected to reach physically farther. Conversely, in Plus condition the virtual stylus appeared to be farther; therefore, participants were expected to reach physically closer. At the end of the session, some participants were asked to repeat particular trials if, for instance, they appeared to make a slow, calculated reach observed by experimenters.

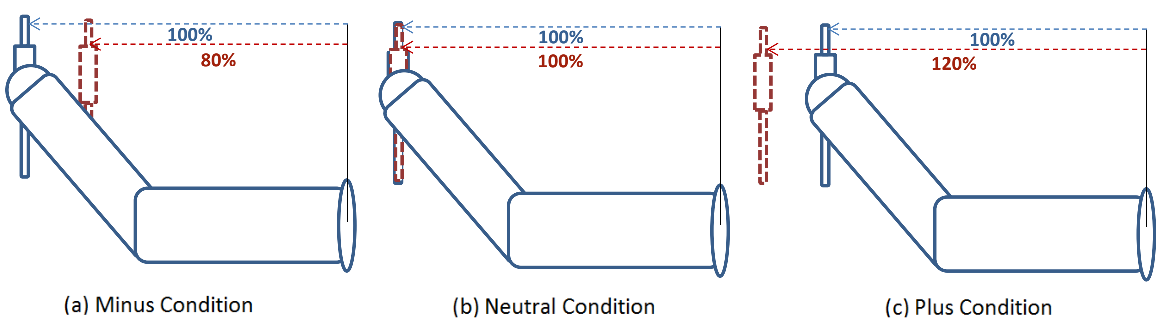

Figure 3.5: (a) Minus Condition: the virtual stylus (red lines) appears 20% closer than its physical position (blue lines). (b) Neutral Condition: physical (blue line) and virtual (red lines) stylus are co-located. (c) Plus Condition: the virtual stylus (red lines) appears 20% farther than its physical position (blue line).

Right after the calibration session, the participants performed the posttest session which was identical to the pretest session. In the posttest session, participants performed 30 open-loop perceptual judgments via physical reach to targets presented at similar distances as in the pretest, in order to assess the carryover effects of calibration on depth perception when compared to the baseline pretest session. The target face, stylus tip, head and eye plane locations were tracked and

logged by the experiment simulation, which was pulled from the electromagnetic tracking system during the course of the experiment. The end of the ballistic reaches were then extracted from the raw data using the method described in Section 3.5.

3.5 Data Preprocessing

Rapid reaches to targets were characterized by a fast ballistic phase and then a much smaller and slower corrective phase. Past work has shown that the most accurate way to measure near field perceptual-motor target depth judgments is via rapid reaches and to use the end point of fast ballistic phase [4, 3, 51, 52, 53]. To be able to extract the end of the ballistic reaches, we used following methods:

1. The target face, stylus tip, head and eye plane locations were tracked and logged by the experiment simulation, which was pulled from the electromagnetic tracking system during the course of the experiment. Using an after action review visualizer, the participants' actions were replayed from the log file data, and the experimenter coded the approximate location of the ballistic reach in the visualizer. In this manner the visualizer was used to code the end of the ballistic reaches for each trial from each participant's data log. Figure 3.6 shows a screen shot of the visualizer.

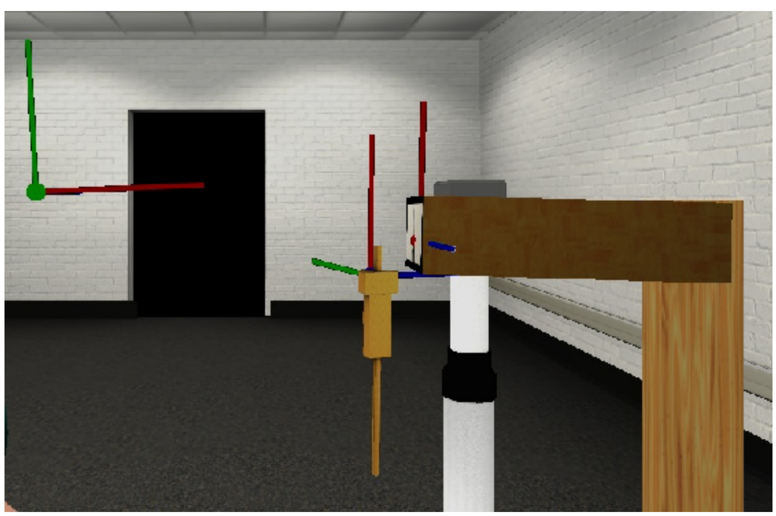

Figure 3.6: A screen shot of the visualizer that was used to tag the approximate location of the end of the ballistic reach. In this image, the coordinate system attached to the stylus, target, and user's eye centered point also can be seen.

2. We extracted the end of the ballistic reach by analyzing the XY position trajectories and speed profile associated with the physical reach motions. To do so, the end of the forward trajectory (motion toward the target) was tagged as a baseline for the end of the ballistic reach. Then, all the tagged data points from XY trajectories were embedded in the speed profile to be used to pick the end of the ballistic reaches. Figure 3.7-Left is an example of an XY trajectory. The blue line represents the forward motion (reach phase) and the red line represents the backward motions (retraction phase) of the stylus, as the participant reached to make a perceptual judgment. The black square is the tagged data point denoting the end of the ballistic reach. The speed (XYZ) and the velocity in all 3 dimensions (X, Y and Z) of the tracked stylus for each trial were also plotted in a separate window. The speed profile was rendered as a blue line. Figure 3.7-Right shows a full view of the speed and velocity profiles for a single trial. The time instance at the end of the ballistic reach, extracted from the previous step, was also denoted in these plots as a magenta line. This line provided an estimate based on the XY trajectory graph as to the location of the end of the ballistic reach, and was then visually confirmed by examining the speed and velocity profiles generated in this step. The end of the ballistic reach was chosen by the experimenter examining the speed profile as the first time instance when the speed reaches a local minima below a threshold of 20 cm/s, immediately after attaining peak speed caused by the forward motion of the stylus. After tagging the speed profile, the data from all the other sensors were automatically extracted based on the temporal information gathered from the previous step in coding the end of the ballistic reach.

3.6 Results

3.6.1 Comparing Pretest and Posttest

The average slopes and intercepts of the functions predicting indicated target distance from actual target distance in the pretest and posttest sessions for the Minus, Neutral and Plus conditions are presented in Table 3.1. Our analyses will proceed in two steps: first, we will test for calibration to determine if the participants' performance improved as a function of the feedback received during the calibration session. This will be evidenced by an increase in r^2 and a change in slope and intercept when comparing the pretest and posttest regressions presented in Table 3.1. Given that perfect

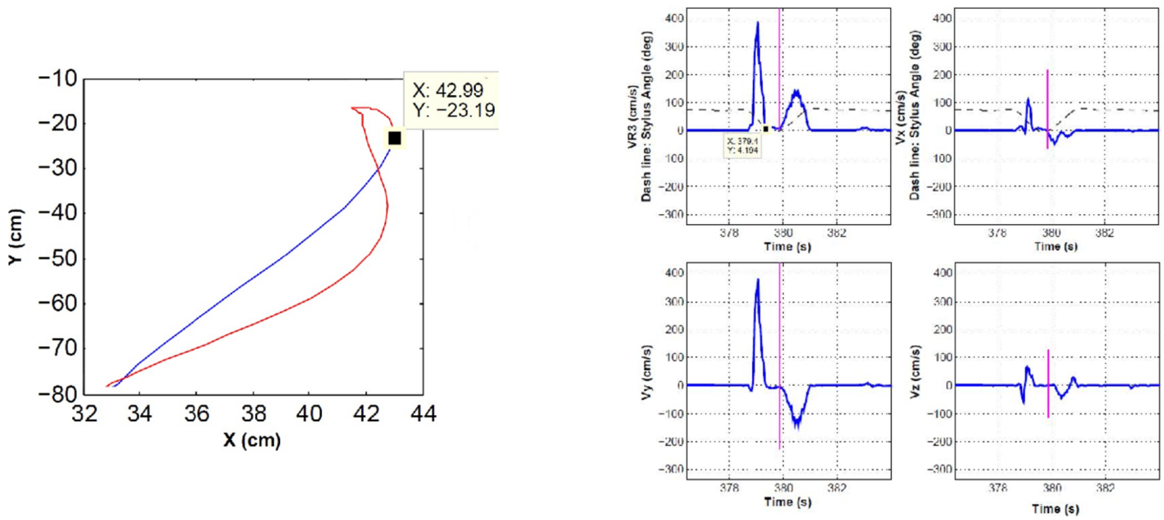

Figure 3.7: **Left**: An example of XY trajectory for a single trial. The black square is the tagged data point denoting the end of the ballistic reach. **Right**: An example of speed and velocity profiles (solid blue line). The magenta line denotes the time instance at the end of the ballistic reach which was initially extracted from XY trajectory.

performance would be r^2 = 1.0, slope = 1.0, and intercept = 0, an improvement in performance would be given by a significant increase in r^2, slope values moving closer to 1.0, and intercept values moving closer to 0. Second, we will test for a different effect of calibration as a function of the calibration condition (Minus, Neutral and Plus). This will be evidenced by comparing the slopes and intercepts of the regressions between Table 3.1, thus comparing the different calibration conditions to each other.

Examination of Table 3.1 reveals that across all three conditions, the r^2 values tended to be higher in the posttest session compared to the pretest session. A paired t-test using the combined r^2 values from all three conditions confirmed that this increase was statistically significant, indicating that the intervening calibration session tended to cause the participants' reaches to become more strongly based on the target distances; t (34) = -7.2, $p < .0001$. The slopes of the simple regressions tended to increase in the posttest session compared to the pretest session, moving more closely to 1.0, and the intercepts decreased, moving more closely to 0. Paired t-tests using the combined r^2 values from all three conditions confirmed that this increase was statistically significant; t (34) = -5.8, $p < .0001$, for the slopes, and t (34) = 7.3, $p < .0001$, for the intercepts. In short, the results revealed an increase in the r^2 values and improvements in both slope and intercept, indicating a calibration effect that is characterized by an improved scaling of the reaches to the actual target

distances.

Next, multiple regression techniques were used to determine if the slopes and intercepts differed between the pretest and posttest sessions within each of the calibration conditions. Multiple regression analyses are preferable to ANOVAs and t-tests because they allow us to predict a continuous dependent variable (indicated target distances) from both a continuous independent variable (actual target distances) and a categorical variable (session) along with the interaction of these two variables (e.g., [4, 51, 52, 53]). Also, the slopes and intercepts given by regression techniques are more useful than other descriptive statistics such as session means and signed error because they describe the function that takes us from the actual target distances to the perceived target distances. For these multiple regressions, and for those reported later to compare the different calibration conditions to each other, we omitted from the analysis the data from any session where and individual participant failed to produce a statistically significant r^2 ($p > .05$), which consisted of r^2 values of .14 and below. Thus the pretest data was not used for 6 participants, and the posttest data was not used for 1 participant. At this stage of the analysis we wished to compare performance where participants were reaching with a minimal level of proficiency. Note that when the r^2 is not statistically significant, the slope and intercept values become meaningless. Thus these non-significant participant sessions were not included in the average values presented in Table 3.1. Also, data from Participant 3 was not included in the data analysis due to technical difficulties.

Table 3.1: Average R^2, Slopes, and Intercepts of Simple Regressions Predicting Reach Distance from Actual Distance (cm) for Each Participant in the Minus, Neutral and Plus conditions (*Intercept)

	Pretest			**Posttest**		
	r2	**Slope**	**Intp.***	**r2**	**Slope**	**Intp.***
Minus	0.53	0.47	29	0.72	0.65	19.1
Neutral	0.46	0.49	25.4	0.68	0.67	12.8
Plus	0.54	0.53	25.2	0.68	0.65	12.4

3.6.1.1 Minus Condition

Overall, the r^2 for the regressions predicting the reached distances from the actual distances were .53 and .72 for pretest and posttest sessions, respectively, the slopes were .44 and .65, and the intercepts were 30.7 and 19.1 (cm). Figure 3.8.a depicts the relation between actual target distance and the distances reported via reaches for the pretest and posttest sessions. Each point in Figure 3.8.a

represents reach estimation made by an individual subject to a given target distance. A multiple regression confirmed that the reaches made in the pretest were different from the reaches made in the posttest. To test for differences between the slopes and intercepts of the two different viewing sessions, this multiple regression was performed using the actual target distances and viewing session (coded orthogonally) to predict the reach distances. The multiple regression was first performed with an actual target distance X session interaction term, yielding an $r^2 = .59$ (n = 685), with a partial F of 885.6 for actual target distance ($p < .0001$). The partial F for the session was 9.9 ($p = .002$) and the interaction term was 4.1 ($p < .05$), with the partial F for the session increasing to 56.8 ($p < .0001$) after the removal of the interaction term.

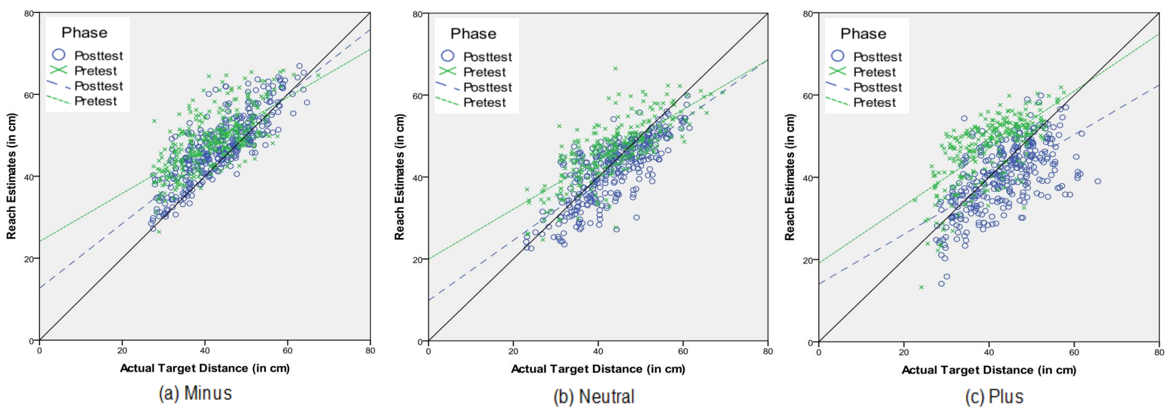

Figure 3.8: Reaches as a function of actual target distances in the pretest and posttest sessions for (a) Minus condition, (b) Neural condition, and (c) Plus condition.

Put simply, the partial F for actual target distance assesses the degree to which the actual target distances predict the variation in the responses after the variation due to the other terms (session and the interaction) had already been accounted for. Thus, the partial F for actual target distance tests for a main effect of actual target distance. The partial F for the session assesses the degree to which the intercepts for the two sessions differ from each other and thus test for a main effect of the session. The partial F for the interaction term assesses the degree to which the slopes for the two sessions differ from each other. Thus, the multiple regression revealed a statistically significant main effect for actual target distance, a main effect for the session, as well as an interaction. Therefore, the slopes of the functions predicting reached distance from actual distance and the intercepts differed for the two sessions.

3.6.1.2 Neutral Condition

Overall, the r^2 for the regressions predicting the reached distances from the actual distances were .46 and .68 for pretest and posttest sessions, respectively, the slopes were .38 and .61, and the intercepts were 30.5 and 15.4 (cm). Figure 3.8.b depicts the relation between actual target distance and the distances reported via reaches for the two sessions. Each point in Figure 3.8.b represents reach estimation made by an individual subject to a given target distance. A multiple regression confirmed that the reaches made in the pretest were different from the reaches made in the posttest. To test for differences between the slopes and intercepts of the two different sessions, this multiple regression was performed as the analysis for the plus condition, using the actual target distances and session (coded orthogonally) to predict the reach distances. The multiple regression yielded an $r^2 =$ .63 (n = 594), with a partial F of 840.3 for actual target distance ($p < .0001$), with the interaction term included. The partial F for the session was 25.4 ($p < .0001$), and the interaction term 9.8 ($p < .01$), with the partial F for the session increasing to 132.2 ($p < .0001$) after the removal of the interaction term. Thus, the multiple regression revealed a statistically significant main effect for actual target distance, a main effect for the session (reaches made in the pretest vs. reaches made in the posttest), as well as an interaction.

3.6.1.3 Plus Condition

Overall, the r^2 for the regressions predicting the reached distances from the actual distances were .54 and .68 for pretest and posttest sessions, respectively, the slopes were .45 and .65, and the intercepts were 29.6 and 12.4 (cm). Figure 3.8.c depicts the relation between actual target distance and the distances reported via reaches for the two sessions, with each point representing reach estimation made by an individual subject to a given target distance.

A multiple regression confirmed that the reaches made in the pretest were different from the reaches made in the posttest. To test for differences between the slopes and intercepts of the two different sessions, this multiple regression was performed as the analyses for the Minus and Neutral conditions, using the actual target distances and session (coded orthogonally) to predict the reach distances. The multiple regression yielded an $r^2 = .51$ (n = 599), with a partial F of 422.5 for actual target distance ($p < .0001$), with the interaction term included. The partial F for the session was 24.8 ($p < .0001$), although the interaction term was not significant ($p > .05$), with the partial F

for the session increasing to 314 ($p < .0001$) after the removal of the interaction term. Thus, the multiple regression revealed a statistically significant main effect for actual target distance, a main effect for the session (reaches made in the pretest vs. reaches made in the posttest), although no interaction.

In sum, reaches improved after calibration in all 3 conditions. For the multiple regressions the r^2 for the Plus and Neutral conditions increased, the intercept lowered to become closer to zero, and the slope increased to become closer to 1. For the Plus condition the r^2 increased and the intercept lowered to become closer to zero. The slope increased in the Plus condition to become closer to 1, but this failed to reach statistical significance. The multiple regressions, however, were a very conservative test of the hypothesis because they only assessed the improvement of performance after the worst performing participant sessions were removed from the data set. The fact that 6 participant sessions were removed from the pretest for lack of significant simple regressions while only 1 was removed from the posttest is itself a measure of improved performance. The purpose of the multiple regressions was to separately compare the changes in the average slopes and intercepts for each calibration condition presented in Table 3.1, which only include the statistically significant simple regressions. The t-tests, however, included all of the participant data, and thus they compare the 36 individual slopes, intercepts and r^2 values, combining the data from the three calibration conditions. The t-tests for all three of these variables confirmed an increase in the r^2 values and improvements in both slope and intercept, indicating calibration, which is characterized by an improved scaling of the reaches to the actual target distances.

Our findings suggest that participants generally overestimated distances when reaching to the perceived location of the target without visual guidance. The tendency towards overestimation of reached distance observed in this study is consistent with a similar pattern observed by Rolland et al. [1995] in AR. However, others have reported underestimation when performing similar tasks [Altenhoff et al. 2012; Singh et al. 2010; Napieralski et al. 2011]. The explanation for these diverse results is still unclear and necessitates future research.

3.6.2 Comparing Calibration Conditions (Pretest)

Next, the three conditions within each of the two sessions were compared (see Figure 3.9). In the pretest the slopes of the functions predicting indicated target distance from actual target distance were .47, .49, and .53 for the Minus, Neutral, and Plus conditions, respectively. The intercepts were

29.0, 25.4, and 25.2 (cm), respectively. Multiple regression analyses were conducted for each pairing of conditions (Plus & Minus, Plus & Neutral, and Neutral & Minus).

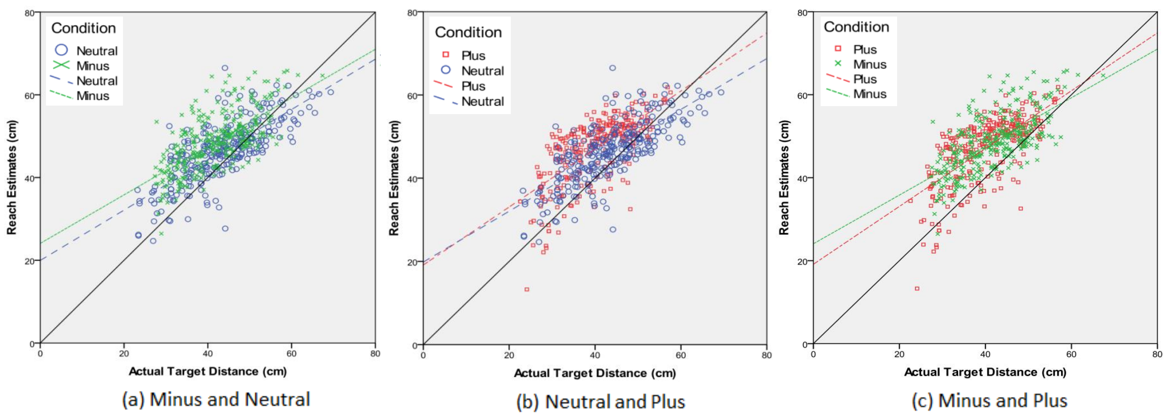

Figure 3.9: Reach estimates in (a) Minus and Neutral conditions, (b) Neutral and Plus conditions and (c) Minus and Plus conditions as a function of the actual target distances for the pretest.

3.6.2.1 Minus and Neutral Conditions

A multiple regression predicting the judgments from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an $r^2 = .522$ (n = 592), with partial F of 612.7 for actual target distance ($p < .0001$), and non-significant partial F for condition and the interaction term ($p > .05$), with the partial F for condition increasing to 59.5. ($p < .0001$) after the removal of the interaction term. Overall, as the actual distances increased, reaches increased at the same rate in the Minus and Neutral conditions, although intercepts differed. A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.471$ (n = 593), indicating that the difference between estimates in the pretests of these conditions accounted for 4.8% of the variance in the responses while actual target distance accounted for 47.1%.

3.6.2.2 Neutral and Plus Conditions

A multiple regression predicting the judgments from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an $r^2 = .522$ (n = 536), with the partial Fs of 574.6 for actual target distance ($p < .0001$), 8.7 for condition ($p < .01$), and 16.0 for the interaction ($p < .0001$). Overall, as the actual distances increased, reaches increased faster in Plus condition than Neutral condition. A simple regression predicting

indicated target distance from actual target distance resulted in an $r^2 = 0.474$ (n = 537), indicating that the difference between estimates in the pretests of these conditions accounted for only 3.4% of the variance in the responses, while actual target distance accounted for 47.4%.

3.6.2.3 Minus and Plus Conditions

A multiple regression predicting the judgments from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an $r^2 = .461$ (n = 595), with the partial Fs of 489 for actual target distance ($p < .0001$), 5.4 for condition ($p = .021$) and 4.8 (p = .028) for the interaction term. However, the partial F for Condition fell to 0.9 (p = .343) after the removal of the interaction term. A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.456$ (n = 595), indicating that the difference between estimates in the pretests of Minus and Plus conditions accounted for only 0.1% of the variance in the responses. Thus, while differences between the two conditions were statistically significant, the actual amount of variance accounted for by differences in the two conditions was very small.

3.6.3 Comparing Calibration Conditions (Posttest)

Next, the three conditions within the posttest session were compared (see Figure 3.10). In the posttests, the slopes of the functions predicting indicated target distance from actual target distance were .65, .67, and .67 for the Minus, Neutral, and Plus conditions, respectively. The intercepts were 19.1, 12.8, and 12.4 (in cm), respectively. Multiple regression analyses were conducted for each pairing of conditions (Plus & Minus, Plus & Neutral, and Neutral & Minus).

3.6.3.1 Minus and Neutral Conditions

A multiple regression predicting the judgments from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an $r^2 = .686$ (n = 687), with a partial F of 1,266.1 for actual target distance ($p < .0001$) and a non-significant interaction term. With the interaction removed the partial F for condition was 219.8 ($p < .0001$). A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.584$ (n = 687), indicating that the difference between estimates in the posttests of these conditions accounted for 10.1% of the variance in the responses, 5.3% greater than in the pretest condition.

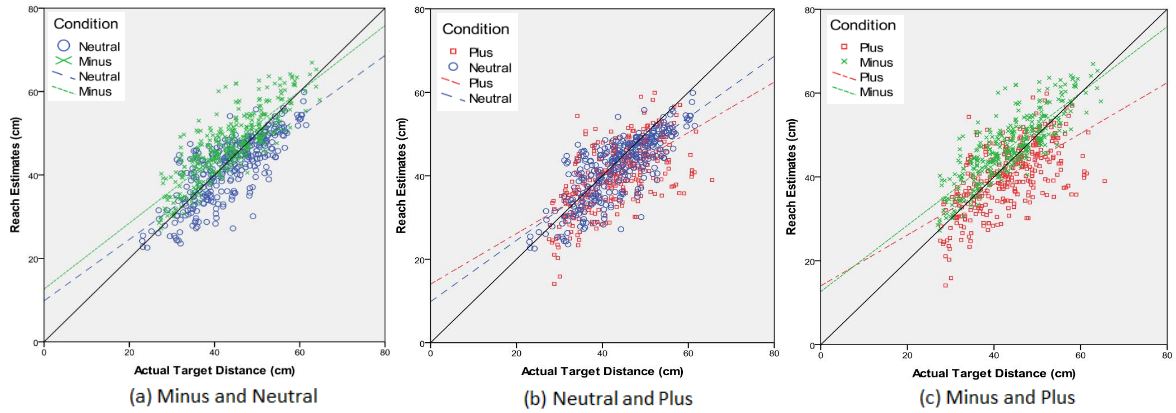

Figure 3.10: Reach estimates in (a) Minus and Neutral conditions, (b) Neutral and Plus conditions and (c) Minus and Plus conditions as a function of the actual target distances for the posttest.

Overall, the participants tended to reach farther in the minus condition, where the hand-held stylus appeared closer to the body.

3.6.3.2 Neutral and Plus Conditions

A multiple regression predicting the judgments from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an r^2 = .503 (n = 656), with partial Fs of 642.5 for actual target distance ($p < .0001$), 12.1 for condition ($p < .01$) and 8.5 ($p < .01$) for the interaction term. A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.488$ (n = 656), indicating that the difference between estimates in the posttests of Neutral and Plus conditions accounted for 1.5% of the variance in the responses. Thus, while differences between the two conditions reach statistical significance, this accounted for a very small amount of the variance in the reaches, and thus overall, the participants tended to reach to similar distances in the Neutral and Plus conditions.

3.6.3.3 Minus and Plus Conditions

A multiple regression predicting the judgments from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an $r^2 = .611$ (n = 689), with partial Fs of 797.2 for actual target distance ($p < .0001$), 40.6 for condition ($p < .0001$) and a non-significant interaction term. A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.461$ (n = 689), indicating that the difference between

estimates in the posttests of Minus and Plus conditions accounted for 14.8% of the variance in the responses, 14.7% greater than in the pretest viewing. Overall, the participants tended to reach farther in the Minus condition, where the hand-held stylus appeared closer to the body.

3.6.4 Discussion

Research in human perceptual-motor coupling has shown that the matching of visual, kinesthetic and proprioceptive information is important for calibrating perceptual information so that visuo-motor tasks become and remain accurate. Many state-of-the art IVEs created for training users in near field visuo-motor tasks suffer from perceptual-motor limitations with respect to a de-coupling of visual, kinesthetic and proprioceptive information due to technological issues such as optical distortions, tracking error and drift. Previous studies have shown that distance estimates became more accurate after a period of interaction with the environment, with reaches improving from pretest to posttest (as revealed by improvements in the r^2 values as well as changes in both the slopes and intercepts of the regressions) [1, 4, 3, 57, 58].

We studied the effects of a visual distortion during a closed-loop physical reach task to near field targets in an IVE. We examined effects of the visual distortion on the calibration of users' reaching behavior. Specifically, we investigated the effects of calibration on egocentric distance perception in an IVE using pretest, calibration and posttest viewing paradigm. Three conditions of visual feedback were examined: scaling of a participant-controlled stylus to appear 20% closer to the viewer than it was physically located (Minus condition), 20% farther away from the viewer than it was physically located (Plus condition), and no scaling with the stylus appearing in its actual physical location (Neutral condition). Within each session and for each trial, manual reaches were given by participants to indicate perceived distance. As reaches were manipulated to appear closer, participants believed they were underestimating, and thus they reached farther after feedback. Similarly, reaches became nearer after they were manipulated to appear farther. The tendency towards calibration to perturbation of visual distance observed in this study is consistent with a similar pattern observed by Bourgeois and Coello [6]. While Bourgeois and Coello [6] investigated the effects of feedback on near-field distance estimation in the real world, our contribution shows that in an IVE, participants similarly scale their depth judgments to visual and proprioceptive information during 3D interactions in the near field.

3.6.5 Constant and Absolute Error

3.6.5.1 Computing Error

Accuracy measures were calculated to examine the differences between participants' estimated and actual target position. These were then combined for individual participants in each condition (Minus, Neutral, or Plus). Constant and Absolute Error were calculated based on techniques described by Schmidt [66], see formula 1 and 2, where T is the target distance of a given trial, x_i is the distance estimate by a participant in a particular trial, and n is the number of trials a participant performed in a session.

Constant error measures the direction of the errors of a participants' responses and the average error magnitude. In essence, this measure indicates the direction and accuracy of each participant. Constant Error was calculated using the following formula to examine average error:

$$\frac{\sum_{i=1}^{n}(x_i - T)}{n} \tag{3.1}$$

Data from two participants was not included in the analysis due to technical difficulties.

3.6.5.2 Open-Loop vs. Closed-Loop Calibration in Neutral Condition

As presented in Table 3.2, Constant Error of reach estimates in the pretest showed that, on average, participants in Neutral condition (no gain condition) reached 3.12cm past the actual target location in the pretest (SD = 2.64), and only 0.03cm in front of the actual target location in the calibration phase (SD = 4.01), indicating that participant reaches were 3.09cm closer to the target after the calibration phase with the stylus appearing at its actual physical location. A paired-samples t-test indicated that this was a significant difference, $t(10) = 2.238$, $p = 0.05$.

Absolute Error of reach estimates showed that on average, participants in Neutral condition were off by 5.86cm in the pretest (SD = 1.68), and 4.79cm in the calibration phase (SD = 1.89), also indicating that participants were more accurate after calibration, although this difference was not significant, $t(10) = 1.588$, p >0.05. On average, participants no longer overestimated to target locations in the calibration phase with the stylus appearing at its actual physical location as they had in the pretest.

	Const. Err		Abs. Err	
C2_PID	**P**	**Calb**	**P**	**Calb**
8	1.04	-0.02	3.88	3.85
12	4.91	8.7	6.15	9.31
18	1.97	-4.23	3.85	4.45
22	5.02	1.54	7.48	4.33
23	4.97	-6.85	6.37	7.28
27	3.1	0.18	8.68	4.62
24	7.88	-0.37	7.92	4.61
25	-0.35	3.35	4.07	4.57
28	-1.1	-1.76	5.95	3.29
33	4.16	0.82	4.47	2.67
34	2.72	-1.69	5.69	3.72
Avg.	**3.12**	**-0.03**	**5.86**	**4.79**

Table 3.2: Constant Error (Const. Err) and Absolute Error (Abs. Err) of reach estimates (cm) in the pretest (P) and calibration phase (Calb) in Neutral condition (no gain condition) for each participant (C2_PID).

3.6.5.3 Minus Condition vs. Plus Condition

As presented in Table 3.3, Constant Error of reach estimates showed that on average, participants reached 3.72cm past the actual target location in the calibration phase of Minus condition (SD = 3.67), and 7.15cm short of the actual target in the calibration phase of Plus condition (SD = 4.22), indicating that participant reaches were 10.87cm farther in the calibration phase of Minus condition than Plus condition, which was significantly different, $t(20) = 6.437$, $p < 0.001$.

Absolute Error of reach estimates showed that on average, participants were off by 5.61cm in the calibration phase of Minus condition (SD = 1.65), and 7.89cm in the calibration phase of Plus condition (SD = 3.56), also indicating that participants were more accurate in the calibration phase of Minus condition than Plus condition, although this was not significantly different, $t(20) = -1.927$, $p > 0.05$. Participant reaches in calibration phase of Minus condition were more accurate and significantly farther than those in Plus condition.

3.6.6 Rate of Visuo-Motor Calibration on Depth Judgments

In this section, we utilized a mixed model analysis of variance (ANOVA) to examine changes in reached distance over the course of the experiment. Since the calibration phase of the experiment consisted of 20 total trials, we subdivided the experiment into 4 groups of 5 trials each. We refer to these groups simply as 5-Trials. The analysis was conducted on reached distance as expressed in

	Const. Err		Abs. Err			Const. Err		Abs. Err
M_PID	**M**	**M_PoAL (%)**	**M**		**P_PID**	**P**	**P_PoAL (%)**	**P**
5	5.4	9.65	5.56		**1**	-9.44	-18.5	9.44
7	-5.03	-9	5.65		**6**	-4.42	-7.49	7.64
9	7	13.53	7.49		**10**	-6.11	-14.12	6.23
11	5.18	9	5.33		**13**	-11.3	-20.73	11.3
14	6.48	13.94	6.81		**17**	-5.43	-11.31	5.45
15	6.51	14	7.2		**20**	-4.91	-9.26	5.19
16	6.03	11.06	6.61		**26**	-1.42	-2.42	3.05
19	3.78	7.7	5.19		**29**	-1.62	-3.15	4.08
21	-0.03	-0.05	1.99		**30**	-14.28	-25.05	14.28
31	1.04	1.97	3.46		**35**	-12.15	-21.14	12.15
32	4.51	8.12	6.38		**36**	-7.54	-15.24	7.95
Avg.	**3.72**	**7.27**	**5.61**		**Avg.**	**-7.15**	**-13.49**	**7.89**

Table 3.3: Constant Error (Const. Err) and Absolute Error (Abs. Err) of reach estimates (cm) in calibration phase Minus condition (M) and Plus condition (P) and the *Proportion of Max Arm Length* (PoAL (%)) for each participant.

terms of percentage of the target distance. This was calculated such that *percent distance = (reached distance / target distance) * 100.* Viewing conditions (Minus, Neutral, and Plus) varied between subjects while 5-Trials varied within subjects. As such, this resulted in analysis with 3 x 4 mixed model ANOVA.

3.6.6.1 Overall Stylus Location

In this section, data has been analyzed based on two sources of sensory information (i.e. 1. visual sensory information with respect to the virtual location of the stylus 2. kinesthetic sensory information with respect to the physical location of the stylus). Note that the physical and visual stylus locations are basically two sides of the same coin (they are only different by the imposed gain factor). Therefore, temporal analysis can be done based on either the physical or visual stylus location. Thus, the temporal analysis has been conducted using the physical stylus location (significance in one entails significance in the other). However, the statistical analysis on the difference between the means for different conditions (Minus, Neutral, and Plus) have been conducted for both physical and visual stylus location.

As can be seen in Figure 3.11, in Neutral condition (0% gain, or gain = 1.0), physically reached distance was typically very close to the target distance, with very little change over the course of the experiment. The overall accuracy and stability of judgments within this condition is not particularly surprising since visual movements very closely matched physical movements. There

appeared to be general tendency toward shortened reaches over time but not significantly so ($F(3, 33) = 1.513$, $p = 0.229$).

However, upon examining the scaled movement conditions (Conditions 1 and 3) we find significant changes in physically reached distance. Particularly, in Plus condition (20% gain, or gain = 1.2), one would expect participants' physical reach to be noticeably shorter than when no gains were applied, because the stylus appears to be farther. This expectation was confirmed in the data with participants reaching significantly shorter (-15.8%) than in Neutral condition (0% gain) ($F(1, 22) = 16.532$, $p = 0.001$). Over the course of the experiment, participants significantly shortened their reached distance ($F(3, 33) = 2.881$, $p = 0.051$). This pattern is qualitatively similar to that seen in Neutral condition.

When examining Minus condition (-20% gain, or gain = 0.8), we would expect to see physical reaches that are longer than those expressed when no gains were applied, because the stylus appears closer. When comparing Minus and Neutral onditions, we see that this is, in fact, the case. Participants in Minus condition reached significantly further (11.5%) than their Neutral condition counterparts ($F(1, 22) = 7.864$, $p = 0.010$). There was no significant change in physically reached distance over the course of the experiment ($F(3, 33) = 0.666$, $p = 0.579$). However, the magnitude of the scaled reaches in this condition was slightly less than that seen in the Plus condition. Neither of the physical reach conditions, however, exactly reached the gain factor applied to the visual reach.

If we examine, instead, the visual distance of the reach as it appeared in the VE, we would expect performance in the scaled conditions (Minus and Plus conditions) to very closely match that of the unscaled condition (Neutral condition). Figure 3.11 summarizes these results. When comparing Conditions 2 and 3, we find that they did not significantly differ (0.1%) in visually reached distance ($F(1, 22) = 0.000$, $p = 0.999$). However, when comparing Minus condition to Neutral condition, that participants in the scaled condition very consistently under reached (-9.2%) relative to their no gain counterparts ($F(1, 22) = 6.709$, $p = 0.017$).

3.6.7 Discussion

3.6.7.1 Comparing Open-Loop vs. Closed-Loop Distances Judgments

We compared constant and absolute error of the perceived distances to targets between the open-loop blind reaching and the closed-loop physical reaching to targets with visuo-motor

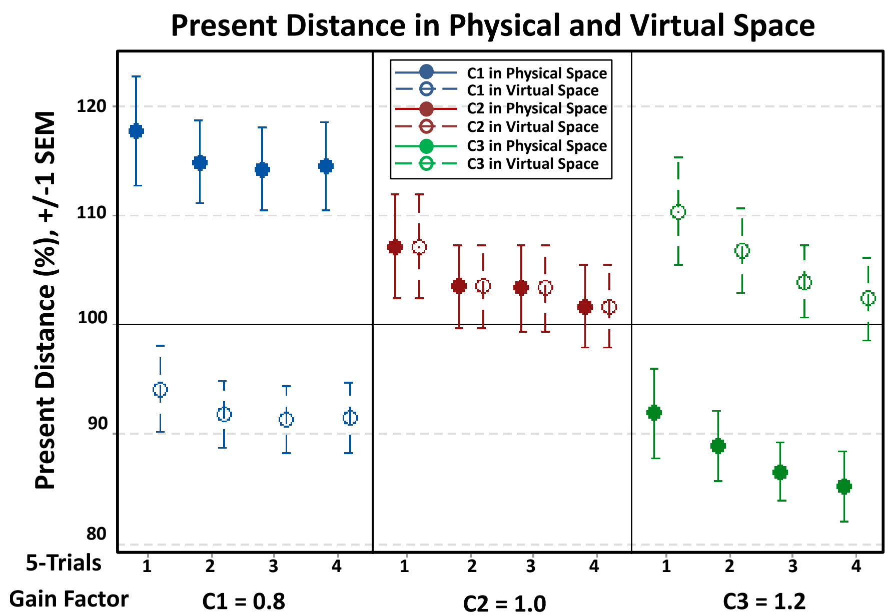

Figure 3.11: Physical and visual stylus location for all closed-loop conditions (C1 (Minus) = 0.8, C2 (Neutral) = 1.0, C3 (Plus) = 1.2)

calibration (section 4.2.2). The closed-loop phase provided participants with visual feedback that was co-located with the physical location of the tracked stylus (Neutral condition), and thus visual and proprioceptive information matched and reinforced the stylus location to the participant during visually guided reaching. Our results indicate that the primary mechanism by which recalibration occurred was visual feedback as the visual position of the stylus strongly influenced the end position of the participants' ballistic reach. Our findings suggest that participants generally over estimated distances to the targets by 3.12 cm, when reaching to the perceived location of the target without visual guidance. The tendency towards overestimation of reached distance observed in this study is consistent with a similar pattern observed by Rolland et. al [62] in the AR. However, others have reported underestimation when performing similar tasks [1, 69, 49]. The explanation for these diverse results is still unclear and necessitates future research.

During the closed-loop visuo-motor calibration trials in Neutral condition, participants received accurate visual and proprioceptive feedback regarding the targets through the precise rendering of visual information of the actual stylus position and the change in stylus tip color when the tip of the stylus was placed within a 1cm diameter groove on the target face. Mean absolute error in perceptual judgments to the targets also decreased from 5.86cm in the open-loop session to 4.79cm in the closed-loop session (Neutral condition), showing an improvement in absolute error of 1.07cm

on average. The mean constant error of physical reach responses of participants in the closed-loop session (Neutral condition), where participants reached with visual guidance, decreased to -0.03cm as compared to 3.12cm in the open-loop session, revealing an improvement of 3.09cm on average. This is similar to Altenhoff et. al. [1], in which we found that closed-loop visuo-motor calibration with visual and haptic (tactile) feedback improved near field distance judgments by 4.27cm as compared to a pre-calibration open-loop baseline. However, our findings suggest that accurate visual feedback alone to the location of the effector (hand/stylus), during closed-loop interactions where users received constant visuo-motor calibration via visual and proprioceptive information, appears as effective as the addition of the kinesthetic and tactile information [1] in calibrating physical reach responses to targets in near field IVE simulations.

3.6.7.2 Rate of Visuo-Motor Calibration on Distance Judgments in Closed-Loop Perturbations

In section 4.3, we performed a statistical analysis to compare the change in percent actual distance reached by the physical/virtual stylus (section 4.3.1) over four sets of trials (each set consisting of 5 trials), during the closed-loop session in which participants received visuo-motor calibration via visual and proprioceptive information (Minus, Neutral and Plus Conditions). In Neutral condition (0% gain), we found that there were no significant changes in participants' physical reach responses over the course of the experiment. However, participants did show a slight over estimation in the initial trials, and the physical reach responses tended to calibrate towards 100% of the actual distance. Whereas in Minus condition (-20% gain) participants' physical reach responses showed an over estimation to favor the proprioceptive information in the first five trials, but participants tended to scale their responses down towards the visual information. In this case, they showed an overall overestimation of physical reach of 11.5% of the actual distance (or 7.25% of the mean maximum arms reach), 3.72cm mean constant error and 5.61cm mean absolute error (section 4.2.3). In Plus condition (+20% gain) participants' physical reach responses showed less of an immediate underestimation in the first five trials (perhaps favoring the visual information, contrary to Minus condition), but the underestimation tended to increase over the course of the session biasing the physical reach response towards the physical location of the hand/stylus (favoring the proprioceptive information). Participants in Plus condition showed an overall underestimation of -15.8% of the actual distance (or -13.5% of their mean maximum arms reach), -7.15cm mean constant error and

7.89cm mean absolute error (section 4.2.3).

In an empirical evaluation, we showed that participants' depth judgments are scaled to be more accurate in the presence of visual and proprioceptive information during closed-loop near field activities in the IVE, as compared to absolute depth judgments in an open-loop session, when measured via physical reaching. These findings are important, as most VR simulations lack tactile haptic feedback systems for training in dexterous manual tasks such as surgical simulation, welding and painting applications. It seems that the use of visual information to reinforce the location of physical effectors such as the hand or stylus appears sufficient in improving depth judgments. However, we have also shown that depth perception can be altered drastically when visual and proprioceptive information, even in closed-loop conditions, are no longer congruent in the IVE. Thus they may cause significant distortions in our spatial perception, and potentially degrade training outcomes, experience and performance in VR simulations.

3.7 Conclusion

While the present results further our understanding of perceptual calibration in general, they also have important implications for the design of virtual reality applications. The results from this experiment support the notion that users of virtual environments adapt their behavior to adjust to visual feedback that conflicts with their physical movements. This is a particularly interesting finding, as it implies that users will likely be able to reasonably adapt to virtual reality systems that may not have tightly corresponding visual and physical movements. This demonstrates that people can likely to somewhat adapt to exaggerated virtual spaces, enabling the design of virtual instrumentation and interfaces that deviate from realistic simulations of the real world. This is of considerable interest to developers of interaction devices for virtual reality systems, in that it implies that a tight coupling between the virtual and physical self is not completely necessary, since the user will likely adapt to small incongruities with little or no notice. When this is taken in conjunction with the reaching behavior seen in the current posttest, we do see that observer's reaches are affected by the mismatched visual and proprioceptive feedback.

3.8 Future Work

Future work should further examine the effect of feedback on the calibration of distance estimates in both IVEs and the real world. We plan to test if calibration of distance estimates in near space carry over to subsequent perception in peripersonal space (beyond maximum arms reach) in IVE. Future research also should examine differences between visual and haptic feedback to see if one is more effective at calibrating distance estimates compared to the other, and to see if there is a benefit to including of both visual and haptic feedback simultaneously.

Chapter 4

An Empirical Evaluation of Visuo-Haptic Feedback on Physical Reaching Behaviors in Real and IVEs

We examine a set of motion related variables to evaluate spatial interaction such as error in reached versus actual target distance, time to complete the task, distance traveled by the hand in all 3 dimensions, distance between paths (using the Dynamic Time Warping (DTW) techniques) [31], as well as velocity of physical reach motion in all 3 dimensions. In this manner, we performed an initial systematic comparison to characterize human physical reach behaviors in the virtual and real world, which could enable us to better understand the discrepancy in task performance between the two [49]. We also examine the relative impact of visual and haptic information on reaching behaviors in these real and virtual environments.

4.1 Research Questions

We asked the following research questions in this empirical evaluation:

1) How do the perceptual differences between virtual and real world affect properties of physical reach motions in the near field?

2) How do the motor responses of participants differ between situations involving the presence or absence of visuo-haptic feedback?

3) How does haptic feedback alone affect human physical reach motion, as compared to vision only and visuo-haptic feedback, in near field distances in IVEs?

4) Is there any difference between the physical reach paths (in terms of distance between the paths) in virtual and real environments as well as in the presence or absence of the visuo-haptic feedback?

4.2 Experiment Methodology and Procedure

63 participants (45 female, 18 male) recruited from a university student population and received course credit for their participation. All participants were right handed.

4.2.1 Apparatus and Materials

Figure 3.1 depicts the experiment apparatus used for this research. The moving components of the apparatus were the target and participant's head and hand which were tracked in 6 Degrees of Freedom (DoF) (position and orientation) using a Polhemus Liberty electromagnetic tracking system. Participants were asked to sit with their backs straight on a chair, to which their shoulders were loosely tied to. This was done to serve as a gentle reminder for them to keep their shoulders in the chair during the physical reaches in the experiment, otherwise they had full control over their head and arm movements. The participant's arm length, inter-occular distance and eye height were measured before the experiment was initiated. Then, the target was adjusted to participants' eye level and midway between the participants' eyes and right shoulder in order to keep the distance from *the eye to the target* the same as the distance from *the right shoulder to the target* during the experiment. Next, all users were asked to hold a tracked stylus in their right hand. Participants then reached to a virtual or physical target with the tracked stylus and were required to position the stylus tip in the groove of the virtual or physical target during the experiment. Each trial began with the stylus positioned back on top of a launch platform beside the participant's right hip. Similarly, participant's head was tracked in 6 DoF in the real and virtual world to be used in the experiment

simulation and also for post-experiment data processing. All the visual components of the apparatus were carefully registered to be accurately co-located with the surface of the corresponding physical components. Thus, the visual geometry of the various components were exactly registered to their physical real world counterparts.

In the IVE or virtual world conditions, participants wore a NVIS nVisor SX111 HMD describe in Section 3.1.3. The simulation was designed so that in the absence of haptic feedback during physical reaching, the tip of the stylus would appear red when it was within a 1 cm radius of target's groove in the immersive virtual environment (IVE) (Figure 3.3). Therefore when participants had visual feedback only, they could perceive when the stylus tip intersected the groove in the target face in the IVE. The virtual target, stylus and apparatus in the virtual world were an exact and carefully registered replica of the physical apparatus. Therefore, in the virtual world condition with haptic feedback, when the participant reached to place the stylus in the groove of the target face they could obtain accurate visual and haptic feedback of contact between the stylus and the target of the apparatus.

4.2.2 Experiment Design

The experiment was conducted during an interaction session with or without visual and/or haptic feedback. A between-subjects design was utilized, where participants were randomly assigned to one of the five conditions detailed below. Participants performed 2 practice trials followed by 30 experiment trials. Trials consisted of 5 random permutations of 6 target distances corresponding to 50, 58, 67, 75, 82, and 90 percent of the participants' maximum arm length. The five conditions were as follows:

Real-V&H: *Real environment with visuo-haptic feedback.* In this condition, participants in the real world reached to a physical target with a fast, ballistic motion, with their eyes open in a closed loop fashion, and then gradually adjusted their initial reach successfully to place the stylus into the target's groove.

Real-NV&NH: *Real environment with no visuo-haptic feedback.* In this condition, participants in the real world viewed a target at a given distance and then performed a blind reach in an open loop fashion to the perceived location of the physical target with a fast, ballistic motion. The participants closed their eyes and the target was removed just prior to reach initiation.

Virtual-V&H: *Virtual environment with visuo-haptic feedback.* This condition was similar

to the Real-V&H condition, except that while the participants made physical reaches in the real world, here they viewed a virtual simulation of that world (including the room, apparatus, target and stylus).

Virtual-V&NH: *Virtual environment with visual and no haptic feedback.* This condition was similar to the Virtual-V&H condition, but with haptic feedback removed by the removal of the physical target just prior to reach initiation. The virtual target remained in view. In order to provide visual feedback to successfully guide the completion of the reach, the simulation was designed so that the stylus's tip would turn red when it was within a 1 cm radius of target's groove.

Virtual-NV&NH: *Virtual environment with no visuo-haptic feedback.* This condition was similar to the Real-NV&NH condition, except they viewed the virtual simulation. The display made blank just prior to reach initiation, so that the physical reaches were made in an open loop manner without visuo-haptic feedback in the IVE.

4.2.3 Data Preprocessing

The procedure and data preprocessing were describe in details in Section 3.5. The total duration of the experiment was on average 15 minutes for all conditions.

Before conducting our analysis, we performed a correlation matrix between all the independent variables to reduce the dimensionality of the analysis. We found that some of the independent variables were highly correlated to each other. Due to the page limit, we have excluded the results of some these independent variables. For instance, the results from the velocity in either of the X, Y or Z dimensions were replaced by the speed of the physical reach task in 3D space. Similarly, the results for the maximum velocity was excluded in this report due to its high correlation with average velocity. We report the results of the analysis from the least correlated variables associated with the physical reach behaviors. For instance, we analyzed average and maximum velocity but pattern of the results were identical to the average velocity. Based on the results of the study, average velocity is strongly correlated to maximum velocity $r = .943, n = 1459, p<.001$. A similar pattern was observed between average and maximum acceleration, $r = .942, n = 1459, p<.001$. Therefore, we decided to proceed with only the average velocity and average acceleration, while excluding maximum velocity and maximum acceleration from the results section.

Table 4.1: Step 1 - 2 × 2 Factorial Design Between Environment and Feedback

	Feedback	
Environment	*Visuo-Haptic Feedback*	*No Visuo-Haptic Feedback*
Real	n=13 (Real-V&H)	n=10 (Real-NV&NH)
Virtual	n=14 (Virtual-V&H)	n=12 (Virtual-NV&NH)

4.3 Results

Out of 63 participants, 62 were considered for data analysis (one participant's data was excluded due to technical difficulties). The participants were distributed as in 13 in Real-V&H, 14 in Virtual-V&H, 10 in Real-NV&NH, 12 in Virtual-NV&NH, and 13 in Virtual-V&NH conditions. We performed a three-step analysis: **First**, we examined the effects of the presence of visuo-haptic feedback in real and virtual worlds via a 2 × 2 factorial independent group design [(Feedback - visuo-haptic feedback vs no visuo-haptic feedback) × (Environment - Real vs Virtual)] utilizing four of five different conditions in the experiment (Table 4.1). We analyzed the data using a 2 × 2 ANOVA on the different performance dimension of the physical reach motion such as accuracy of the estimated reach (Equation 4.1), average velocity, and time to complete the reach. This was followed by post-hoc test to examine main and interaction effects. **Second**, we examined the impact of vision and haptic feedback in the IVE. We compared the physical reach motion characteristics of the three virtual world conditions (Virtual-V&H, Virtual-V&NH, and Virtual-NV&NH). Thus, we conducted a one-way independent sample ANOVA on the various performance dimension of the physical reach motion data in IVE (Table 4.2). **Third**, we used dynamic time warping to examine the difference between the paths in different experiment conditions.

$$Error(\%) = \frac{EstimatedDistance - ActualDistance}{ActualDistance} * 100 \tag{4.1}$$

Table 4.2: Step2 - Effect of Feedback in Virtual Environment

<table>
<tr><td rowspan="3">Environment</td><td colspan="3">Feedback</td></tr>
<tr><td colspan="2">Visually Guided</td><td>Non-Visually Guided</td></tr>
<tr><td>Haptic Feedback</td><td>No Haptic Feedback</td><td>No Haptic Feedback</td></tr>
<tr><td>Virtual</td><td>n=14
(V&H)</td><td>n=13
(V&NH)</td><td>n=12
(NV&NH)</td></tr>
</table>

4.3.1 Effects of the Presence of Visuo-haptic Feedback in Real and Virtual Worlds

4.3.1.1 Accuracy of the Estimated Reach (aka Error(%))

First, a 2×2 factorial ANOVA was used to test the effects of the feedback (presence or absence of visuo-haptic feedback) and environment (real vs virtual) on the accuracy of the reaches (Figure 4.1). The results indicate that a significant main effect of the environment, $F(1, 1455) = 113.29$, $p<.001$, $\eta^2 = .07$. As expected, participants distance estimation in real condition was more accurate ($M = 4.35, SD = 12.28$) compared to the participants distance estimation in the virtual condition ($M = 11.85, SD = 19.29$) in reaching towards the perceived location of the target. We also found a significant main effect for the feedback, $F(1, 1455) = 474.12$, $p<.001$, $\eta^2 = .25$. The mean error revealed that the participants in the visuo-haptic feedback condition were highly accurate on estimating distance to the target ($M = 0.98, SD = 7.28$) as compared to the no visuo-haptic feedback ($M = 17.79, SD = 20.48$), which was expected due to the continuous closed loop visual feedback in the former condition. There was also a significant interaction between feedback and environment, $F(1, 1455) = 128.01$, $p<.05$, $\eta^2 = .08$. Post hoc analysis indicated that participants in no visuo-haptic feedback made significantly more accurate depth judgments when in real environment ($M = 8.80, SD = 17.20$) as compared to participants in the IVE ($M = 24.70, SD = 20.13$), $p<.001$. However, participants with visuo-haptic feedback condition made similar distance judgments when in the virtual ($M = .74, SD = 8.82$) and in the real ($M = 1.23, SD = 5.03$). Similarly, participants in virtual condition made significantly better depth judgments when in visuo-haptic feedback as compared to no visuo-haptic feedback condition, $p<.001$. Moreover, participants in real condition made significantly better depth judgments when in visuo-haptic feedback as compared to those in condition with no visuo-haptic feedback, $p<.001$. These results indicate that reaches become inaccurate when visuo-haptic feedback is removed, with this effect being much greater in the virtual

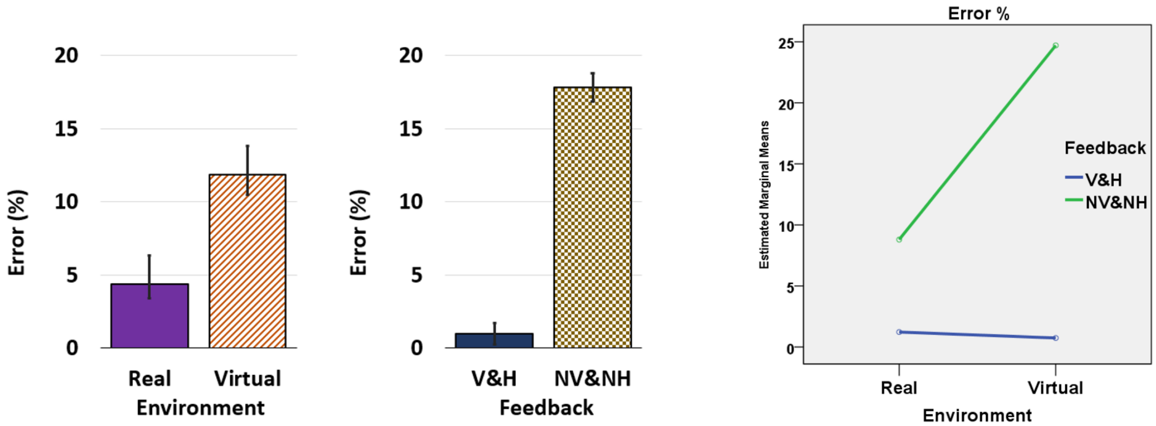

Figure 4.1: % Error for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

condition than with real world viewing. When visuo-haptic feedback is present, the virtual condition is as accurate as viewing in the real world.

4.3.1.2 Time to Complete the Reach (s)

Results regarding the "time to complete the reach" revealed a significant main effect for the two independent variables: environment, $F(1, 1455) = 18.72$, $p<.05$, $\eta^2 = .01$, and feedback, $F(1, 1455) = 208.62$, $p<.001$, $\eta^2 = .13$ (Figure 4.2). There was also a significant interaction between environment and feedback, $F(1, 1455) = 38.17$, $p<.001$, $\eta^2 = .03$. Post hoc analysis indicated that participants in the no visuo-haptic feedback condition spend significantly less time to complete the reach when in real environment ($M = .85, SD = .17$) as compared to those in virtual environment ($M = 1.00, SD = .36$), $p<.001$. However, participants in visuo-haptic feedback condition spent about same amount of time to complete the reaches in virtual environment ($M = .71, SD = .19$) and in the real world ($M = .74, SD = .29$). Similarly, participants in the real world spent significantly less time to complete the reach when receiving visuo-haptic feedback as compared to those that did not, $p<.001$. Moreover, participants in virtual environment spent significantly less time to complete the reaches when receiving visuo-haptic feedback than those that did not, $p<.001$. Overall, participants in real condition took less time to complete the reach task ($M = .78, SD = .25$) as compared to the virtual condition ($M = .84, SD = .32$). One interesting finding was that participants in the virtual condition seemed to move their arm slower than those in the real world, which could be due to the levels of uncertainty in the virtual world as compared to the real world. Similarly, participants completed their reaches faster when they had visuo-haptic feedback ($M = .72, SD =$

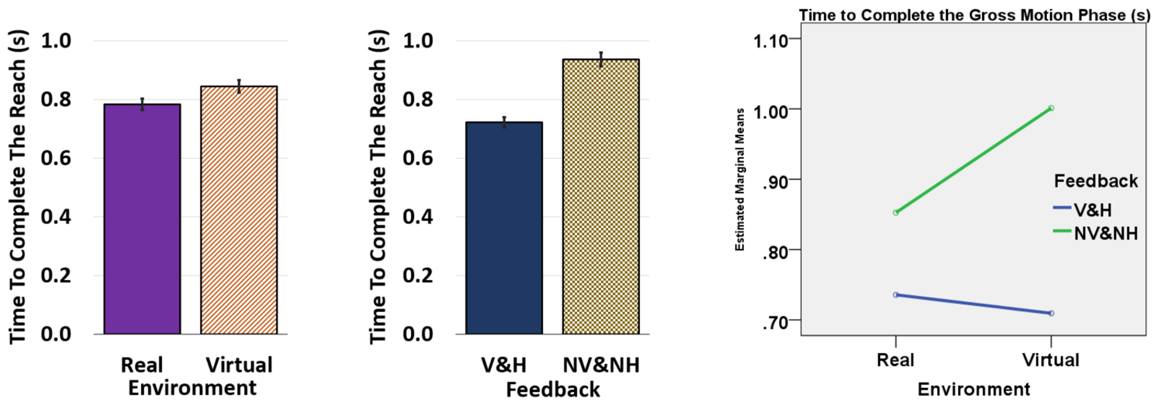

Figure 4.2: Time (s) to complete the task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

.24) as compared to the no feedback condition ($M = .94, SD = .30$). In sum, the reaching time measure mirrored the error measure discussed previously; reaches become slower when visuo-haptic feedback is removed, with this effect being much greater in the virtual world than in real world viewing. When visuo-haptic feedback was present, the virtual and real world times were similar. When comparing the time and error measures, it is important to note that, in general, conditions with the slower reaches were less accurate, while more rapid ballistic reaching seemed to be more accurate.

4.3.1.3 Distance Traveled (cm)

Distance traveled is the path line or arc taken to reach the target. It is calculated as the cumulative distances ($\sum_{i=1}^{N-1} \Delta D_i$). Distance traveled is always equal to or longer than the target distance that participants eventually reached to because the target distance is unidimensional (extending horizontally away from the participant), while the Distance Traveled occurs in 3D-space. The Distance Traveled takes into account the differing heights between the start of the hand's path and the target. More importantly, it also takes into account any curvature to the hand's path. Hence, it is possible to reach to a same destination when taking two different arcs in terms of the length and the shape of the arc. To better understand the differences between the shapes of the arcs we used Dynamic Time Warping (DTW) which will be explained in Section 4.3.3. Equation (4.2) was used to calculate the displacement at each timestamp (ΔD_i). This one step displacement was

then used to calculate the total length of the arc (D from Equation (4.3)).

$$\Delta D_i = \sqrt{x_i^2 + y_i^2 + z_i^2}, where \begin{cases} \Delta x_i = x_{i+1} - x_i \\ \Delta y_i = y_{i+1} - y_i \\ \Delta z_i = z_{i+1} - z_i \end{cases} \tag{4.2}$$

$$D = \sum_{i=1}^{N-1} \Delta D_i \tag{4.3}$$

Results based on the "distance traveled" in the ballistic phase of the reaching motion towards the target revealed no main effect of the environment but a significant main effect of the feedback $F(1, 1455) = 1272.69$, $p<.001$, $\eta^2 = .47$, and a significant interaction, $F(1, 1455) = 68$, $p<.001$, $\eta^2 = .05$ (Figure 4.3). Post hoc analysis indicated that participants in the no visuo-haptic feedback condition reached significantly farther when in the real environment ($M = 84.73, SD = 9.19$) as compared to participants in the virtual environment ($M = 76.80, SD = 21.13$), $p<.001$. Similarly, participants in the virtual environment reached significantly farther when in the absence of visuo-haptic feedback as compared to participants that received visuo-haptic feedback, $p<.001$. Combined with the results from Section 4.3.1.1, participants underestimated distance in virtual condition in the no feedback condition. However, participants in visuo-haptic feedback condition reached with shorter distances traveled when in real environment ($M = 35.87, SD = 30.57$) as compared to the virtual counterpart ($M = 46.28, SD = 14.31$). Similarly, combined with the results from Section 4.3.1.1, participants overestimated distance in virtual condition in visuo-haptic feedback condition. Overall, participants in virtual environment reached slightly farther ($M = 60.43, SD = 23.42$) as compared to the real condition ($M = 56.03, SD = 34.09$). Likewise, participants reached farther in the no visuo-haptic feedback condition ($M = 80.24, SD = 17.44$) as compared to the visuo-haptic feedback condition ($M = 41.22, SD = 24.20$). These results suggest that the reaching path become longer when visuo-haptic feedback is removed; this effect is greater in the real condition than in the virtual world. However, when visuo-haptic feedback was present, the path lines were longer in the virtual world as compared to the real world viewing. Thus the reaches were less efficient in the virtual world, even though the final accuracy of the reaches was the similar in both conditions in the presence of closed loop visuo-haptic feedback (Section 4.3.1.1). This inefficiency may have been caused by a lack of visual information regarding the configuration of the hand relative to the target

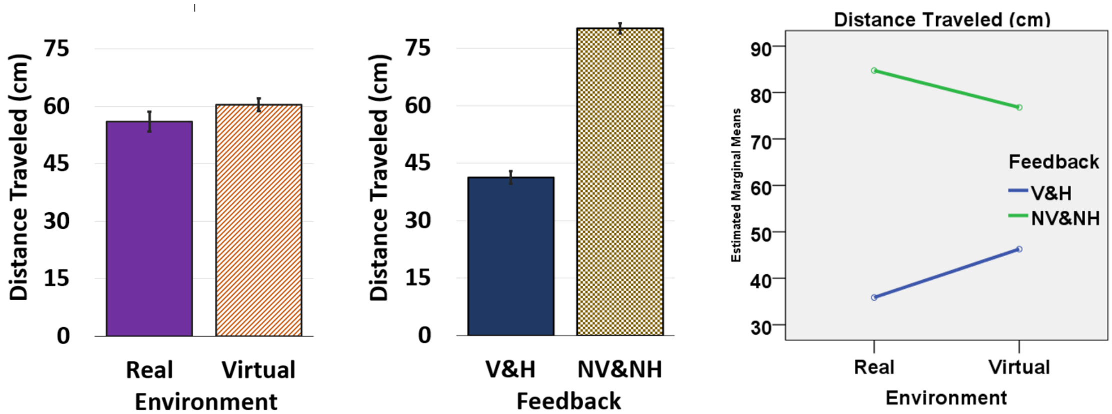

Figure 4.3: Distance traveled (cm) to complete the task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

and the remainder of the body. Future research will be directed at the possibility that adding a self-avatar to the virtual view may improve manual reach performance.

4.3.1.4 Average Velocity (cm/s)

The average velocity was calculated using the equation (4.5) in which the instantaneous velocity was generated using the ΔD and Δt (time) vector (equation 4.4).

$$\Delta V_i = \frac{\Delta D_i}{\Delta t_i}, where \left\{ \Delta t_i = t_{i+1} - t_i \right. \tag{4.4}$$

$$V = \frac{1}{N} \sum_{i=1}^{N-1} \Delta V_i \tag{4.5}$$

The average velocity results revealed no main effect of the environment. However, there was a significant main effect of feedback for the average velocity, $F(1, 1455) = 1358.21$, $p<.001$, $\eta^2 = .48$. The mean differences revealed that the participants in the visuo-haptic feedback condition had a lower average velocity towards the target ($M = 43.16, SD = 25.46$) as compared to the no visuo-haptic feedback condition ($M = 89.72, SD = 25.67$). This finding supports the notion that participants with visual feedback performed distance estimation with higher accuracy (4.3.1.1) as compared to those in no visuo-feedback feedback condition. We also found a significant interaction between environment and feedback, $F(1, 1455) = 131.10$, $p<.001$, $\eta^2 = .08$ (Figure 4.4). Post hoc analysis indicated that participants in the no visuo-haptic feedback condition reached towards the target faster when in the real environment ($M = 99.33, SD = 19.80$) as compared to participants

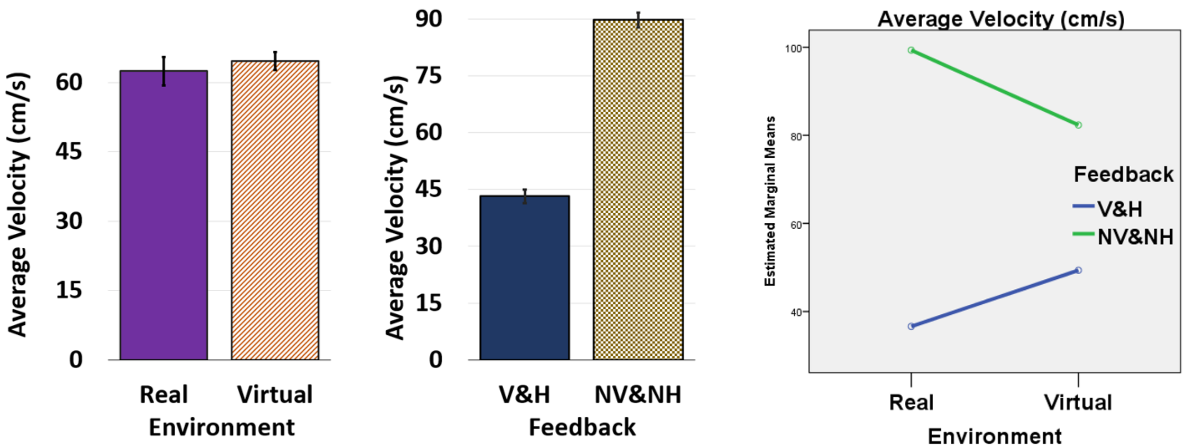

Figure 4.4: Average velocity (cm/s) during the physical reach task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

in the virtual environment ($M = 82.34, SD = 27.21$), p<.001. Similarly, participants in the visuo-haptic feedback condition reached towards the target slower when in the real environment ($M = 36.61, SD = 30.27$) as compared to participants in the virtual environment ($M = 49.35, SD = 17.83$), p<.001.

4.3.1.5 Average Acceleration (cm/s^2)

Similarly, the average Acceleration was calculated using the equation (4.7) in which the instantaneous acceleration was generated using the ΔV and Δt (time) vector (equation 4.6).

$$\Delta A_i = \frac{\Delta V_i}{\Delta t_i}, where \begin{cases} \Delta t_i = t_{i+1} - t_i \end{cases} \tag{4.6}$$

$$A = \frac{1}{N} \sum_{i=1}^{N-1} \Delta A_i \tag{4.7}$$

Similarly, the average acceleration results revealed no main effect of the environment. However, there was a significant main effect of feedback for the average acceleration, $F(1, 1455) = 1389$, p<.001, $\eta^2 = .49$. The mean differences revealed that the participants in the visuo-haptic feedback condition had a significantly lower average acceleration towards the target ($M = 649.15, SD = 383.14$) as compared to the no visuo-haptic feedback condition ($M = 1360.51, SD = 389.35$). We also found a significant interaction between environment and feedback, $F(1, 1455) = 130.70$, p<.001, $\eta^2 = .08$ (Figure 4.5). Post hoc analysis indicated that participants in the no visuo-haptic feedback

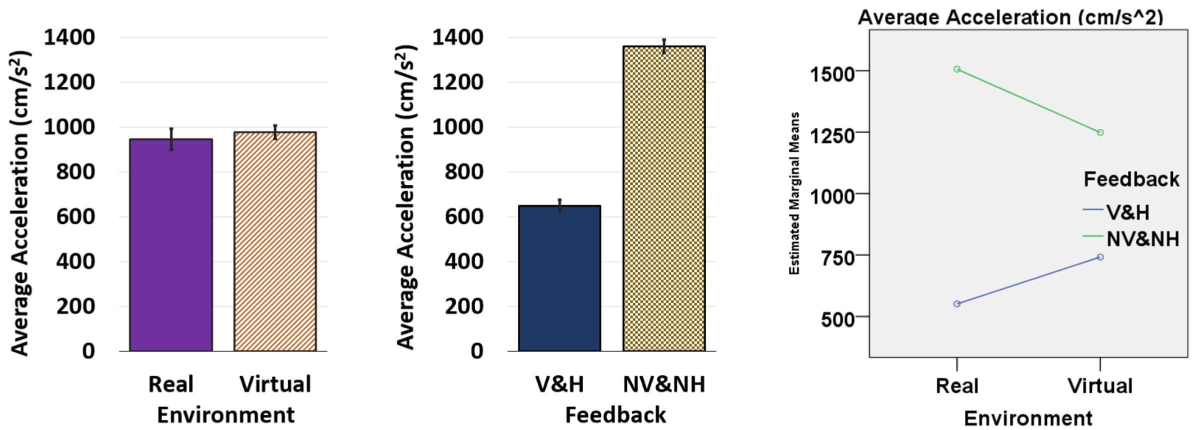

Figure 4.5: Average acceleration (cm/s^2) during the physical reach task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

condition reached towards the target faster when in the real environment ($M = 1506.14, SD = 300.54$) as compared to participants in the virtual environment ($M = 1248.58, SD = 412.50$). Similarly, participants in the visuo-haptic feedback condition reached towards the target slower when in the real environment ($M = 551.10, SD = 455.43$) as compared to participants in the virtual environment ($M = 741.83, SD = 268.57$).

4.3.1.6 Discussion

Human depth judgments to near field distances in real environments have been shown to be accurate [49]. On the contrary, in the virtual world, the distances are usually misjudged [17]. We compared the presence and absence of visuo-haptic feedback on various properties of physical reaches in the real world and in IVE. The results suggest that physical reach responses vary systematically between real and virtual environments and in situations with and without visuo-haptic feedback. Generally, participants were more accurate in the real world than in the virtual world, and also were both more accurate and more efficient when presented with sensory feedback than with no feedback. More importantly, the results indicate that the participants performed similarly in the virtual and real environments, which emphasizes the importance of providing visuo-haptic feedback to the users of VR applications.

Additionally, participants reached towards the target with a slower trajectory in the real world condition than in the IVE condition and also in the presence of visuo-haptic feedback than in the absence of visuo-haptic feedback. Possibly because real environment and visuo-haptic feedback

Table 4.3: Summary of 2×2 Factorial Design Between Environment and Feedback

Variable (n=49)		F value	p	η^2		Mean	SD
Accuracy	***Environment***	113.29	<.001	0.07	*Real*	4.35	12.28
					Virtual	11.85	19.29
	Feedback	474.12	<.001	0.25	*V&T*	0.98	7.28
					NV&NT	17.79	20.48
	Interaction	128.01	<.05	0.08			
Time to complete the reach	***Environment***	18.72	<.05	0.01	*Real*	0.78	0.25
					Virtual	0.84	0.32
	Feedback	208.62	<.001	0.13	*V&T*	0.72	0.24
					NV&NT	0.94	0.30
	Interaction	38.17	<.001	0.03			
Distance Traveled	***Environment***	1.25	0.26	0.001	*Real*	56.03	34.09
					Virtual	60.43	23.42
	Feedback	1272.69	<.001	0.47	*V&T*	41.22	24.20
					NV&NT	80.24	17.44
	Interaction	68	<.001	0.05			
Average Velocity	***Environment***	2.67	.102	.002	*Real*	62.49	40.67
					Virtual	64.64	28.00
	Feedback	1358.21	<.001	0.48	*V&T*	43.16	25.46
					NV&NT	89.65	34.46
	Interaction	131.10	<.001	0.08			
Average Acceleration	***Environment***	2.91	.088	.002	*Real*	945.27	616.68
					Virtual	976.76	425.86
	Feedback	1389.70	<.001	0.49	*V&T*	649.15	383.14
					NV&NT	1360.51	389.35
	Interaction	130.70	<.001	0.08			

seemed more natural to users, and the accuracy of depth judgments was enhanced because the slower trajectory allowed then time to guide their performance based on the sensory feedback. Summary of the results from Section 4.3.1 are presented in Table 4.3.

4.3.2 Impact of Vision and Haptic Feedback in IVEs

In this section, we will examine the different characteristics of three VR conditions (Virtual-V&H, Virtual-V&NH, and Virtual-NV&NH). We investigate the relative differences between properties of reaching towards the perceived location of targets in the virtual environment when participants have visuo-haptic feedback vs. visual feedback only vs. no visual or haptic feedback.

4.3.2.1 Accuracy of the Estimated Reach (aka Error)

A one-way between subject ANOVA was conducted to compare the effect of virtual interaction conditions (Virtual-V&H, Virtual-V&NH, and Virtual-NV&NH) on the accuracy of the

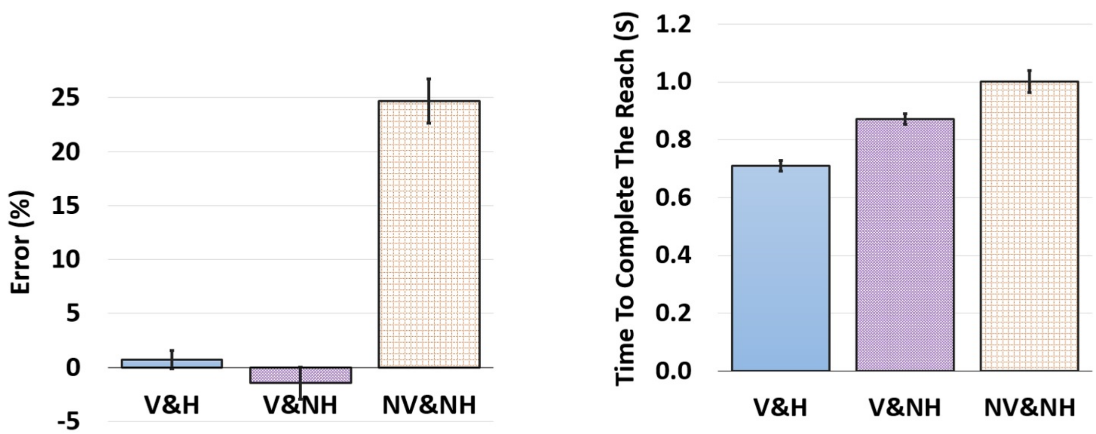

Figure 4.6: **Left:** % Error. **Right:** Time to complete a reach for three virtual conditions (Visual and Haptic Feedback (V&H), Visual and No Haptic Feedback (V&NH), and No Visual and No Haptic Feedback (NV&NH)

reach judgments to the targets. There was a significant main effect of virtual interaction condition on the accuracy of the estimated reaches to targets, $F(2, 1174) = 351.66$, $p<.001$, $\eta^2 = .38$. Post hoc comparisons using the Tukey HSD test indicated that the mean error in the NV&NH condition ($M = 24.70, SD = 20.13$) was significantly higher than the mean error in the V&H ($M = 0.74, SD = 8.82$) and the V&NH ($M = -1.47, SD = 14.70$) conditions (Figure 4.6-Left). However, the V&H and the V&NH conditions were not significantly different from each other.

4.3.2.2 Time to Complete the Reach (s)

Similarly, a one-way between subject ANOVA was conducted to compare the effect of three virtual interaction conditions (Virtual-V&H, Virtual-V&NH, and Virtual-NV&NH) on the time to complete the reach. We found that there was a significant main effect of virtual interaction condition, $F(2, 1174) = 126.46$, $p<.001$, $\eta^2 = .18$. Post hoc comparisons using the Tukey HSD test indicated that the mean time to complete the reach for the NV&NH condition ($M = 1.00, SD = .36$) was significantly higher than the mean time to complete the reach of the V&H condition ($M = .71, SD = .19$) and the V&NH condition ($M = .87, SD = .20$) (Figure 4.6-Right). Similarly, the mean time to complete the reach of the V&NH condition was significantly higher than the mean time to complete the reach of the V&H condition. In sum, the results suggest that participants in the non-visually guided condition spent more time to complete the reach as compared to the visually guided conditions. These results support the finding from Section 4.3.2.1, in which participants

in the NV&NH condition perceived the target to be farther from them (overestimated distance), perhaps taking them longer to complete a reach with larger trajectories of reaching.

4.3.2.3 Distance Traveled (cm)

Results regarding the effect of three virtual interaction conditions on the distance traveled revealed a significant main effect, $F(2, 1174) = 571.23$, $p<.001$, $\eta^2 = .49$. Post hoc comparisons using the Tukey HSD test revealed that the mean distance traveled in the NV&NH condition ($M = 76.80, SD = 21.13$) was significantly higher than the mean distance traveled in the V&NH condition ($M = 42.40, SD = 8.19$) and the V&H condition ($M = 46.28, SD = 14.31$) (Figure 4.7-Left). Similarly, the mean distance traveled in the V&NH condition was significantly higher than the mean distance traveled in the V&H condition.

4.3.2.4 Average Velocity (cm/s)

A one-way between-subject ANOVA was conducted to compare the effect of three virtual interaction conditions on the average velocity of the physical reaches. We found that there was a significant main effect of virtual interaction conditions on the average velocity, $F(2, 1174) = 567.61$, $p<.001$, $\eta^2 = .49$. Post hoc comparisons using the Tukey HSD test indicated that the mean velocity for the NV&NH condition ($M = 82.34, SD = 27.21$) was significantly higher than the mean velocity of the V&NH condition ($M = 36.77, SD = 8.52$) and the V&H condition ($M = 49.35, SD = 17.83$). Similarly, the mean velocity of the V&NH condition was significantly lower than the mean velocity of the V&H condition (Figure 4.7-Middle), $p<.001$.

4.3.2.5 Average Acceleration (cm/s^2)

Finally, a one-way between subject ANOVA was conducted to compare the effect of three virtual interaction conditions on the average acceleration of the physical reaches. The results indicated significant main effect of virtual interaction conditions on the average acceleration, $F(2, 1174) = 581.75$, $p<.001$, $\eta^2 = .50$. Post hoc comparisons for average acceleration using the Tukey HSD test indicated that the mean acceleration for the NV&NH condition ($M = 1248.58, SD = 412.50$) was significantly higher than the mean acceleration of the V&NH condition ($M = 551.69, SD = 127.81$) and the V&H condition ($M = 741.83, SD = 268.57$) (Figure 4.7-Right). The mean acceleration of the V&NH was significantly lower than the V&H condition.

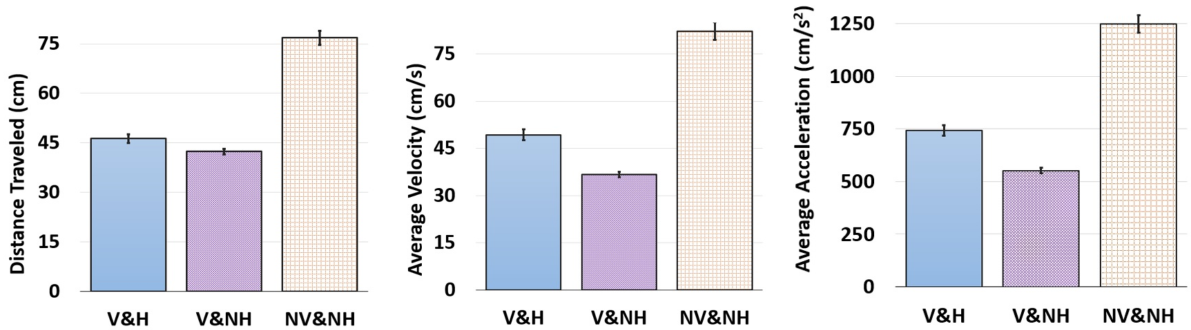

Figure 4.7: **Left**: Distance traveled. **Middle**: Average velocity **Right**: Average acceleration for three virtual conditions (Visual and Haptic Feedback (V&H), Visual and No Haptic Feedback (V&NH), and No Visual and No Haptic Feedback (NV&NH))

4.3.2.6 Discussion

Overall, the results from Section 4.3.2 (Table 4.4) indicate that the presence of haptic feedback had a significant effect on all the properties of physical reach motion except on the accuracy of the reaching task. When visual feedback was present, accuracy of the reaches to the target location was statistically similar in conditions with or without haptic feedback (V&H and V&NH) and significantly different from the condition in which the visual feedback was absent (NV&NH). Participants in the visually guided conditions were more accurate in estimating distance to target and reaching accurately towards them compared to the non-visually guided condition in which participants over-reached to the depth of targets. However, presence or absence of the haptic feedback did not have a significant effect on participants' distance judgment. Participants took shorter distances traveled to reach to the target when they had visuo-haptic feedback than when they had no visuo-haptic feedback and visual feedback only.

The average velocity results suggest that participants in the no visuo-haptic condition reached significantly faster towards the perceived location of targets as compared to the visually guided conditions (V&H and V&NH). These results were evident in the previous section as well in which participants in the non-visually guided reach conditions had more error or distance overestimation and larger reach trajectory distance as compared to the visually guided conditions. However, comparing the two visually guided reach conditions surprisingly revealed that the absence of haptic feedback resulted in slower or more attentive physical reaching towards the perceived location of targets in the virtual world. It appears that participants who had simultaneous visual guidance and haptic feedback (V&H), were more confident about where they were reaching, and consequently

Table 4.4: Summary of Effect of Feedback in Virtual Environment

Variable (n=39)	***F value***	***p***	η^2	***Mean V&H***	***SD V&H***	***Mean V&NH***	***SD V&NH***	***Mean NV&NH***	***SD NV&NH***
Accuracy	351.66	<.001	0.38	0.74	8.82	-1.47	14.70	24.70	23.13
Time to complete the reach	126.46	<.001	0.18	0.71	0.19	0.87	0.20	1.00	0.36
Distance Traveled	571.23	<.001	0.49	46.28	14.31	42.40	8.19	76.80	21.13
Average Velocity	567.61	<.001	0.49	49.35	17.83	36.77	8.52	82.34	27.21
Average Acceleration	581.75	<.001	0.50	741.83	268.57	551.69	127.81	1248.58	412.50

reached faster with about the same accuracy as compared to the visually guided no haptic feedback condition (V&NH). These findings support the notion that lack of feedback increases the level of uncertainty and consequently decreases the accuracy and control over the hand movement trajectory and motion in IVEs.

4.3.3 Visualization Using Dynamic Time Warping (DTW)

We also investigated the difference between the trajectories reached by the participants in terms of the closeness of the paths for each specific target distance for different conditions. Thus, we used Dynamic Time Warping (DTW) which is a well-known method for normalizing a signal based on a reference signal [31, 8]. Using DTW, paths were compared pairwise and the distance between them was calculated. For example, consider two paths A and B with lengths of n and m, respectively (Figure 4.8-1):

$$\begin{cases} A = a_1, a_2, ..., a_i, ..., a_n \\ B = b_1, b_2, ..., b_j, ..., b_m \end{cases} \tag{4.8}$$

Using the method described in Keogh and Ratanamahatana [31], an n-by-m matrix was constructed, where the ith and jth element of the matrix (M_{ij}) is the distance d(a_i, b_j) between the two points a_i and b_j. Then, we calculated the Euclidean distance between each pair of points a_i and b_j:

$$d(a_i, b_j) = (a_i - b_j)^2 \tag{4.9}$$

Each matrix element (M_{ij}) corresponds to the distance between the points a_i and b_j. Then, accumulated smallest distance was computed using the following formula (Figure 4.8-2 and 4.8-3):

$$D(a_i, b_j) = min[D(a_{i-1}, b_{j-1}), D(a_{i-1}, b_j), D(a_i, b_{j-1})] + d(a_i - b_j) \tag{4.10}$$

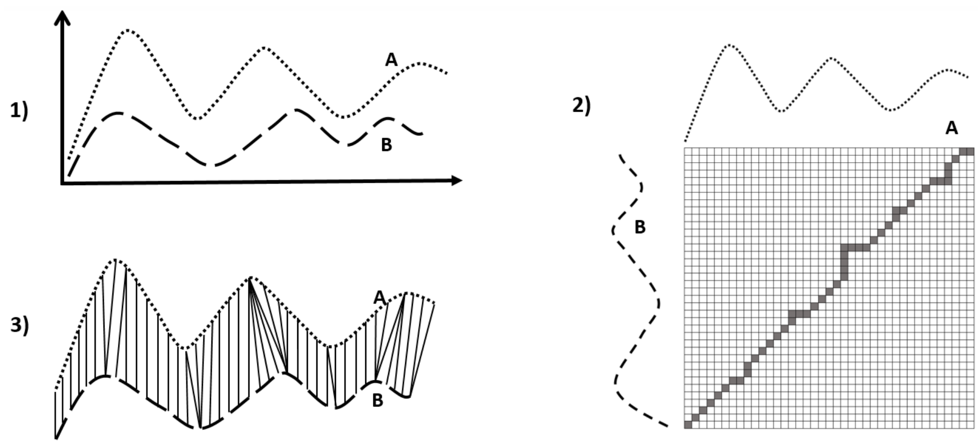

Figure 4.8: **1)** Two paths each representing a physical reach. Time is represented on the horizontal axis and one of the spatial dimensions is represented on the vertical axis **2)** Optimal warping path shown with gray squares. **3)** Time alignment of the two sequences. Aligned points are indicated by the solid lines.

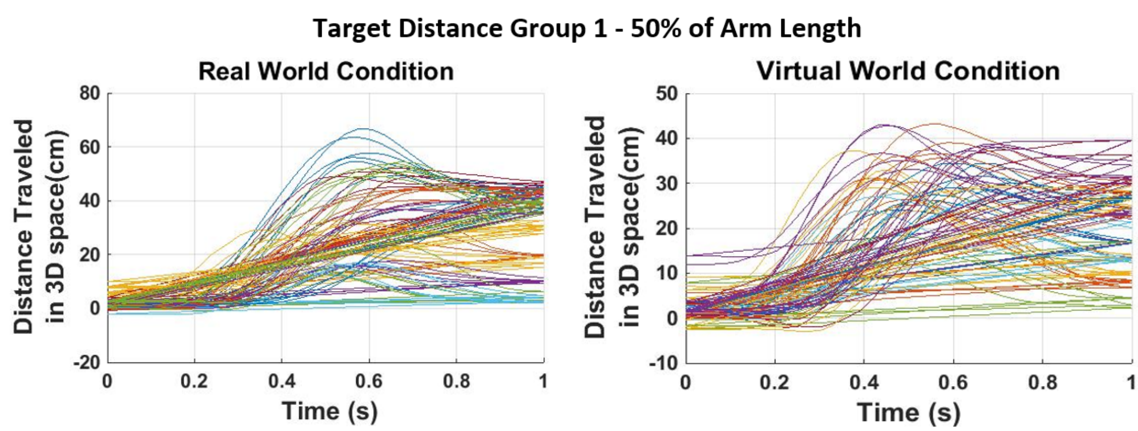

Figure 4.9: Spaghetti plots of physical reach motion in real environment (Left Image) and virtual environment (Right Image) for target distances corresponding to 50% of participants' maximum arm length. The variability between the paths when reaching to close distances was significantly more in virtual world than in the real world condition.

Next, we categorized the paths into six groups corresponding to the different target distances (50%, 58%, 67%, 75%, 82% and 90% of participants' maximum arm length) to compare each of these target distances in different conditions (real vs virtual and visuo-haptic vs no visuo-haptic

feedback). As explained in Section 4.2.2, we had 5 repetitions for each target distance. Then, the pairwise distances between the paths of each group were calculated and the path with the minimum average distance to the other paths was selected as the reference path. Next, the four paths were normalized based on the reference path to be used for the data analysis. Finally, we computed the Euclidean distances between the reference path and the four normalized paths.

The results from a 2x2 ANOVA analysis indicated that the distance between the paths were similar in the presence and absence of visuo-tactile feedback. However, we observed a significant difference between real and virtual environments ($F(1, 266) = 3.97, p < 0.05, \eta^2 = 0.02$). In a post hoc analysis, we found that the distance between the trajectories in group 1 with the target distance corresponding to 50% of participants maximum arm length was significantly different in real and virtual environments ($F(1, 47) = 4.96, p < 0.05, \eta^2 = 0.01$) (Figure 4.9). The distance between the paths was significantly smaller in the real environment ($M = 190, SD = 78.28$) as compared to the immersive virtual environment ($M = 429, SD = 73.62$). This indicates that the variability between the paths when reaching to close distances was much less in the real environment as compared to the immersive virtual environment. These results support the findings in Section 4.3.1.3 in which path lines become longer and less direct, and thus less efficient, in virtual as compared to real world viewing. Overall, due to the fact that physical reach motions in near field distances are very short in terms of reaching space, it is hard to make any strong conclusion based on these results and further investigation is warranted.

4.4 Conclusions and Future Work

In an empirical evaluation, we showed that characteristics of physical reach motions are different under viewing and feedback circumstances. Generally, participants were more accurate in the perceptual-motor task of reaching to the perceived location of targets in the real world condition as compared to its immersive virtual counterpart. Participants spent less time to complete the reaching task in the real world, but interestingly also had slower physical reach motion in the real world. This could be due to the fact that participants' depth judgments were more accurate in the real environment and consequently reached more accurately to the precise location of the targets in the real world. Whereas participants in the IVE overestimated depth and consequently overreached taking longer trajectories to reach the target. We also noticed that participants in the real world took

shorter duration of the reaches and lower speed as compared to the participants in the virtual world condition. However, in the IVE participants took slightly longer time to complete the reach task, but reached with higher speed and acceleration. This increase in speed of the physical reach motions could also potentially contribute to near field distance overestimation. Generally, participants in the no visuo-haptic feedback condition were less accurate and took less efficient path trajectories to the target in the virtual world as compared to real world viewing. Participants spent significantly higher velocity to account for the inefficient and indirect path towards the target in virtual environment as compared to real world viewing. However, these negative effects were not present in the presence of visuo-haptic feedback, in which participants in real and virtual environments performed very similarly [47]. In sum, providing feedback during manual activity in VR is highly important as it can remedy many of the perceptual-motor differences between real and virtual environments.

We also investigated the effects of visual and/or haptic feedback on properties of physical reach motion in IVEs. We found that lack of visual information could greatly degrade physical reach performance especially by increasing the perceptual error, the time to complete the reach, as well as the velocity of physical reach motion. In our research, we also found that the presence or absence of haptic feedback does not seem to have any positive or negative effects on the error rate or the ratio between the reached location to the actual target location with respect to the participants' physical reaches in the IVE. Therefore, having accurate visual feedback alone may alleviate the lack of haptic feedback on the accuracy of reaches to the target during physical reaching in 3D interaction in IVEs. However, the presence of haptic feedback significantly changed other properties of the physical reach motion, such as time to complete the reach task, distance traveled, and average velocity towards the target. In most applications of Virtual Reality technology as well as in most experimental work conducted in laboratories, there is limited or no opportunity for the users to receive multi-sensory feedback during manual task performance. In the majority of the best current existing applications, haptic feedback is missing, which could potentially result in inaccurate or inefficient performance. So, in VR applications where users are interacting with the environment, such as manufacturing, search and rescue missions, and military training, it is important to provide users with ample sensory feedback and opportunity to calibrate perceptual-motor systems [4] for enhanced performance.

One of the limitations of this study was that we characterized human reach motion using the end effector location only. Therefore all the observations in this work could only apply to selection types of activities based on the location of the end effector in a manner similar to using

a 3D input device such as a stylus, wand or joystick. In future studies, we would like to also track the elbow, shoulder and neck to investigate how users reach from different vantage points and approach angles using a richer kinematic data. Thus, we plan to employ a motion capture system to track the torso and limb joint positions and angles to investigate physical reaching behaviors, and how their properties differ between real and virtual environments and in the influence of visuo-haptic feedback. Another limitation of this study was the lack of a self-avatar in virtual interaction conditions. In the IVE, participants were unable to see their hand and arm, and only saw a floating stylus representing their end effector location. Whereas in the real world condition, they were able to see their hand and arm in the different feedback conditions along with the stylus denoting the end effector location. Therefore, we also plan to empirically evaluate the impact of an immersive self-avatar in the immersive virtual environment, and examine its effects on altering the properties of human reach motion as compared to the current no self-avatar interaction conditions in the IVE.

Chapter 5

Effects of Anthropometric Fidelity on Reach Boundary Estimation

In VR applications, avatars are a digital representation of the users from either a third-person or a first-person perspective. A life-size visual representation of the user from a first-person perspective is also known as immersive self-avatar where the user's body is co-located with its virtual representation. Research has shown the presence of an avatar in the IVE affects how people perceive their environment. The presence of other virtual agents also influences the user's behavior in IVE [24, 70, 81]. Recent perception research suggests the presence of an avatar influences the user's space perception in medium field in IVEs [48, 37, 79]. Mohler et al. [48] showed that accuracy of users' distance estimation was altered via the self-avatar representation; fully-articulated and tracked self-avatars that animated in correspondence with the users' movements produced the highest improvement and no avatar produced lowest improvement on users' space perception through blind walking for distances greater than 1m. Similarly, Ries et al. [60] investigated the effect of self-avatar visual fidelity on users' spatial perception via direct blind walking. They provided users with either a fully tracked, high-fidelity avatar or a fully tracked but simplified avatar (only the tracking marker locations were presented using small spheres). They then compared their results with no avatar condition and found that participants with low-fidelity avatars performed only slightly better than those in a no avatar condition. However, participants' distance estimation with high-fidelity avatar was significantly more accurate than the low-fidelity and no avatar conditions. They concluded that

a minimal level of avatar visual fidelity may be required to improve users' distance judgment.

Most of the previous research has investigated the space perception in medium field via walking. The main visual contributors during walking are height of the eyes and a fixation point on the ground which is approximately two steps ahead [21]. However, the two main visual contributors in on-line control of hand movements while reaching are a) the position of the hand and b) the hand motion [65]. Generally, walking and reaching use two distinct mechanisms which can affect distance estimation quite differently in the presence of the self-avatar. It has been shown that the reaches become more accurate when users can see their arm while reaching in the real-world [55, 25]. McManus et al. [44] showed that the users' performance in terms of accuracy and time to complete in the presence of self-avatars improved when users were allowed to interact with the environment. Overall, it is not well understood if the anthropometric symmetry of self-avatar with its real-world representation have any effect on users' distance estimation via walking and reaching tasks in IVE. The presence of self-avatar and its visual fidelity may have a greater impact on users' distance estimation in reaching activities when the fixation point is at the end-effector (hand) as compared to walking tasks as the fixation point is somewhere in front of legs. Thus, we are interested to explore how the anthropometric characteristics of the arm and hand affect users' perception of their hand position and movements. In this experiment, the real-world condition (Figure 5.2.a) is the reference group to which all the other three conditions in IVEs with different anthropometric similarities to the real-world representation (Immersive Self-Avatar, Low-Fidelity Self-Avatar and End-Effector only) will be compared[1]. The Immersive Self-Avatar condition has the highest anthropometric similarity to the real-world condition in which a customized male or female self-avatar (figure 5.1) was created using an inverse kinematic system with an accurate head and hands positions using HTC Vive HMD and two controllers (figure 5.2.b). In this condition, it is expected that the participants' reaching behavior will be very similar to real-world condition in terms of accuracy and perceived reachability to the target.

However, creating a self-avatar that correspond to users' movements and arm lengths is computationally expensive as compared to the rendering of the joint positions only. Based on the basic principle of visual vector analysis, the human brain automatically connects a series of proximal elements if they move equally and together [28]. From the mechanical point of view, by knowing two joints' positions, we are able to connect those two proximal points with a known length which is the

[1]The results from the real-world data was published at Acta Psychologica Journal [15].

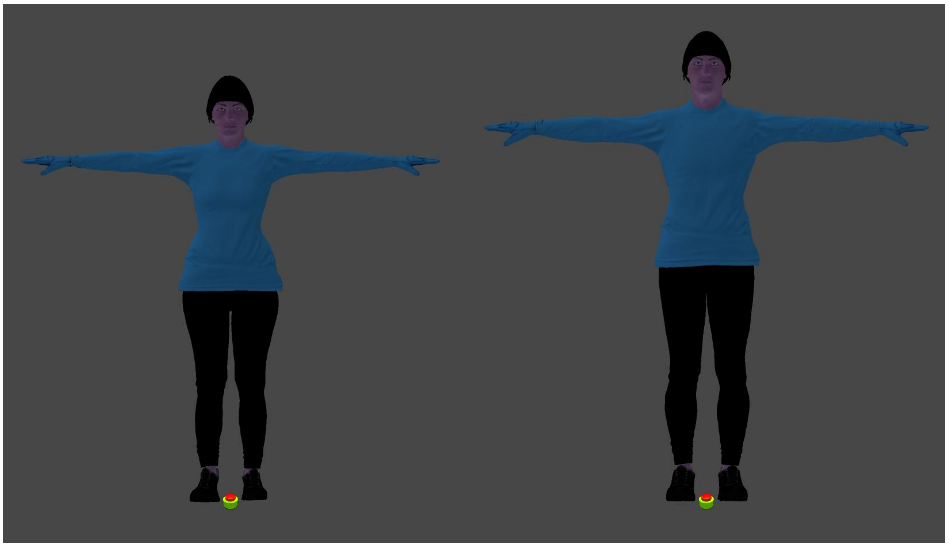

Figure 5.1: A male (right image) or female (left image) avatar was used in this experiment based on the users' gender. A calibration phase was conducted at the beginning of the experiment to scale each participants arm length and height accordingly.

length of the bone between the joints. Therefore, we are able to determine the end position of the limb. Runeson and Frykholm [63] studied the effects of the real-world joint positions representation on medium distance estimation. They attached retroreflective cloth-based tapes to the ankles, knees, wrists, elbows, hips, shoulders, and forehead of two actors. They then recorded the throwing action of those actors towards 6 target distances at various locations from 1.75 m to 8 m. Runeson and Frykholm demonstrated that by showing the joint positions only to the participants, they were able to accurately estimate the distance towards the targets. In this study, the low-fidelity self-avatar uses a similar method as Runeson and Frykholm [63], but in IVEs. In the low-fidelity self-avatar viewing condition, the main joints[2] will be illustrated using blue spheres. The radius of each of the spheres representing the joints was extracted from the Anthropometric source book [12] to create a custom low-fidelity avatars. The same inverse kinematic system was employed to calculate the position of the joints with addition of two HTC Vive trackers to track the elbows accurately (figure 5.2.c).

The third condition mainly focuses on the end-effector or the hands position and movement. The End-Effector viewing condition only renders the tool held by the participants to reach to the target without any other information regarding joint or limb positions (figure 5.2.d). If the position of the hand and its movements are the main visual contributors while reaching [65] then eliminating

[2]Illustrated joints are: ankles, knees, wrists, elbows, hips, shoulders, neck and forehead

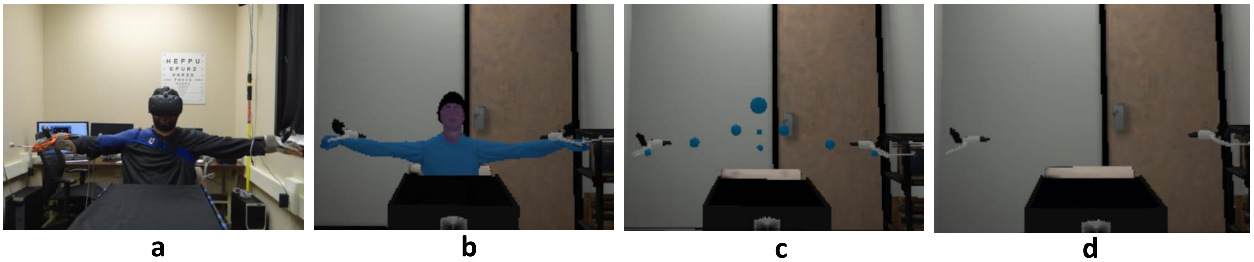

Figure 5.2: Left to right: Real-World condition and a digital illustration of I) Immersive Self-Avatar, II) Low-Fidelity Self-Avatar, and III) End-Effector (no avatar).

the self-avatar should not significantly affect reach estimates. However, other studies showed that having self-avatars impact distance estimation in medium field as compared to having no avatar or static avatars [48, 37, 79]. Thus, it is expected that the participants in the End-Effector viewing condition perform poorly relative to the other two conditions with higher anthropometric fidelity. Current VR systems such as Oculus Rift and HTC Vive provide the user with an accurate end-effector position and orientation tracking. Therefore, it is particularly interesting to study the differences between Immersive Self-Avatar and End-Effector only. The results of this study may help other researchers to decide between rendering Immersive Self-Avatars or the End-Effector/controllers in their VR simulations.

Therefore, we are investigating the effect of the visual fidelity of the self-avatar on users' distance perception, reach boundaries, and physical reaching properties in near-field in IVEs. To create a realistic animation depicting users' motion in near field, the simulation requires very accurate head and hand tracking. Many techniques have been developed to improve the real-time rendering and animation to produce a high-fidelity Immersive Self-Avatar in IVEs. In the following experiment we will use HTC Vive HMD and its two controllers to track the head and hands, along with two Vive trackers to track elbows positions (only for the Low-Fidelity Self-Avatar condition). Our research questions are as follows:

- How anthropometric fidelity affects reach estimates (accuracy)? How does anthropometric fidelity affect reach boundary perception?
- How does perceived reachability (verbal responses) differ in relation to anthropometric fidelity?
- How does anthropometric fidelity affect the properties of physical reach motion?

5.1 Hypothesis

There is little or no research on the visuo-motor calibration effects of visual fidelity of immersive self-avatars on distance estimation in interaction space in IVE. This study has four primary hypotheses. First, we hypothesize that just the existence of self-avatar or end-effector position will calibrate users' interaction space depth perception in an IVE. Therefore, participants' distance judgments will be improved after the calibration phase regardless of self-avatars' visual fidelity. Second, the magnitude of the changes from pre-test to post-test will be significantly different based on the visual details of the self-avatar presented to the participants (Self-Avatar vs Low-Fidelity Self-Avatar and End-Effector). Third, we predict distance estimation accuracy will be the highest in Immersive Self-Avatar condition and the lowest in End-Effector condition. Forth, we predict that the properties of physical reach responses vary systematically between different visual fidelity conditions.

5.2 Experiment Methodology

5.2.1 Participants

Forty one undergraduate students (26 females and 15 males) from the student population of Clemson University were recruited and received course credit for their participations in the study. In this experiment, all participants required to be right-handed as all equipment to be used was for right-handed participants. As participants enter the testing area, they will be given a brief overview of the purpose of the experiment and informed consent will be obtained. All participants will be tested for visual stereo acuity. Participants will be randomly assigned to one the three conditions 1) Immersive Self-Avatar, 2) Low-Fidelity Self-Avatar and 3) End-Effector, described in Section 5.3.1. The real-world data was also gathered from eleven undergraduate students and was used as the reference group[3] (Figure 5.3).

5.2.2 Apparatus and Material

Figure 5.4 depicts the experiment apparatus which consists of a custom table and a chair, HTC Vive HMD and two controllers, and five Polhemus electromagnetic sensors. The table was 50 cm wide and 130 cm long, and 76.2 cm tall which is standard table height. An array of 125 red

[3] The results from the real-world data was published at Acta Psychologica Journal [15].

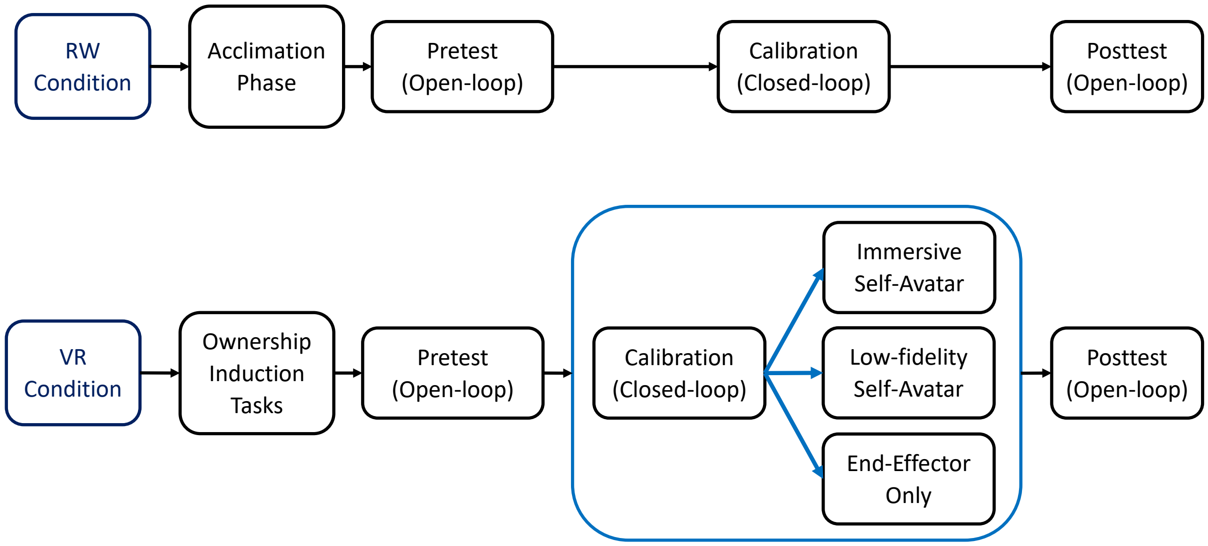

Figure 5.3: Experiment design.

LED lights at 1 cm interval was lined up in the center of the table as visual targets for the reaching task. Participants were asked to sit with their backs against the back of the chair. The chair was placed approximately 20 cm from the table and aligned midway between participants' eyes and right shoulder. That was done in order to keep the distance from the center of the eyes to the LED target line the same as the distance from the right shoulder to the LED target line on the table.

Each target consisted of a set of three neighboring LED-lights that could be turned on and off via an Arduino controller. The LED-light configuration made the target area easier to see and it also provided visual cues for binocular depth perception as well as the motion parallax (Figure 5.5). Participants were instructed that only the mid-LED light corresponded to the target distance on the table, with the other two lights illuminated the length of the target area was 3 cm. Blender and Unity3D were used to model the visual replica of the experimental apparatus and surrounding environment. All these visual components were carefully registered to be co-located with the corresponding physical components.

The HTC Vive controllers were mounted using a wrist brace and a 3D-printed plastic mold on top of the participants' wrists. This configuration helped to provide a consistent orientation of HTC Vive controllers across all trails and all participants, which allowed experimenters to accurately model their wrist and hand position and orientation in VEs. A plastic rod with a rubber tip was inserted in a 3D printed plastic mold. Participants were instructed to lie their index finger on the

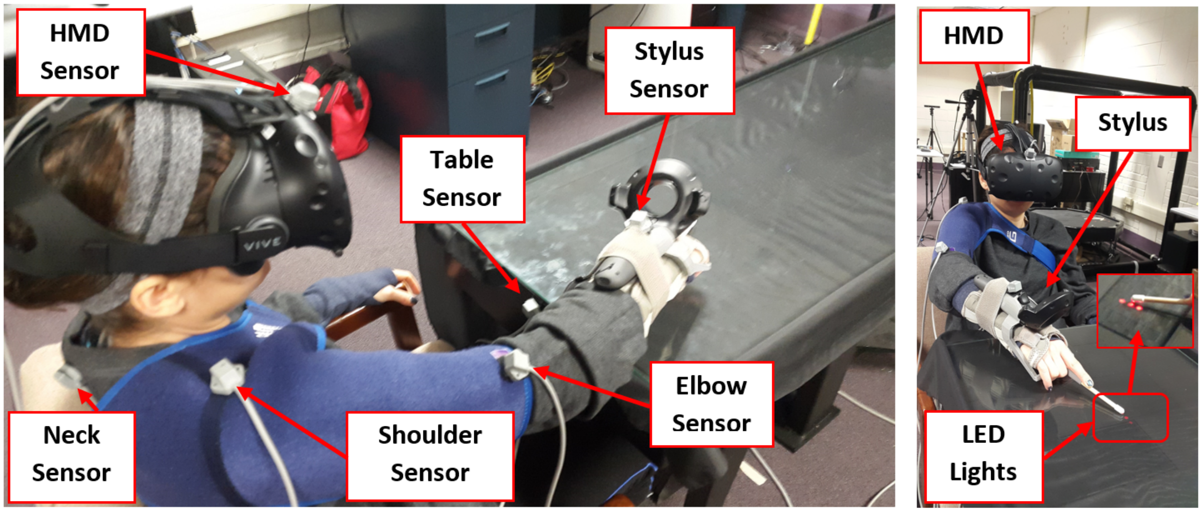

Figure 5.4: Shows the near-field distance estimation apparatus. The participant's head, neck, shoulder, elbow and stylus are tracked in order to record perceived distances of physical reach in the IVE.

Figure 5.5: Three LED lights will be illuminated on the table for each trial.

rod and reach to the target with the tip of the tool on their right hand (Figure 5.4).

Participants' movements were tracked and logged by the experiment simulation in a six degrees of freedom using a Polhemus Liberty electromagnetic tracking system. Participants were outfitted with five Polhemus sensors, placed on their forehead, neck, right shoulder, right elbow and tip of the plastic rod in their right hand. Aside from the sensor on the forehead, the other four sensors were placed on the bony protrusions at those points on the body. The base for the Pohlemus system was located underneath the table and out of view of the participants. The virtual environment, which was a recreation of the room in which the experiment took place, was displayed using a HTC Vive HMD.

Participants were instructed on how to make a physical reach as demonstrated by the experimenter. Participants were required to reach as quickly and accurately as possible to the target. Before participants made their physical reaches, they were asked to make a verbal judgment on the reachability of the target by saying yes or no, indicating if the target was reachable or unreachable, respectively. During the experiment participants were seated on a chair and were instructed to remain seated while reaching to the target. Thus, the major restriction participants had was that they must remain seated (meaning stay on the seat pan) during any attempted reach. During the course of the actual reach participants may engage their arm only, or may engage their entire upper body (i.e. bending at the waist to reach farther). Participants rested their arms on the armrests of the chair. Each trial started and ended from the same resting position on the right armrest. To ensure uniformity in starting positions across participants, it was emphasized to participants that their starting posture was critical for the study. Participants were instructed to maintain a good posture during the experiment and started each trial with their backs touching the back of the chair.

In pre-test and post-test phases, trials consisted of 5 random permutations of 13 target distances corresponding to LED numbers (14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, 91, and 98) for a total of 65 trials. The LED target distances ranged from 20.5 cm to 121.5 cm with approximately 8 cm interval between each two targets. Similarly, in calibration phase, only 45 trials were presented which were 5 random permutations of 9 target distances corresponding to LED numbers (10, 20, 30, 40, 50, 60, 70, 80, and 90) ranged from 15.7 cm to 107.65 cm with approximately 11.5 cm interval between each two targets.

In any given block of trials, participants were asked to reach for a target with their right arm and hand. Participants were given a Vive controller to hold. The Vive controller was 26.5 cm

Figure 5.6: HTC Vive controller with its plastic mold attached to the participant hand using a wrist brace.

long from base to tip, 3 cm wide at the base of the handle, 5 cm wide at the top of the handle, 3 cm deep at the handle, and was 12 cm wide at its widest point. The Vive controller allowed the experimenters to accurately model participants' wrist position in VR. The controller was outfitted with a plastic mold that can hold a 10 cm plastic rod with a rubber tip (Figure 5.6).

5.2.3 Visual aspects

Participants wore a HTC Vive HMD with a combined resolution of 2160 x 1200 pixels, field of view of 110 degrees, and the weight of 563 g for viewing a stereoscopic virtual environment. Participants inter-occular distance was measured before the experiment was initiated and this was then used to set the distance between the two displays on the HMD. The simulation consisted of the virtual model of the experimental room and apparatus created using Blender and Unity3D. The virtual replica of the room, apparatus, self-avatar or end effector, chair, HTC Vive controllers and accessories were included in the model.

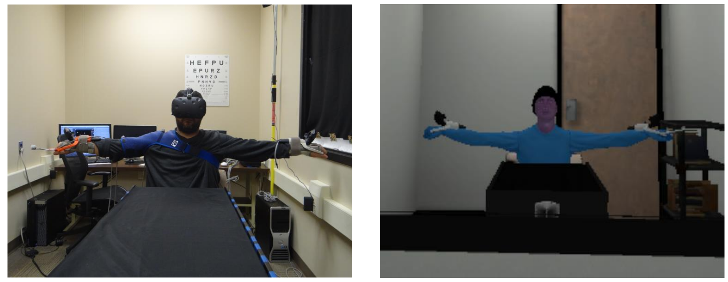

Figure 5.7: Participants were instructed to make a T-Pose to measure the distance between the two controllers using the HTC Vive positions. This distance was then used to calculate the arm length of the participant to generate a custom avatar. The position of the head was also logged and was used to calculate the height of the participants.

5.3 Procedure

As participants entered the testing area, they were given a brief overview of the purpose of the experiment and informed consent was obtained. All participants were asked to sit on the wooden chair at one end of the wooden table. Various motion sensors were placed on the participant through the use of a long-sleeve shirt and a shoulder strap support (Figure 5.4).

Before any trials occurred, the distance between two controllers attached to the hands and wrists was measured and collected using the HTC Vive controllers (Figure 5.7). The experimenter then measured participant sitting height (floor to top of head) and various aspects of their arm, such as the length from shoulder to elbow, and the length from the elbow to the end of the index finger. The experimenter also measured various aspects of the participants' arms relative to the positions of the sensors.

5.3.1 Experiment Design

This experiment utilized a 4 (Condition: Immersive Self-Avatar, Low-Fidelity Self-Avatar and End-Effector plus the reference group (Real-World condition)) by 3 (Phase: Pretest, Calibration, Posttest) mixed groups design (Figure 5.3). Participants were assigned to one of the experiment conditions. Condition was a between-subjects variable and phase was a within-subjects variable. The first two conditions involved the use of a self-avatar that was directly proportional to the dimensions of the users own arm where the visual fidelity was altered in the calibration phase. All participants completed three successive stages (1) induction/acclimation stage, 2) testing stage 3) measurement stage) depicted in Figure 5.3.

- **Real World** ***(RW)*** - *Reference group*: Participants completed all three stages (Figure 5.3) in the real-world (all other conditions were conducted in the virtual environment). The accli-

mation phase was performed only to get participants used to the equipment that they were outfitted with described in 5.2.2.

- **Immersive Self-Avatar *(SA)***: Participants arm length and eye height were measured using the HTC Vive HMD and its two controllers (also measured for the Low-Fidelity Self-Avatar and End-Effector conditions) to create a custom self-avatar for each participant. This self-avatar was then used during the induction and testing stages.

- **Low-Fidelity Self-Avatar *(LF-SA)***: Participants were shown the joint positions only presented by blue spheres at the location of the head, neck, shoulders, hips, elbows, wrists, knees, and ankles similar to Runeson and Frykholm [33] during the induction and testing stages.

- **End-Effector *(EE)***: Participants only were able to see their end-effectors (i.e. the controller and the rod) in the induction and testing stages to perform the required tasks.

As discussed in section 5.3.1, the experiment consisted of three stages (Induction, Testing, and Measurement) depicted in Figure 5.3.

- ***Induction Stage*** To get participants acclimated to the new environment (mainly for VR conditions) and be well grounded in the IVE, they spent a few minutes interacting with the environment immediately after they were outfitted with all the equipment described in section 5.2.2. The virtual experiment room in the induction stage was decorated with several objects such as a poster, clock, lamp, bookshelf, and a mirror. In this stage, participants were asked to extend their arms to the sides of their body, above their head and in front of them, respectively, and move them around while looking at themselves in the mirror to enforce self-embodiment. Participants were then instructed to complete some additional tasks to adopt the self-avatar as their own suggested in previous work [2, 32, 42].

  – *Pointing to Environment:* Pointing to different objects in the room with the tip of the stylus (Figure 5.9).

  – *Pointing to Self:* Touching their shoulders, elbows and wrists using the right and left controllers, respectively (Figure 5.10).

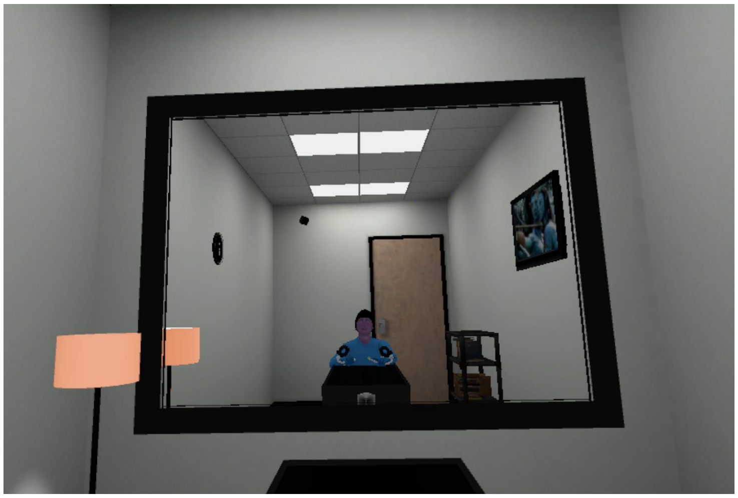

Figure 5.8: The virtual experiment room in the induction stage. A poster, a clock, a lamp, a bookshelf, and a mirror were placed in the room to be used for the induction tasks.

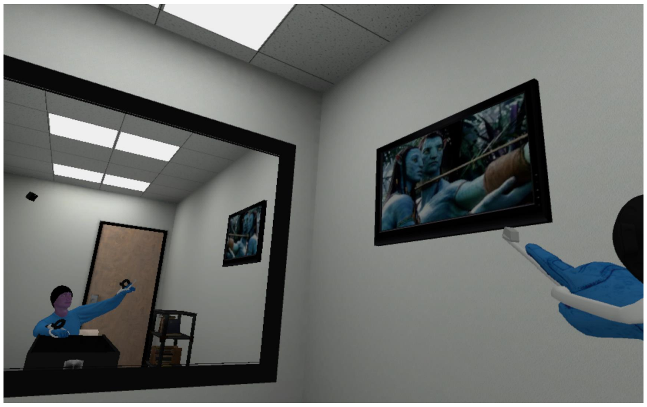

Figure 5.9: In the induction stage, participants were asked to point to different objects in the room.

a b c

Figure 5.10: In the induction stage, participants were asked to touch their a. shoulders, b. elbows and c. wrists using the right and left controllers.

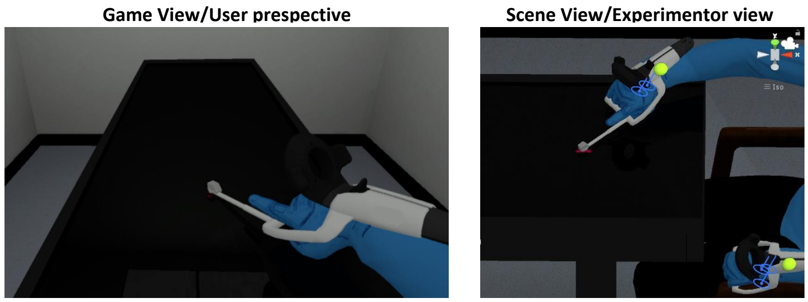

Figure 5.11: **Right:** Participant adjusted the tip of the stylus therefore it was co-located with the centered LED-lights. **Left:** Experimenter could visually monitor the users' performance.

- *Peripheral Stimulation:* Touching the inner part of their forearm and moving one of the controllers from their elbow to wrist and back several times. Then repeating the same task with the other hand.

These tasks were completed in the induction stage where participants were able to see their actions either by looking directly at themselves or by looking in the mirror. The induction stage took about five minutes to conclude.

- ***Testing Stage***

  - *Pre-test Phase:* Participants were instructed to make a verbal judgment on the reachability of illuminated targets. If they stated they could reach the target, they made their physical reach with their eyes closed (a memory based or an open-loop task). After reaching to the target, participants were instructed to return their hand and arm to the starting point to begin the next trial. In this phase, participants only received haptic feedback associated with the tip of stylus coming in contact with the surface of the table during physical reaching to the perceived location of the target. They were not required to reach to targets they perceived unreachable.

  - *Calibration Phase:* Similar to the pre-test phase, participants were required to make a verbal judgment before attempting to reach. However, regardless of their verbal judgement they were required to attempt a reach in order to enforce calibration for all the target distances (i.e. allow them to calibrate distances they are able to reach to that they perceive as unreachable). After the physical reach was made, participants vision was then restored, providing them with visual feedback of their performance and they were asked to correct their estimations (Figure 5.11).

– <u>*Post-test Phase:*</u> This phase was identical to the pre-test phase and occurred immediately after completion of the calibration phase to preserve the modified action capabilities of different conditions for the post-test (i.e. a long delay between these two phases might cause the calibration to disappear).

- ***Measurements Stage*** Participants actual reaching ability was measured with two types of reaches; 1) reach to the table without engaging their shoulders or backs (measuring preferred reach boundary) 2) reach absolutely as far as they could with no restrictions other than keeping their feet flat on the floor and remaining seated on the chair (measuring absolute reach boundary). The experimenters again measured various aspects of the participants arm to ensure that the positions of the sensors. Lastly, a body ownership questionnaire was completed which measured the degree of body ownership they felt over the avatar or altered avatar conditions in IVE.

5.4 Data Preprocessing

Similar to previous chapters, we extracted the start and the end of the ballistic reach by analyzing the XY position trajectories and speed profile associated with the physical reach motions for the sensors attached to the user's head, neck, shoulder, elbow, and hand. These data was then used to analyze the reaching behavior of the users under different circumstances.

5.5 Results

As discussed in section 5.2.2, five electromagnetic sensors were utilized to tracked movements of participants head, neck, right shoulder, right elbow and tip of the tool. An initial analysis showed that there was a high correlation between the data from different sensors. Therefore, in order to eliminate the suppression within model, only the data collected from the tool, which was the strongest predictor, was added to the model. Furthermore, the data from the other sensors could be used to look at the human upper body movements while performing a reaching tasks in different environments and conditions discussed in section 5.7.

Participants' maximum arm reach, measured by the tracking system, was utilized in the analysis instead of participants' arm length since it is a better measurement variable of action

capabilities for the affordance of reaching. There are three categorical variables within the analyses listed below:

- *Condition:* real-world condition was used as reference group
- *Phase:* pre-test phase was used as reference group
- *Error Directionality:* overestimation was used as reference group

5.5.1 Transformed Variables

Three new variables were created using the "actual/presented distance", "perceived distance" and "maximum arm reach" to be used for data analysis. The new variables are as follows:

- ***Error term*** was calculated by taking the distance between the actual distance and perceived distance using the following equation.

  $$Error = PerceivedDistance - PresentedDistance \tag{5.1}$$

  This is the liner error term where negative and positive values indicate underestimation and overestimation, respectively. The error term was then broken down into two separate variables named error directionality and absolute error. Directionality is a binary variable indicating whether the participant over- or underestimated distance. Furthermore, by extracting the directionality from the error term, the absolute error will remain. For the data analysis, overestimation (also known as positive error) was used as reference group and coded as 0 while underestimation (also known as negative error) was coded as 1.

- ***Action taken*** variable or verbal response indicates whether or not participants made a reach towards the target during each trial. For the data analysis, "reaching" was used as the reference category and coded as 0 while not reaching was coded as 1. This variable was then used in the creation of the third variable.

- ***Correct judgment*** is another binary variable created taking into account the reach envelope (also known as maximum arm reach), actual or target distance, and action taken (also known as verbal report). Trials in which the participants reached to a target where the presented distance was within the reach envelope or did not reach where the presented distance was

outside the reach envelope marked as correct judgment (reference group). On the other hand, incorrect judgments were defined where participants reached while the target was outside the reach envelope or did not reach where the target was within reach envelope and coded as 1.

5.5.2 Outlier Analysis

For each analysis full models were conducted in order to obtain residual. Then the standardized residuals were calculated and the potential outliers were identified. Trials with excessive standardized residuals outside of a normal distribution were removed from the analysis [13]. Overall, less than 1% of the data was eliminated from the data analysis.

5.5.3 Hierarchical Linear Modeling (*HLM*)

The repeated-measure design of this experiment created natural nesting of the variables within participants. To determine the amount of nesting, the intraclass correlation (ICC) of the null model (i.e. the intercept only model) was calculated for each of the main dependent variables (absolute error, action taken, and correct judgment). The high ICCs were obtained running the null model of all the dependent variables (e.g. ICC = 23% for the absolute error). A multilevel modeling approach is required for an ICC greater than 2-3% [5, 26]. One of the great advantages of HLM is that all levels of variance across all trials and within participants could be used and not be reduced to just the mean value similar to mean based analysis. This type of approach is more flexible and allows for the estimates, errors, and effect sizes to be more accurately modeled than traditional approaches such as repeated-measures ANOVA [13].

Variables were categorized as either level 1 (L1) or level 2 (L2) predictors. Level 1 variables change within a participant and they are collected at each measurement occasion (e.g. presented distance, presented distance quadratic, phase, and directionality). These variables are going to be carrying residual variance. Thus, error variance for L1 predictors and intra-level interactions (L1*L1) is indexed by a reduction in residual variance. Level 2 variables do not change within a participant (i.e condition). These variables are going to be carrying intercept variance. Thus, the L2 error variance is accounted for the reduction in intercept variance. Lastly, cross-level interactions (L1*L2) are indexed by the reduction in Level 1 slope variance. In multilevel modeling, the effect sizes are known as pseudo-R^2 and are the percent in the reduction in error variance of the corresponding

variance (e.g. residual for L1 predictor and intercept for L2 variance). Pseudo-R^2 (also known as ΔR^2) is only calculated for significant effects with all other predictors remaining within the model to control the unique effects.

For the data analyses, only the pre- and post-test data were included. Participants in the calibration phase were performed a different task where they were able to see the results of their reach and also were forced to reach to presented targets even if they perceived the target to be outside of their reach envelope [4]. However, it is common to compare pre- and post-test data to determine the effect of calibration phase similar to the initial studies [18, 19, 15] discussed in previous chapters.

The current study had four primary hypotheses. The first hypothesis was based on previous findings in which calibration phase or interaction with the virtual environment would improve accuracy and make responses more consistence. Therefore, it is predicted that calibration would occur regardless of the amount of visual information participants received during calibration phase which evidenced by the effect of phase. Secondly, it was hypothesized that the magnitude of change from pre- to post-test would be impacted by the visual information participants received. Thus, the second hypothesis is depended upon a significant two-way interaction involving phase moderated by condition. Although, the two-way interaction was not significant, a trivial but significant three-way interaction involving the quadratic presented distance moderated by phase and condition was found stating that the interaction between phase by condition is dependent on the quadratic presented distance. The third hypothesis emphasis was on the general differences between all the experiment conditions that could be due to the induction stage or calibration phase. It is predicted that participants in immersive self-avatar would have the lowest error when estimating distance (closest to the real world condition) and end-effector condition would have the highest error term as compared to other conditions which evidenced by the effect of condition. The forth hypothesis was based on the second study in which the properties of reach motion would be affected by the phase and condition. Thus, it is predicted that the properties of physical reach responses vary systematically between different visual fidelity conditions and from pre- to post-test evidenced by the main effect of phase and condition for each of the dependent variables. It is expected that participants would take a faster reaches, shorter time and longer path length in no avatar condition as compared to self-avatar viewing conditions. It is predicted that participants responses gradually move towards slower reaches, longer time to complete and shorter path length when more detailed self-avatar is

[4] A separate analysis will be conducted on the calibration data which will be discuss in the section 5.7

presented similar to the finding in initial study 2 [19].

5.5.4 Absolute Error

A multilevel model was conducted with absolute error as the dependent variable and actual/presented distance (PD), quadratic presented distance (QPD), phase, directionality, and condition as independent variables. All of the independent variables and appropriate interactions were included into the model as predictors. In terms of predicting absolute error, a significant main effect of presented distance (F = 12.64, p = 0.001) was obtained which indicates a linear relationship between the presented distance and absolute error. However, a significant main effect of quadratic presented distance (F = 9.53, p = 0.003) showed a non-linear relationship between the absolute error and QPD which indicates that distance judgments were not consistent across all target distances. Thus, error would increase as the target distance gets farther. Therefore, the quadratic presented distance is a better fit for the model and will be used throughout the document (Table 5.1). The other two Level 1 predictors, phase (F = 7.88, p = 0.007) and directionality (F = 5.63, p = 0.024), had significant main effects and a two-way interaction (F = 4.25, p = 0.045). Participants tended to overestimate distance with a higher overestimation in pre-test as compared to post-test. The amount of underestimation was smaller in post-test as compared to pre-test phase (Figure 5.12). There was two other Level 1 interactions, quadratic presented distance moderated by phase ($F = 34.11$, $p < 0.001$) stating that absolute error decreased from pre- to post-test as the presented distance increased and quadratic presented distance moderated by directionality ($F = 85.65$, $p < 0.001$) stating that participants tended to overestimated distance as the presented distance got farther (Table 5.2). Condition ($F = 3.06$, $p = 0.039$) had a significant main effect as well. Although, a two way interaction of phase moderated by condition was not statistically significant, there was a significant three-way interaction of quadratic presented distance moderated by phase and condition (F = 3.61, p = 0.016). Further analysis revealed that only the self-avatar condition was different from real-world condition. A three-way interaction of quadratic presented distance moderated by phase and directionality was also significant ($F = 3.85$, $p = 0.05$).

Overall, participants preformed better in post-test phase (M = 3.25, SE = 0.19) as compared to pre-test phase (M = 3.63, SE = 0.21) suggesting that calibration phase improved the accuracy of reach estimates. As predicted participants' reach estimates were significantly different from real-world condition. Participants in real world condition had the smallest error while

Phase	Directionality	
	Underestimation	Overestimation
	Mean (SE)	*Mean (SE)*
Pre-test	3.08 (0.32)	4.18 (0.22)
Post-test	2.69 (0.24)	3.8 (0.22)

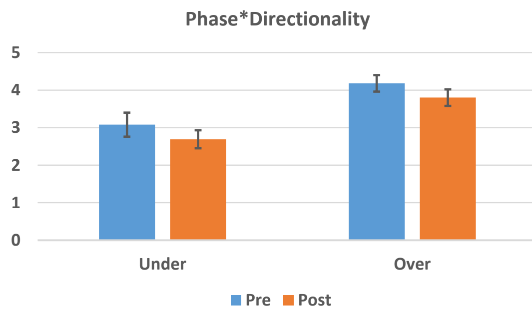

Figure 5.12: Phase*Directionality interaction bar graph.

Table 5.1: F values, Significance Tests, and ΔR^2 for Absolute Error.
Dirc., Cond., PD, QPD, L1, and L2 stand for Directionality, Condition, Presented Distance, Quadratic Presented Distance, Level 1, and Level 2 respectively.

	Variance Location	**Predictors**	**F-Test**	**P-value**	R^2		
					L1	**L2**	**Interaction**
Main Effects	**L1**	PD	12.64	0.001	1.4		
		QPD	9.53	0.003	0.5		
		Phase	7.88	0.007	1.8		
		Dirc.	5.63	0.024	0.3		
	L2	Cond.	3.06	0.039		12.5	
Two-way Interactions	**L1**	PD*Phase	6.62	0.013	0.4		
		QPD*Phase	34.11	<0.001	0.3		
		PD*Dirc.	74.63	<0.001	2.8		
		QPD*Dirc.	85.65	<0.001	1.4		
		Dirc. *Phase	4.25	0.045	0.3		
	Cross-Level	PD*Cond.	0.47	0.708			NA
		QPD*Cond.	0.56	0.643			NA
		Phase*Cond.	2.42	0.077			NA
		Dirc. *Cond.	1.46	0.245			NA
Three-way Interactions	**L1**	PD*Phase*Dirc.	30.69	<0.001	0.6		
		QPD*Phase*Dirc.	3.85	0.05	0.06		
	Cross-Level	PD*Phase*Cond.	1.85	0.15			NA
		QPD*Phase*Cond.	3.61	0.016			<0.001 (trivial)
		Dirc.*Phase*Cond.	1.94	0.138			NA
		PD*Dirc.*Cond.	1.6	0.202			NA
		QPD*Dirc.*Cond.	0.34	0.794			NA
Four-way Interactions		PD*Phase*Cond.*Dirc.	0.36	0.79			NA
		QPD*Phase*Cond.*Dirc.	1.03	0.38			NA
				TOTAL R^2:	9.86	12.5	

Table 5.2: Fixed coefficients for the binary logistic regression regarding absolute error.

Predictors	**Coefficient (SE)**	**P-value**
Intercept	3.54 (0.44)	<0.001
PD	0.03 (0.01)	0.001
QPD	<0.001 (<0.001)	0.003
Phase	-0.71 (0.25)	0.01
Directionality	-0.56 (0.24)	0.02
EE Condition	1.50 (0.54)	0.01
LF-SA Condition	1.32 (0.56)	0.02
SA Condition	1.23 (0.54)	0.03
PD*Phase	-0.02 (0.01)	0.01
QPD*Phase	<-0.001 (<0.001)	<0.001
PD*Directionality	0.04 (0.004)	<0.001
QPD*Directionality	0.002 (<0.001)	<0.001
Directionality*Phase	-0.79 (0.38)	0.05
PD* EE Condition	-0.02 (0.02)	0.45
PD*LF-SA Condition	-0.002 (0.02)	0.93
PD*SA Condition	-0.02 (0.02)	0.34
QPD* EE Condition	<-0.001 (<0.001)	0.94
QPD*LF-SA Condition	<-0.001 (<0.001)	0.29
QPD*SA Condition	<-0.001 (<0.001)	0.98
Phase* EE Condition	-0.98 (0.71)	0.17
Phase* LF-SA Condition	-0.57 (0.72)	0.43
Phase* SA Condition	0.71 (0.71)	0.32
Directionality* EE Condition	-1.01 (0.69)	0.15
Directionality* LF-SA Condition	-1.38 (0.72)	0.06
Directionality* SA Condition	-0.48 (0.68)	0.49
PD*Phase*Directionality	-0.04 (0.01)	<0.001
QPD*Phase*Directionality	-0.04 (0.01)	<0.001
PD*Phase* EE Condition	0.01 (0.02)	0.68
PD*Phase*LF-SA Condition	-0.04 (0.02)	0.1
PD*Phase* SA Condition	-0.02 (0.02)	0.4
QPD*Phase*EE Condition	<0.001 (<0.001)	0.44
QPD*Phase*LF-SA Condition	<-0.001 (<0.001)	0.37
QPD*Phase*SA Condition	<-0.001 (<0.001)	0.03
Directionality*Phase*EE Condition	0.25 (1.03)	0.81
Directionality*Phase*LF-SA Condition	-0.32 (1.09)	0.77
Directionality*Phase*SA Condition	-1.91 (1.01)	0.07
PD*Directionality* EE Condition	0.04 (0.02)	0.06
PD*Directionality*LF-SA Condition	0.04 (0.02)	0.07
PD*Directionality* SA Condition	0.04 (0.02)	0.2
QPD*Directionality* EE Condition	<0.001 (0.001)	0.42
QPD*Directionality* LF-SA Condition	<0.001 (0.001)	0.49
QPD*Directionality* SA Condition	<0.001 (0.001)	0.92
PD*Phase*Directionality*EE Condition	-0.002 (0.04)	0.95
PD*Phase*Directionality*LF-SA Condition	0.02 (0.04)	0.58
PD*Phase*Directionality*SA Condition	-0.02 (0.04)	0.63
QPD*Phase*Directionality*EE Condition	<-0.001 (0.002)	0.36
QPD*Phase*Directionality*LF-SA Condition	-0.003 (0.002)	0.09
QPD*Phase*Directionality*SA Condition	-0.002 (0.002)	0.24
***p<0.05, **p<0.01, ***p<0.001**		

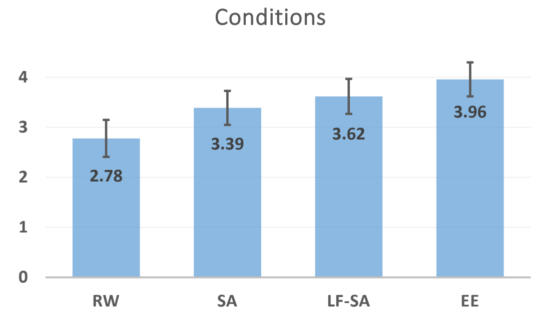

Figure 5.13: The mean and SE of all the conditions: RW: real-world, SA: self-avatar, LF-SA: low-fidelity self-avatar, and EE: end-effector conditions.

reaching towards targets ($mean = 2.78$, $SE = 0.37$) and the highest error was measured in the end effector condition ($mean = 3.96$, $SE = 0.34$), in which participants had the minimum amount of visual information. In the immersive self-avatar condition ($mean = 3.39$, $SE = 0.34$) participants performed slightly worse than the real world but better than the low-fidelity self-avatar ($mean = 3.62$, $SE = 0.35$) (Figure 5.13). A further investigation on the significant three-way interaction of quadratic presented distance, phase and condition was conducted and the data was split by phase. The results revealed that only the immersive self-avatar was significantly different from real-world condition Figure 5.14 and 5.15. As evidence in Figure 5.14, in pre-test phase, participants in self-avatar condition showed a similar behavior regarding the absolute error with real-world condition that could be due to the induction stage. The induction stage tried to evoke the self-embodiment without letting participants to calibrate to any of the target distances which could potentially cause participant to perform similarly to real-world condition in pre-test. However, after calibration phase in which participants received feedback, their performance in the self-avatar condition averted from the real world condition. Participants' distance estimation became more accurate for closer and far distances but the error increased for mid target distances which requires further investigation. Additionally, in the post-test phase, the two self-avatar viewing conditions' absolute error pattern became more similar to each other and parted from real-world condition.

5.5.5 Correct Judgment

The F-test for each of the predictors of whether participants made a correct judgment can be found in Table 5.3 and the fixed coefficients and standard errors can be found in Table 5.4. Both pre- and post-test data were included in the model. The real world condition was used as the

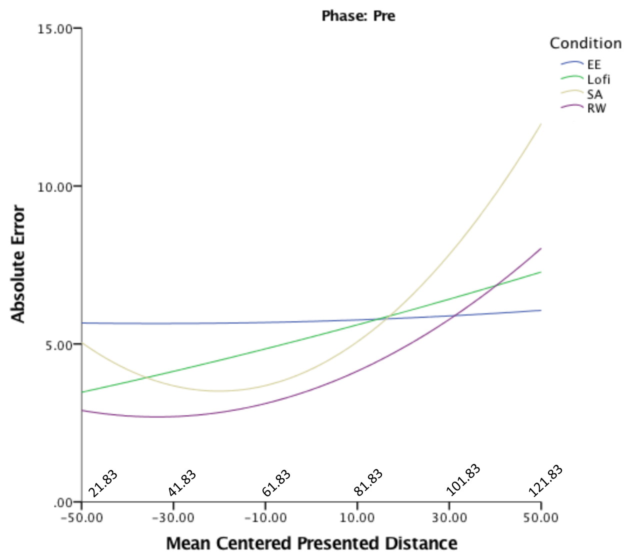

Figure 5.14: The pre-test graph of the two-way interaction of quadratic presented distance by condition. Presented distance is mean centered with the actual values listed above the x-axis for reference.

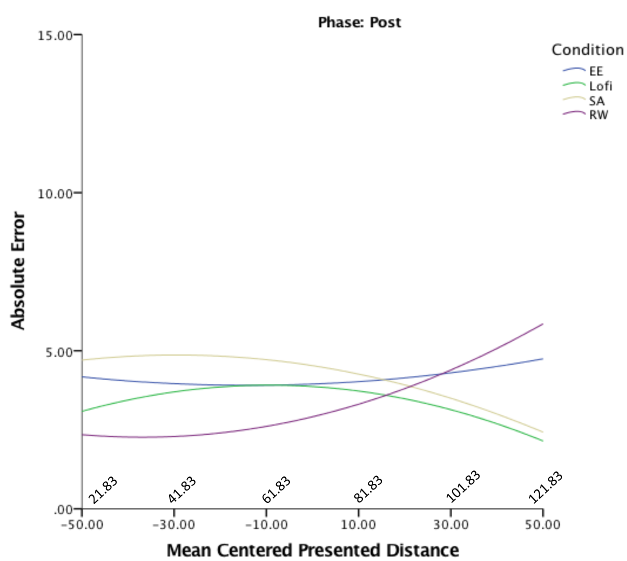

Figure 5.15: The post-test graph of the two-way interaction of quadratic presented distance by condition. Presented distance is mean centered with the actual values listed above the x-axis for reference.

Table 5.3: Fixed effect F-Tests for the binary logistic regression regarding correct judgment.

Fixed Effects		
Predictors	**F**	**P**
Presented Distance (PD)	209.12	<0.001***
Quadratic Presented Distance (QPD)	247.26	<0.001***
Phase	13.68	<0.001***
Trial Number	0.003	0.954
Condition	0.2	0.896
PD* Phase	0.1	0.756
QPD*Phase	1.15	0.285
Trial*Phase	1.96	0.162
PD*Trial	3.13	0.08
Phase* Condition	2.16	0.09
PD* Condition	5.42	0.001
QPD*Condition	15.54	<0.001***
PD*Phase*Condition	1.5	0.21
*p <0.05, **p <0.01, *** p <0.001		

reference condition (i.e. the coefficients for the other three conditions are the difference between them and the reference condition). The pre-test phase was used as the reference for phase (i.e. for phase this is the difference of the post-test phase from the pre-test phase).

There are several main effects that were significant in terms of predicting correct judgment. While the linear term of presented distance ($F = 209.12$, $p < 0.001$) was significant, what is more interesting is the quadratic term ($F = 247.26$, $p < 0.001$). This finding indicates that while there is a linear term for correct judgments the data fits better with a quadratic function. Therefore, judgments were dependent on presented distance meaning that judgments were not consistent across the presented distances which would result in a linear pattern. Instead, participants were much more likely to make an incorrect judgment either stopping to reach before the max of their reach envelope or trying to reach beyond their reach envelope around their maximum reach critical point. However, at extreme endpoint values (e.g. very close target distances and very far target distances) participants were most likely to make correct judgments (Figure 5.16). The other significant main effect was phase ($F = 13.68$, $p < 0.001$). Participants were more likely to make incorrect judgments in the pre-test ($mean = 0.91$, $SE = 0.02$) compared to the post-test ($mean = 0.93$, $SE = 0.02$).

There were five significant two-way interaction terms: presented distance moderated by both avatar conditions (SA: $F = 3.24$, $p < 0.001$ and LF-SA: $F = -0.13$, $p < 0.001$), quadratic presented distance moderated by the end effector condition ($F = 4.14$, $p < 0.001$) and both avatar conditions (SA: $F = 4.08$, $p < 0.001$ and LF-SA: $F = -5.65$, $p < 0.001$). While both avatar

Table 5.4: Fixed coefficients for the binary logistic regression regarding correct judgment.

Fixed Effects		
Predictors	**Coefficient (SE)**	**t**
Intercept	1.89 (0.21)	9.10***
Presented Distance (PD)	-0.11 (0.01)	-14.49***
Quadratic Presented Distance (QPD)	0.003 (>0.01)	15.74***
Phase	0.37 (0.10)	3.74***
Trial Number	>-0.001 (>0.01)	-0.06
EE Condition	0.16 (0.23)	0.71
LF-SA Condition	0.08 (0.24)	0.35
SA Condition	0.18 (0.23)	0.77
PD* Phase	-0.001 (0.01)	-0.21
QPD*Phase	0.001 (>0.01)	1.25
Trial*Phase	-0.01 (0.01)	-1.36
PD*Trial	>0.01 (>0.01)	1.63
Phase*EE Condition	0.02 (0.28)	0.07
Phase*LF-SA Condition	0.57 (0.29)	1.95
Phase*SA Condition	-0.01 (0.28)	-0.04
PD*EE Condition	0.001 (0.01)	0.14
PD*LF-SA Condition	0.03 (0.01)	3.24***
PD*SA Condition	-0.001 (0.01)	-0.13***
QPD*EE Condition	0.002 (0.001)	4.14***
QPD*LF-SA Condition	0.002(0.001)	4.08***
QPD* SA Condition	0.004 (0.001)	5.65***
PD*Phase *EE Condition	-0.04 (0.02)	-1.91
PD*Phase*LF-SA	-0.02(0.02)	-0.86
PD* Phase* SA	-0.001 (0.02)	-0.06
*p <0.05, **p <0.01, *** p <0.001		

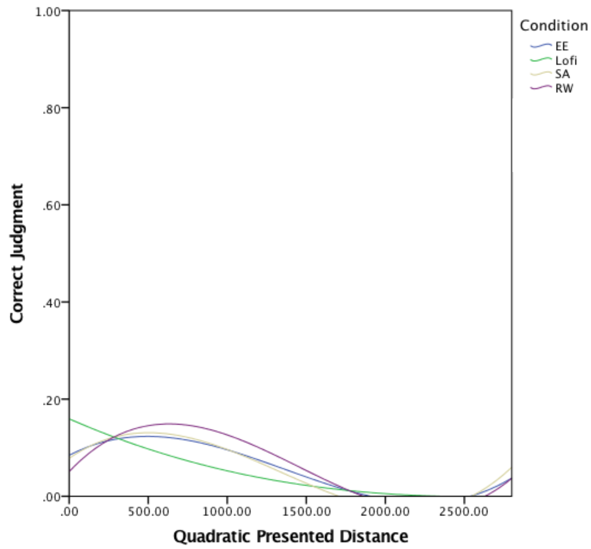

Figure 5.16: Probability of making an incorrect judgment based on quadratic presented distance by condition.

conditions moderated the linear presented distance term, again, the quadratic term demonstrates a better fit for the data. All three experimental conditions were significantly different from the real world control condition moderating the quadratic presented distance term. As discussed previously, the correct judgment was the reference group and coded as 0 (y axis in Figure 5.16). The x axis shows the quadratic presented distance, in which 0 is the mean of the presented distance and then going towards the positive values we are getting closer to the extreme endpoints of the data (close targets and far targets).

With this data we cannot speak more specifically to the four type of actual judgment combinations (action take: reach, no reach, and reachability of target: reachable, not reachable). However, due to an issue of unbalanced and scarce data in terms of the number of trials between the four types of actual judgments (reach vs. no reach, and the target being reachable vs. unreachable), a multinomial regression could not be performed [38]. Yet, it is still necessary to determine how reachability affects whether participants made reaches. Therefore, reachability was used as an additional predictor for the action taken variable.

5.5.6 Action Taken

Table 5.5 shows the fixed coefficients and standard errors for the predictors modeling whether participants reached or did not reach to the target. Recall that the coding for whether a reach was

Table 5.5: Fixed effects F-tests for the full model predicting action taken.

Fixed Effects		
	F-tests	**p**
Reachability	1742.58	<0.001
Phase	5.22	0.02
Condition	2.15	0.09
Reachability*Phase	23.8	<0.001
Phase*Condition	4.38	0.004
Reachability*Condition	2.17	0.09
Reachability*EE Condition*Phase	1.89	0.13

Table 5.6: Fixed coefficients and standard errors for the full model predicting action taken.

Fixed Effects		
	Coefficient (SE)	**t**
Intercept	1.81 (0.36)	5.05***
Reachability	-6.00 (0.14)	-41.86***
Phase	-0.22 (0.10)	-2.23*
End Effector Condition	0.30 (0.47)	0.64
Lo Fi Avatar Condition	1.01 (0.48)	2.10*
Avatar Condition	-0.02 (0.47)	-0.05
Reachability*Phase	-1.10 (0.23)	-4.91***
Phase * End Effector Condition	-0.60 (0.30)	-2.04*
Phase * LF-SA Condition	-0.33 (0.29)	-1.15
Phase * Self Avatar Condition	0.35 (0.29)	1.2
Reachability* End Effector Condition	-0.53 (0.38)	-1.4
Reachability*LF-SA Condition	-0.74 (0.40)	-1.86
Reachability*SA Condition	-1.09 (0.43)	-2.56**
Reachability* EE Condition*Phase	-0.59 (0.72)	-0.82
Reachability* LoFi Condition*Phase	-0.74 (0.65)	-1.14
Reachability* SA Condition*Phase	0.75)(0.75)	1
*p<0.05, **p<0.01, ***p<0.001		

attempted was independent of whether it was a correct or incorrect judgment. Whether the target distance was within reach was included in this model as reachability.

In predicting action taken there was a significant main effect of reachability ($F = 1742.58$, $p < 0.001$) and phase ($F = 5.22$, $p = 0.02$). For reachability people were less likely to attempt to reach if the target was outside their reach envelope (a probability of 0.98 of attempting a reach to a target that was within reach vs. a probability of 0.15 of reaching to a target that was out of reach). In terms of phase, participants were 1% more likely to reach in the post-test ($mean = 68\%$, $SE = 0.08$) than in the pre-test ($mean = 67\%$, $SE = 0.08$).

There were two significant interaction terms; reachability moderated by phase ($F = 23.80$, $p < 0.001$) and condition moderated by phase ($F = 4.38$, $p = 0.04$). In the reachability moderated

Table 5.7: Predicted probability of attempting a reach by phase.

	Pre-Test		Post-Test	
	Mean	**SE**	**Mean**	**SE**
Reachable	0.95	0.21	0.98	0.14
Unreachable	0.16	0.36	0.14	0.35

Table 5.8: Predicted probability of attempting a reach by real world and end effector conditions and phase.

	Pre-Test		Post-Test	
	Mean	**SE**	**Mean**	**SE**
End Effector	0.67	0.09	0.71	0.08
Real World	0.69	0.09	0.70	0.06

by phase interaction, participants were more likely to attempt to reach to unreachable targets during the pre-test ($mean = 0.16$, $SE = 0.36$) than the post-test ($mean = 0.14$, $SE = 0.35$), suggesting that participants calibrated to their reaching ability over the course of the experiment (Table 5.7). Condition moderated by phase, the only condition significantly different from the real world control was the end effector (Table 5.8). In the pre-test, the end-effector group ($mean = 0.67$, $SE = 0.47$) was less likely to reach than the real world group ($mean = 0.69$, $SE = 0.47$). However the end effector group ($mean = 0.7$, $SE = 0.45$) was more likely to reach similar to the real world group ($mean = 0.7$, $SE = 0.46$) in the post-test.

5.5.7 Effects of the Visual Fidelity of Self-Avatar on Properties of Reach Motion

The path length (distance traveled), time to complete the reach, average velocity and average acceleration were calculated using the raw data extracted from the sensor attached to the tool. Path length is the path line or arc taken to reach the target (similar to previous chapter). It is calculated as the cumulative distances ($\sum_{i=1}^{N-1} \Delta D_i$). Path length ($cm$) is always equal to or longer than the target distance that participants eventually reached to (perceived distance) because the target distance is unidimensional (extending horizontally away from the participant), while the path length occurs in 3D space. The path length takes into account the differing heights between the start of the hands path and the target. More importantly, it also takes into account any curvature to the hands path. Hence, it is possible to reach to a same destination when taking two different arcs in

Table 5.9: F values, Significance Tests, and ΔR^2 for path length.

	Variance Location	**Predictors**	**F-Test**	**P-value**	R^2		
					L1	**L2**	**Interaction**
Main Effects	**L1**	Distance	3660.49	<0.001	86.52		
		Phase	5.98	0.018	1.47		
	L2	Condition	0.18	0.91		NA	
Two-way Interactions	**L1**	Distance*Phase	21.28	<0.001	4.5		
	Cross-Level	Distance*Condition	5.824	0.002			23.22
		Phase*Condition	2.25	0.095			NA
Three-way Interactions		Distance*Phase*Condition	0.259	0.855			NA
				TOTAL R^2:	92.49		23.22

terms of the length and the shape of the arc. Equation 5.2 was used to calculate the displacement at each timestamp. This one step displacement was then used to calculate the total length of the arc (Equation 5.3).

$$\Delta D = \sqrt{x_i^2 + y_i^2 + z_i^2}, where \left\{ \begin{array}{c} \Delta x_i = x_{i+1} - x_i \\ \Delta y_i = y_{i+1} - y_i \\ \Delta z_i = z_{i+1} - z_i \end{array} \right\} \tag{5.2}$$

$$D = \sum_{i=1}^{N-1} \Delta D_i \tag{5.3}$$

Main effect of distance (F = 3660.49, p < 0.001) and phase (F = 5.98, p = 0.018) was found. Main effect of distance was expected since the path length would obviously be affected by how far away the target was. What is most interesting is the main effect of phase. Both phases had about the same mean presented distance, so participants were taking shorter path distances in the post-test ($mean = 40.27$, $SE = 0.80$) as compared to pre-test ($mean = 42.15$, $SE = 0.80$): however, we cannot determine if this was due to induction stage, calibration or fatigue. There was not a main effect of condition, however, an interesting pattern was observed regarding the path length. The path length became smaller as the visual fidelity of the avatar decreased however it failed to reach a statistical significance (Figure 5.17).

Time to complete (s) was extracted using the start and end of the ballistic motion for each trial (Equation 5.4). There were only significant main effects of distance (F = 335.26, p < 0.001) and condition (F = 3.0, p = 0.04) (Table 5.11). Similar to path length, main effect of distance was expected as when the presented distance got larger participants had to take longer paths which took

Table 5.10: Fixed coefficients and standard errors for the full model regarding the path length.

Predictors	**Coefficient (SE)**	**P-value**
Intercept	42.15 (1.74)	<0.001
Distance	0.89 (0.02)	<0.001
Phase	-1.96 (0.80)	0.018
EE Condition	-1.31 (2.26)	0.564
LF-SA Condition	-0.15 (2.30)	0.95
SA Condition	0.07 (2.26)	0.976
Distance*Phase	0.04 (0.01)	<0.001
Distance* EE Condition	-0.04 (0.04)	0.271
Distance* LF-SA Condition	0.04 (0.04)	0.234
Distance* SA Condition	-0.10 (0.04)	0.011
Phase* EE Condition	-2.49 (2.25)	0.273
Phase* LF-SA Condition	-2.19 (2.29)	0.343
Phase* SA Condition	2.37 (2.25)	0.297
Distance*Phase* EE Condition	-0.05 (0.08)	0.547
Distance*Phase* LF-SA Condition	-0.07 (0.08)	0.39
Distance*Phase* SA Condition	-0.05 (0.08)	0.565
*p<0.05, **p<0.01, ***p<0.001		

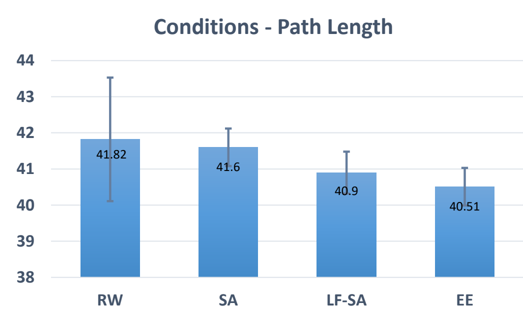

Figure 5.17: Shows the mean and SE of the different conditions for path length.

Table 5.11: F values, Significance Tests, and ΔR^2 for time to complete the task.

	Variance Location	**Predictors**	**F-Test**	**P-value**	R^2		
					L1	**L2**	**Interaction**
Main Effects	**L1**	Distance	335.26	<0.001	21.24		
		Phase	0.24	0.63	NA		
	L2	Condition	3	0.04		11.38	
Two-way Interactions	**L1**	Distance*Phase	0.07	0.79	NA		
	Cross-Level	Distance*Condition	0.43	0.74			NA
		Phase*Condition	0.76	0.52			NA
Three-way Interactions		Distance*Phase*Condition	2.03	0.11			NA
				TOTAL R^2:	21.24	11.38	

Table 5.12: Fixed coefficients and standard errors for the full model regarding the time to complete the reach.

Predictors	**Coefficient (SE)**	**P-value**
Intercept	1.28 (0.07)	<0.001
Distance	0.01 (<0.001)	<0.001
Phase	0.01 (0.03)	0.63
EE Condition	-0.14 (0.09)	0.12
LF-SA Condition	-0.17 (0.09)	0.06
SA Condition	-0.26 (0.09)	0.01
Distance*Phase	<0.001 (<0.001)	0.84
Distance* EE Condition	<0.001 (0.001)	0.97
Distance* LF-SA Condition	0.001 (0.001)	0.34
Distance* SA Condition	<0.001 (0.001)	0.87
Phase* EE Condition	-0.10 (0.08)	0.19
Phase* LF-SA Condition	-0.05 (0.08)	0.51
Phase* SA Condition	-0.09 (0.08)	0.22
Distance*Phase* EE Condition	<0.001 (0.001)	0.94
Distance*Phase* LF-SA Condition	0.001 (0.002)	0.28
Distance*Phase* SA Condition	0.002 (0.001)	0.04
*p<0.05, **p<0.01, ***p<0.001		

more time to complete the reach. Regarding main effect of condition, a further analysis revealed that only the self-avatar ($mean$ = 1.04, SE = 0.06) was significantly different from real-world ($mean$ = 1.30, SE = 0.06) (Table 5.12). It took participants a longer time to complete a reach in real-world as compared to self-avatar condition (Figure 5.18).

$$T_i = (t_i)_{end} - (t_i)_{start} \tag{5.4}$$

Equation 5.5 was used to calculate the average velocity (Equation 5.6) in which the instantaneous velocity (cm/s) was generated using the ΔD and Δt. There was only a main effect of

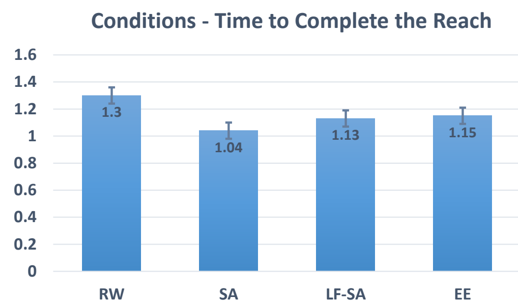

Figure 5.18: Shows the mean and SE of the different conditions for the time to complete the reach.

Table 5.13: F values, Significance Tests, and ΔR^2 for average velocity.

	Variance Location	Predictors	F-Test	P-value	R^2		
					L1	L2	Interaction
Main Effects	L1	Distance	1560.13	<0.001	25.4		
		Phase	0.01	0.91	NA		
	L2	Condition	0.99	0.41		NA	
Two-way Interactions	L1	Distance*Phase	1.83	0.18	NA		NA
	Cross-Level	Distance*Condition	2.07	0.1			NA
		Phase*Condition	0.99	0.95			NA
Three-way Interactions		Distance*Phase*Condition	0.69	0.56			NA
				TOTAL R^2:	25.4		

distance ($F = 1560.13$, $p < 0.001$) which basically showed that participants took faster reaches as the distance increased (Table 5.13 and 5.14).

$$\Delta V_i = \frac{\Delta D_i}{\Delta t_i}, where \, \{\Delta t_i = t_{i+1} - t_i\} \tag{5.5}$$

$$V = \frac{1}{N} \sum_{i=1}^{N-1} \Delta V_i \tag{5.6}$$

Similarly, the average acceleration was calculated using the following equations (Equation 5.7 and 5.8). There were significant main effect of distance ($F = 112.54$, $p < 0.001$) and phase ($F = 5.32$, $p = 0.02$). Similar to Velocity analysis, longer distance required faster reaches which was evidence in the main effect of distance. Additionally, the main effect of phase revealed that participants tool faster reaches in post-test ($mean = 538$, $SE = 29.45$) as compared to pre-test

Table 5.14: Fixed coefficients and standard errors for the full model regarding the average velocity.

Predictors	**Coefficient (SE)**	**P-value**
Intercept	33.13 (3.14)	<0.001
Distance	0.59 (0.01)	<0.001
Phase	2.89 (4.18)	0.49
EE Condition	5.61 (4.26)	0.19
LF-SA Condition	6.58 (4.18)	0.12
SA Condition	-5.30 (135.07)	0.97
Distance*Phase	0.08 (0.06)	0.18
Distance* EE Condition	-0.05 (0.04)	0.22
Distance* LF-SA Condition	-0.04 (0.05)	0.36
Distance* SA Condition	-0.10(0.04)	0.01
Phase* EE Condition	-0.21 (1.91)	0.91
Phase* LF-SA Condition	0.90 (1.98)	0.65
Phase* SA Condition	2.60 (1.91)	0.17
Distance*Phase* EE Condition	-0.11 (0.17)	0.52
Distance*Phase* LF-SA Condition	-0.21 (0.18)	0.25
Distance*Phase* SA Condition	-0.22 (0.17)	0.2
*p<0.05, **p<0.01, ***p<0.001		

Table 5.15: F values, Significance Tests, and ΔR^2 for average acceleration.

	Variance Location	**Predictors**	**F-Test**	**P-value**	R^2		
					L1	**L2**	**Interaction**
Main Effects	**L1**	Distance	112.54	<0.001	2.32		
		Phase	5.322	0.02	0.1		
	L2	Condition	2.051	0.12		NA	
Two-way Interactions	**L1**	Distance*Phase	2.4	0.12	NA		
	Cross-Level	Distance*Condition	1.48	0.22			NA
		Phase*Condition	1.3	0.27			NA
Three-way Interactions		Distance*Phase*Condition	1.34	0.26			NA
				TOTAL R^2:	2.33		

($mean$ = 475.69, SE = 29.67). Taken together with path length, the participants took higher acceleration but reached to shorter distance in post-test and took lower acceleration but reached to farther distances in pre-test.

$$\Delta A_i = \frac{\Delta V_i}{\Delta t_i}, where \{\Delta t_i = t_{i+1} - t_i\} \tag{5.7}$$

$$A = \frac{1}{N} \sum_{i=1}^{N-1} \Delta A_i \tag{5.8}$$

Table 5.16: Fixed coefficients and standard errors for the full model regarding the average acceleration.

Predictors	**Coefficient (SE)**	**P-value**
Intercept	386.35 (58.06)	<0.001
Distance	6.48 (0.61)	<0.001
Phase	63.00 (27.31)	0.021
EE Condition	42.76 (75.46)	0.57
LF-SA Condition	169.35 (77.27)	0.03
SA Condition	124.72 (75.41)	0.11
Distance*Phase	1.86 (1.2)	0.12
Distance* EE Condition	2.86 (1.71)	1
Distance* LF-SA Condition	0.23 (1.84)	0.9
Distance* SA Condition	2.50 (1.72)	0.15
Phase* EE Condition	75.13 (78.18)	0.34
Phase* LF-SA Condition	25.91 (81.21)	0.75
Phase* SA Condition	142.33 (78.07)	0.07
Distance*Phase* EE Condition	6.37 (3.39)	0.06
Distance*Phase* LF-SA Condition	3.23 (3.61)	0.37
Distance*Phase* SA Condition	5.31 (3.12)	0.12
*p<0.05, **p<0.01, ***p<0.001		

5.5.8 Discussion

In summation, the first three of the hypotheses were supported by the results from the absolute error. First, we expected that calibration would decrease the absolute error from pre- to post-test regardless of the visual fidelity of the self-avatar. We found after calibration participants' reaches became more consistence and absolute error also reduced and reached a statistical significance which supports our previous findings. From correct judgment analysis, it was shown that participants made more correct judgments and reached to more targets after receiving feedback in the calibration phase. Participants tended to reach to more unreachable targets in pre-test relative to post-test suggesting that they calibrated to their reaching ability after the intervention phase. Secondly, we expected that the rate of improvement in the accuracy would be different from pre- to post-test between different experimental conditions. The second hypothesis was supported via a three-way interaction between quadratic presented distance moderated by phase and condition revealing that interaction between phase and condition was also dependent on the quadratic presented distance. However, further investigation revealed that only the self-avatar condition was different from the real-world condition which was unexpected. The low-fidelity self-avatar and end-effector conditions had the least similarity to the real-world and were expected to be different from it, although, the results did not support it. Thirdly, we predicted that the four viewing conditions would have

different absolute errors with the end-effector and real-world conditions being the highest and lowest, respectively. The results revealed the expected trend, the error increased as the visual fidelity of the self-avatar decreased, therefore the absolute error was the highest in the end-effector conditions, was lower in the low-fidelity self-avatar condition, and lowest in self-avatar condition. The smallest absolute error was for the real-world condition. Additionally, the pattern of the absolute error from pre- to post-test stayed same in real-world and end-effector conditions, however, it differed from real-world in the two self-avatar viewing conditions. Further analysis is required to explore why such a pattern was observed. Moreover, participants showed a consistence behavior by correctly judging the reachability of the very close or very far targets. However, at the max of their reach envelope, participants in three VR conditions judged the reachability of the presented target more accurately than the real-world condition overall. We also found that participants were more likely to reach to the targets that were within their reach envelope in all VR conditions.

For the forth hypothesis, we studied the properties of physical reach motion such as path length, time to complete the reach, average velocity and acceleration. As expected distance had an effect on all the properties of reach motion, as when the distance increased it naturally created longer paths and times with higher velocity and acceleration. We also found a systematic differences between the path length from pre- to post-test where participants took shorter paths in post-test, which could be due to calibration phase or fatigue or both. Additionally, we observed an interesting trend regarding the path length; participants took longer paths as the visual fidelity of the scene was increased which is in contract with our findings discussed in previous chapter[5] which requires further investigation. In other words, participants in real-world condition took the longest path as compared to the other three VR viewing conditions. Interestingly, participants in end-effector condition had the shortest path length towards the target with the other two self-avatar viewing conditions somewhere in between. We also found a main effect of phase on average acceleration. Participants took a higher acceleration reaching towards the presented distance in post-test phase, however, as discussed earlier, they took a shorter path as compared to the pre-test phase (which had lower acceleration and longer path length) which requires further investigation as well.

[5]Section 4.3.1.3: Participants took longer paths to reach to the presented distances in virtual world as compared to real-world.

5.6 Conclusion

Previous work showed that the presence of a self-avatar affects users' behavior, their perception of the environment, and more specifically, their space perception in medium field IVEs [24, 70, 48, 79]. It is argued that a minimum level of self-avatar fidelity is required to change a users' perceptual judgments [60, 48] as well as a proper interaction with the virtual environment [44, 17]. However, it is not clear how much self-avatar's visual information is required for participants to improve their spatial perception in near-field.

Based on real-world studies, three different theories are suggested when estimating distance in order to properly scale ones' reach; First, the main visual contributor is the position of the end-effector/hand [65]. Our results showed that when calibrated to the end-effector only, participants perceived reachability to the presented target distance became similar to real-world condition although the error was higher than in the real-world. Additionally, distance estimation in end-effector condition had the highest dissimilarity and inaccuracy as compared to real-world. Therefore, depending on the application of the VR system, the existence of the end-effector could suffice where only the perceived reachability is critical. Second, it is discussed that the joint positions are crucial to create an accurate body map and consequently a better distance estimate [28, 63]. Therefore, the low-fidelity self-avatar condition tried to replicate the same condition in which only the joint positions are presented to the users in VR when estimating distance. We found that distance estimation improved as compared to end-effector condition but still was statistically worse than real-world. Similarly, participants were incorrect judging the reachability of the presented target. Third, it is shown that the presence of self-avatars improved distance estimation in virtual environment [48, 79]. Thus, we created a realistic, accurately scaled self-avatar to investigate this possibility in the near-field. We found that visuo-motor calibration to a realistic self-avatar improved near-field distance estimation as compared to as compared to the other two VR self-representations, but it still failed to reach to the same accuracy as the real-world. Therefore, depending on the near-filed depth information needs of a VR application, VR developers could decide the level of the self-representation that could be utilized by users to recalibrate their near-field distance estimation and effectively perform fine motor tasks. Different self-avatar conditions also changed the properties of reach motion although it requires further investigation as some of the results are in contrast with previous findings.

5.7 Future Work

The results of the current study indicated that there was a systematic differences between the path length from pre- to post-test where participants took shorter paths in post-test, which could be due to calibration phase or fatigue or both. Thus, a further investigation is required to differentiate the effects of the calibration phase from any potential fatigue due to the duration of the study. Therefore, a new experiment will be run in which the calibration phase is replaced with a blind reaching task (or memory based task) similar to pre- and post-test. Based on the results, it can be determined the weight of the calibration phase on the path length. Additionally, the closed-loop or calibration session can be studied separately and the users' performance can be compared in all three VR conditions when they were provided with feedback. A time-series analysis could be performed to study how human calibrates their reach estimates over the course of the environment.

Similarly, the effect of high or low induction phase on task performance can be studied on near-field distance estimation. As evidence in Figure 5.14, in pre-test phase, participants in self-avatar condition showed a similar behavior regarding the absolute error with real-world condition that could be due to the high induction stage. Therefore, if the similarities of the self-avatar condition with real-world was due to a high induction stage, then different pattern should be observed when a low induction stage is performed. Thus, another experiment will be conducted in which the induction phase is more concise and limited to one task only. The data analysis from that study could shed some lights on the difference in the pre-test phases.

In most of the previous work, the self-avatar was created using the IK system with a few tracked points on the users' body. In these systems, there is a small mismatch between visual and propreceptive information which could potentially affect distance estimation. Thus, the effect of the high-fidelity self-avatars could be investigated on distance estimation, reach boundary perception and properties of physical reach motion via motion tracking suit in addition to the IK system. The goal of using a full body tracking suit is to eliminate any incongruity between different sensory channels. Additionally, the effects of full body tracking versus upper body tracking on near-field distance estimation can be studied and be compared to previous findings [65, 21].

Appendices

Appendix A Consent Form

Information about Being in a Research Study
Clemson University

Distance Perception

Description of the research and your participation:
You are invited to participate in a research study conducted by Dr. Chris Pagano and Dr. Sabarish Babu. The purpose of this research is to investigate distance perception in real and virtual worlds.

We are investigating how accurate people are at perceiving and subsequently reporting distances from themselves to targets in real and virtual environments. You will be asked to view targets and then report the targets' distance by one of several methods, such as reaching to the target with the hand or with a tool, walking a short distance to the target location, throwing a light beanbag to the target, giving a verbal report of the target's distance, etc. Some subjects may feel the target manually rather than view it. Some subjects may reach with their wrist immobilized by a standard wrist splint or while wearing a motion capture suit. You may be asked to complete a brief assessment of your spatial abilities and gaming experience. In some conditions, you may be video recorded and we may use electronic tracking devices and a computer to track the movements of your head, arm, hand, or your whole body.

Some subjects will navigate through a town or city using using a panoramic virtual environment such as Google Streetview. The environment will be depicted on a head mounted display, large screen projection systems, or a standard desktop monitor. Your ability to form an accurate mental model of the environment may be assessed by asking you to point in the direction of a remembered landmark, by measuring your ability to navigate through the environment and/or by other memory tests.

Depending on the nature of the tasks that you are assigned, the amount of time required for your participation will be between one and two hours. Depending on the tasks, you may be asked to participate in multiple research sessions. You have already been informed about the number of sessions that you will be asked to participate in, and you already have been given a more specific estimate of the duration of each session.

Risks and discomforts:
By participating in this study, you may exhibit none/some/all of the following symptoms from viewing the virtual reality display: dizziness, weakness, nausea, headache, vomiting. These symptoms will go away when the virtual reality display is ended. You may ask to end the display at any time.

If you continue to feel badly after the study, please contact Redfern Health Center at 656-2451.

Exclusion Requirements:
Participants must have normal, or corrected to normal, vision and full use of their neck, arms, and hands.

Potential Benefits:
There are no known benefits to you that would result from your participation in this research. Information that is obtained from this study may be used scientifically and may be helpful to others. Possible benefits you attain may include extra credit towards a course grade for Clemson University

students, and may include the satisfaction of contributing to the advance of science and technological innovation. This research may help us develop more effective virtual reality systems.

Incentives/Compensation:
Some subjects will receive $15 or students in some Psychology courses at Clemson University may receive up to 4 course credit. For some experimental conditions involving multiple sessions, some subjects will receive $15 or 4 credits per session. Participation for about 1 hour is required for full compensation. For participants who do not complete an experimental session compensation will be pro-rated according to the proportion of time completed.

Voluntary Participation:
Your participation in this research study is voluntary. You may choose not to participate and you may withdraw your consent to participate at any time. You will not be penalized in any way if you decide not to participate or if you withdraw from this study.

Confidentiality:
We will do everything we can to protect your privacy. The records of your participation are confidential. The investigator will maintain your information, and this information may be kept on a computer. Your identity will not be revealed in any publication that might result from this study. All data, including recordings, will be maintained indefinitely and may be used in future research studies. All recordings will be used in a confidential manner. If used in conferences or other presentations, they will be rendered such that personal identities are obscured. If you do not want the data used in future studies, you must notify one of the researchers in writing.

In rare cases, a research study will be evaluated by an oversight agency, such as the Clemson University Institutional Review Board or the federal Office for Human Research Protections. This would require that we share the information we collect from you. If this happens, the information would only be used to determine if we conducted this study properly and adequately protected your rights as a participant.

Contact information:
If you have any questions or concerns about this study or if any problems arise, please contact Chris Pagano at Clemson University at 864.656.4984. If you have any questions or concerns about your rights as a research participant, please contact the Clemson University Institutional Review Board at 864.656.0636.

Consent:
I have read this consent form and have been given the opportunity to ask questions. I give my consent to participate in this study.

Participant's signature: ________________________________ Date: ______________

Participant's name printed: ______________________________

A copy of this consent form will be given to you.

CLEMSON
RESEARCH COMPLIANCE

IRB Number: 99018
Approved: 5/27/17
Expiration: 5/26/18

Appendix B Handedness Questionnaire

Participant #:

1. With which hand do you draw?	___Left	___Right	___Either
2. Which hand would you use to throw a ball to hit a target?	___Left	___Right	___Either
3. In which hand would you use an eraser on paper?	___Left	___Right	___Either
4. Which hand removes the top card when you are dealing from a deck?	___Left	___Right	___Either
5. With which foot would you kick a ball to hit a target?	___Left	___Right	___Either
6. If you wanted to pick up a pebble with your toes, which foot would you use?	___Left	___Right	___Either
7. Which foot would you use to step on a bug?	___Left	___Right	___Either
8. If you had to step up onto a chair, which foot would you place on the chair first?	___Left	___Right	___Either
Sum	Left	Right	

Appendix C Demographic Survey

Participant # __________

Date: (Trial 1):

- Gender: Male Female
- Age
- Dominant Hand: Left Right

For experimenter use:

HC Visual Acuity	
Stereo Acuity	
Arm Length	cm
IO Distance	cm
Chair Position	cm
Eye Height	

1. Do you currently have any problems with your hands, arms, or neck? Yes No
   If yes, please describe:

2. Do you currently have any vision problems (aside form corrected vision)? Yes No
   If yes, please describe:

3. Do you have any experience with videogames? Yes No
   If yes, please describe:

   - Console type(s):
   - Types of games:
   - Current hours per week:
   - Estimated past usage:

Appendix D Experiment Protocol

Experimenter Protocol VR Experiments 2016-2017
Experiment 3
(Self-Avatar vs Low-Fidelity Self-Avatar vs End-Effector)

GIVE THEM THE INFORMED CONSENT FORM

After reading the document, ask them to sign and date it if they agree.

Hello, thank you for coming today. In this experiment, you will be asked to make a variety of different reaches. Some reaches will be completed in virtual reality. Before we get into that part of the experiment we will have you complete a few questionnaires and some simple tests. Once you are done with those we will help to outfit you with a shirt and some sensors which will help us track your movements. Once you are outfitted, for the most part you will be sitting in that chair, and when you do it is important to remember to keep your feet flat on the floor.

One thing I need to stress is that if at any time you are feeling uncomfortable please let one of us know. If you are experiencing any sort of discomfort, please let us know.

1. At this point, we need to ask you if you are wearing any jewelry of any kind (***PHONE***, watches, bracelets, necklace, rings, etc.). If you are, can you please take it off and place it with your belongings?

Also, are you wearing any hair clips? If so, you will probably have to take those off as well.

2. First, I will need you to complete a few quick tests and surveys.

1. Administer the **stereo acuity test**, and then 2. administer **the handedness and footedness questionnaire**. 3. Then administer the **inter-pupillary distance task**.

****We will need to specify in the sign up instructions online that all participants should be right handed, for the sake of consistency.*** Including the handedness questionnaire is just a way to check that all participants are right hand dominant and will reach with their right hands.*

3. The EXPERIMENTER will place the appropriate sensors on the participant while they are standing. EXPERIMENTER needs to be sure that the sensor on the stylus is present. Sensors also need to be placed on the shoulder apparatus (near the bony protrusion of the shoulder), and on the elbow, head, and neck.

The Experimenter will then physically measure the distances between each of the sensors when they are on the participant. Be sure to record this on the physical data sheet.

Once the shirt and the sensors are attached, and while the participant is still standing, help them put on the wrist braces and the wrist holsters for the VIVE controllers.
*********At this point, have the participant sit in the chair and show them the kinds of reaches we are looking for. Ask them to complete two reaches to predefined points on the table, so we can show them the "right" way to do the task.*******

Then, have the participant stand back up, and put on the VR headset. Have them adjust the headset so that it is 100% comfortable for them.

Calibration Task

With the VR headset on, the participant can now engage in the calibration tasks while sitting.

Once calibration is complete, we can help them to remove the headset, and have the participant sit in the chair at the pre-defined location.

When the participant is seated, help them put the VR headset back on. **Ask them how comfortable they are at this point.**

The Experimenter will also measure the sitting shoulder height of the participant (measure from floor to the bony protrusion of the shoulder).

Now we are good to go for data collection.

Body Ownership Task:

(For this task all participants will be in VR, and this is where the simulation will begin).

For this part of the experiment, please remain seated with your feet flat on the floor. Can you see yourself in the mirror?

First, bring your hands to your side and move them. Second, stretch your hands straight out and move them. Can you see yourself?

Lastly, stretch your arms straight up in the air and move them.

"Egocentric Pointing"

Next, please look around the room (you don't have to turn all the way around you though!). I am going to ask you to point to several object in the environment, please always use your right hand and point with the tip of the tool that you are holding.

- Now, please look at your right, do you see the bookshelf? Can you point to it?
- Now, please look to your left, do you see the clock? Can you point to it? And tell me what time is it?
- Now, look in front of you, please point to different corner of the mirror with the tip of the tool that you are holding (start from top right, then top left, then lower left, and finally the lower right!).
- Now, please look to your right again, do you see the TV screen? Can you point to it? What movie poster is on the screen?
- Now please look straight ahead, do you see the lamp? Can you point to it?

"Exocentric Pointing"

Now we need to perform a new set of tasks:

- Please use the tool that you are holding in you left hand and touch your shoulder.
- Now use the right controller and touch your left shoulder.
- Please perform the same task but this time touch your elbows.
- Next, please use the tip of the right controller to touch the inner part of your wrist.

"Peripheral Stimulation"

- Next, please put your hands on the table. First with your right hand touch and rub the inner part of your left hand from elbow to wrist (*do it for about 30 secs*).
- Next, please use your left hand and touch and rub the inner part of your right hand from elbow to wrist (*45 secs*)
- Touch and rub the right controller's tip using your left controller (*30 secs*).

PreTest:

(In this block of trials all participants should be using an avatar with a normal sized arm).

For this first set of trials, please remain seated with your feet flat on the floor. Please extend your index finger out so it is resting on the tool. Please maintain this hand position for the entire experiment.

Your job is to watch for a light to appear on the table in front of you. There is a red target area on the table in front of you – can you see it? This is an example of the targets you will be reaching to; they will look just like that.

Once you see the light, please alert the experimenter if you can reach to the center of the illuminated area with the tip of the tool you are holding in your right hand. If you think you can, please say yes. If you think you cannot reach to the target, please say no.

If you tell the experimenter that you can reach to the target, you will then be asked to reach to the target. Once you say 'yes', please begin to reach to the target. The screen will go blank as soon as you attempt to reach to the target. Please reach with your right hand to the center of the illuminated spot as quickly and accurately as you can. Please only reach to the target when the screen is blank. You may reach in any manner that is comfortable and appropriate. It is important that you reach as fast as you can, but also try your best to be as accurate as possible. Try your best to place the tip of the tool in the very center of the illuminated area and hold it on the table for one second. Please try to make contact with the table, but you do not need to press hard on the table at all.

Once you have completed your reach, please return your hand to the starting point which is on the side of the table, and make sure that your back is resting on the back of the chair. Every time you initiate a reach you need to be sure that you are starting from this same starting point. It is also important that you attempt to maintain as good of posture as possible for the entire experiment. Remember, your starting posture must remain the same. You must also keep your feet flat on the floor and remain seated/touching the bottom of the chair. However, you may reach in any manner that is comfortable and appropriate to you.

When you have returned to your starting position, another area will become illuminated and you will be asked to complete the same task.

If, at any point, you believe that you absolutely cannot reach to the light please inform the experimenter by saying "no" or "I cannot reach that". We will then show you another target and ask you to make another judgment.

Do you have any questions?

Experimental Session:

(In this block of trials participants in the "normal" condition will be reaching with an avatar arm that is the same size as their real arm, and participants in the "altered" condition will be reaching with an avatar arm that has been increased by 30 cm.

Do not alert participants to this change – just tell them that we have to adjust something on the controller).

Please leave your arm right where it is on the armrest, we need to adjust something with one of the controllers. (***If the participant is in the long tool/arm condition switch out the short tool for the long tool. But do not alert them to this change.).*** Ok, we are all set.

The instructions for this block of trials is very similar to the previous block of trials, except this time you will have the opportunity to see the result of your reach and then make an adjustment.

Most of the instructions are the exact same as before – please remain seated the entire time, please reach as quickly and accurately as you can to the illuminated area, and return to the same starting position for every trial.

If you can reach to the target, please tell the experimenter “yes”. If you cannot reach to the target please let the experimenter know by saying “no”.

The major difference between this block of trials and the last is that after every judgment you give, regardless if it is a yes or no, please attempt to reach to the target area. After you have completed your initial reach, the virtual scene will be restored to your headset so you can see the target.

When you can see the target please adjust your reach so that you are reaching to the center of the target if the target is within reach. Please hold there for about 1 second after you adjust your reach. If the target is not within reach, you do not need to stretch or over exert yourself to try and reach the target.

Do you have any questions?

The instructions for the PostTest are the exact same as the PreTest.

BE SURE to immediately proceed into the PostTest once the experimental session has ended.

For the long arm/tool condition, we need to replace the tool with the short tool, so again, just tell them that we have to adjust something with the controller.

Post Experiment Data and Anthropometry collection:

1. Now there are a few more tasks we need you to complete. First, without moving your shoulder, reach your right arm out straight in front of you and hold it there. Please complete this action two more times.

Next, please attempt to reach absolutely as far as you can while keeping your feet flat on the floor and seated on the bottom of the seat. Please complete this action two more times.

2. Now I just need to collect a few more measurements. Be sure to measure the distance between the sensors on the right arm for each participant.

Collect the same measurements as from before the experiment.

3. Once all of this data has been recorded, assist the participant in removing the wrist apparatus’ and the shoulder strap. Once these are removed, ask the participant to remove the VR headset themselves. Then help them remove the shirt.

4. Administer the body ownership questionnaire. Be sure to record participant number on the questionnaire.

5. Ask them the last two questions about noticing anything odd with the avatar and if they felt sick.

6. Thank them for coming and let them know they will be granted credit within 24 hours. If they do not receive credit before then, tell them they can email hsolini@g.clemson.edu to resolve the issue.

NOTE TO ALL EXPERIMENTERS:

Once the last participant has been run for the day, we need to collect the VIVE controllers and plug them in so they can recharge.

Appendix E Body Ownership Questionnaire

Participant Number

Body Ownership

1. When you were looking down from above how much did you feel a strong connection with the avatar as if you were looking down at yourself?

NOT AT ALL 0	1 2 3 4 5 6 7 8 9	10 VERY MUCH

2. How much did you feel that the seated avatar's body was your body?

NOT AT ALL 0	1 2 3 4 5 6 7 8 9	10 VERY MUCH

3. How strong was the feeling that the movements of the avatar were caused by your own movements?

NOT AT ALL 0	1 2 3 4 5 6 7 8 9	10 VERY MUCH

4. How much did you feel that the virtual body was another person?

NOT AT ALL 0	1 2 3 4 5 6 7 8 9	10 VERY MUCH

5. How much was this experience more like watching a scene from the outside compared to being part of the scene?

NOT AT ALL 0	1 2 3 4 5 6 7 8 9	10 VERY MUCH

6. How strong was the feeling that the body of the person in the mirror was your body?

NOT AT ALL 0	1 2 3 4 5 6 7 8 9	10 VERY MUCH

Bibliography

[1] Bliss M Altenhoff, Phillip E Napieralski, Lindsay O Long, Jeffrey W Bertrand, Christopher C Pagano, Sabarish V Babu, and Timothy A Davis. Effects of calibration to visual and haptic feedback on near-field depth perception in an immersive virtual environment. In *Proceedings of the ACM Symposium on Applied Perception*, pages 71–78. ACM, 2012.

[2] Domna Banakou, Raphaela Groten, and Mel Slater. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, 110(31):12846–12851, 2013.

[3] Geoffrey Bingham and Jennifer L Romack. The rate of adaptation to displacement prisms remains constant despite acquisition of rapid calibration. *Journal of Experimental Psychology: Human Perception and Performance*, 25(5):1331, 1999.

[4] Geoffrey E Bingham and Christopher C. Pagano. The necessity of a perception-action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance*, 24(1):145–168, 1998.

[5] Paul D Bliese. Group size, icc values, and group-level correlations: A simulation. *Organizational Research Methods*, 1(4):355–373, 1998.

[6] Jérémy Bourgeois and Yann Coello. Effect of visuomotor calibration and uncertainty on the perception of peripersonal space. *Attention, Perception, & Psychophysics*, 74(6):1268–1283, 2012.

[7] Doug A Bowman, Ernst Kruijff, Joseph J LaViola Jr, and Ivan Poupyrev. *3D user interfaces: theory and practice*. Addison-Wesley, 2004.

[8] Armin Bruderlin and Lance Williams. Motion signal processing. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 97–104. ACM, 1995.

[9] Martinus Buekers, Gilles Montagne, Aymar de Rugy, and Michel Laurent. The regulation of externally paced human locomotion in virtual reality. *Neuroscience Letters*, 275(3):171–174, 1999.

[10] Jennifer Casper and Robin R. Murphy. Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center. *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on*, 33(3):367–385, 2003.

[11] Benjamin J Chihak, Jodie M Plumert, Christine J Ziemer, Sabarish Babu, Timofey Grechkin, James F Cremer, and Joseph K Kearney. Synchronizing self and object movement: how child and adult cyclists intercept moving gaps in a virtual environment. *Journal of experimental psychology: human perception and performance*, 36(6):1535, 2010.

[12] Edmund Churchill, JT McConville, LL Laubach, Peggy Erskine, K Downing, and T Churchill. *Anthropometric source book. Volume II: handbook of anthropometric data.* 1978.

[13] Jacob Cohen, Patricia Cohen, Stephen G West, and Leona S Aiken. Applied multiple correlation/regression analysis for the behavioral sciences. *UK: Taylor & Francis*, 2003.

[14] James E Cutting. Potency, and contextual use of different in_fi) rmation about depth. *Perception of space and motion*, page 69, 1995.

[15] Brian Day, Elham Ebrahimi, Leah S Hartman, Christopher C Pagano, and Sabarish V Babu. Calibration to tool use during visually-guided reaching. *Acta Psychologica*, 181:27–39, 2017.

[16] Patrick S. Dukes, Austen Hayes, Larry F. Hodges, and Michelle Woodbury. Punching ducks for post-stroke neurorehabilitation: System design and initial exploratory feasibility study. 2013 IEEE Symposium on:47–54, 2013.

[17] Elham Ebrahimi, Bliss Altenhoff, Leah Hartman, J. Adam Jones, Sabarish V. Babu, Christopher C. Pagano, and Timothy A. Davis. Effects of visual and proprioceptive information in visuo-motor calibration during a closed-loop physical reach task in immersive virtual environments. *In Proceedings of the ACM Symposium on Applied Perception*, pages 103–110, 2014.

[18] Elham Ebrahimi, Bliss M Altenhoff, Christopher C Pagano, and Sabarish V Babu. Carryover effects of calibration to visual and proprioceptive information on near field distance judgments in 3d user interface. pages 97–104, 2015.

[19] Elham Ebrahimi, Sabarish V Babu, Christopher C Pagano, and Sophie Jörg. An empirical evaluation of visuo-haptic feedback on physical reaching behaviors during 3d interaction in real and immersive virtual environments. *ACM Transactions on Applied Perception (TAP)*, 13(4):19, 2016.

[20] John M Foley et al. Effect of distance information and range on two indices of visually perceived distance. *Perception*, 6(4):449–460, 1977.

[21] Tom Foulsham. Eye movements and their functions in everyday tasks. *Eye*, 29(2):196–199, 2015.

[22] James Jerome Gibson. The senses considered as perceptual systems. 1966.

[23] Timofey Y Grechkin, Tien Dat Nguyen, Jodie M Plumert, James F Cremer, and Joseph K Kearney. How does presentation method and measurement protocol affect distance estimation in real and virtual environments? *ACM Transactions on Applied Perception (TAP)*, 7(4):26, 2010.

[24] Austen L Hayes, Amy C Ulinski, and Larry F Hodges. That avatar is looking at me! social inhibition in virtual worlds. In *International Conference on Intelligent Virtual Agents*, pages 454–467. Springer, 2010.

[25] Matthew Heath, Nicola J Hodges, Romeo Chua, and Digby Elliott. On-line control of rapid aiming movements: Unexpected target perturbations and movement kinematics. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, 52(4):163, 1998.

[26] Ronald H Heck, Scott L Thomas, and Lynn N Tabata. *Multilevel and longitudinal modeling with IBM SPSS*. Routledge, 2013.

[27] Larry F. Hodges, Page Anderson, Grigore C. Burdea, H. G. Hoffmann, and Barbara O. Rothbaum. Treating psychological and phsyical disorders with vr. *Computer Graphics and Applications, IEEE*, 21(6):25–33, 2001.

[28] Gunnar Johansson. Visual perception of biological motion and a model for its analysis. *Perception & psychophysics*, 14(2):201–211, 1973.

[29] J. Adam Jones, J. Edward Swan II, Gurjot Singh, and Stephen R. Ellis. Peripheral visual information and its effect on distance judgments in virtual and augmented environments. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, pages 29–36. ACM, August 2011.

[30] Jonathan W Kelly, William W Hammel, Zachary D Siegel, and Lori A Sjolund. Recalibration of perceived distance in virtual environments occurs rapidly and transfers asymmetrically across scale. *IEEE Transaction on Visualization and Computer Graphics*, 20(4):588–595, 2014.

[31] Eamonn Keogh and Chotirat Ann Ratanamahatana. Exact indexing of dynamic time warping. *Knowledge and information systems*, 7(3):358–386, 2005.

[32] Konstantina Kilteni, Raphaela Groten, and Mel Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012.

[33] B. R. Kunz, S. H. Creem-Regher, and W. B. Thompson. Does perceptual-motor calibration generalize across two different forms of locomotion? investigations of walking and wheelchairs. *PLOS one*, 8(2), 2013.

[34] Benjamin R. Kunz, Leah Wouters, Daniel Smith, William B. Thompson, and Sarah H. Creem-Regehr. Revisiting the effect of quality of graphics on distance judgments in virtual environments: A comparison of verbal reports and blind walking. *Attention, Perception, & Psychophysics*, 71(6):1284–1293, 2009.

[35] Lorraine Lin and Sophie Jörg. Need a hand?: how appearance affects the virtual hand illusion. In *Proceedings of the ACM Symposium on Applied Perception*, pages 69–76. ACM, 2016.

[36] Sally A Linkenauger, Jessica K Witt, Jeanine K Stefanucci, Jonathan Z Bakdash, and Dennis R Proffitt. The effects of handedness and reachability on perceived distance. *Journal of Experimental Psychology: Human Perception and Performance*, 35(6):1649, 2009.

[37] Benjamin Lok, Samir Naik, Mary Whitton, and Frederick P Brooks. Effects of handling real objects and self-avatar fidelity on cognitive task performance and sense of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, 12(6):615–628, 2003.

[38] J Scott Long and Jeremy Freese. *Regression models for categorical dependent variables using Stata*. Stata press, 2006.

[39] Jack M Loomis, James J Blascovich, and Andrew C Beall. Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers*, 31(4):557–564, 1999.

[40] Jack M. Loomis and Joshua M. Knapp. Visual perception of egocentric distance in real and virtual environments. *Virtual and Adaptive Environments*, 11:21–46, 2003.

[41] Ke Ma and Bernhard Hommel. The role of agency for perceived ownership in the virtual hand illusion. *Consciousness and cognition*, 36:277–288, 2015.

[42] Antonella Maselli and Mel Slater. The building blocks of the full body ownership illusion. *Frontiers in human neuroscience*, 7:83, 2013.

[43] Rachel McDonnell, Martin Breidt, and Heinrich H Bülthoff. Render me real?: investigating the effect of render style on the perception of animated virtual humans. *ACM Transactions on Graphics (TOG)*, 31(4):91, 2012.

[44] Erin A McManus, Bobby Bodenheimer, Stephan Streuber, Stephan De La Rosa, Heinrich H Bülthoff, and Betty J Mohler. The influence of avatar (self and character) animations on distance estimation, object interaction and locomotion in immersive virtual environments. In *Proceedings of the ACM SIGGRAPH Symposium on applied perception in graphics and visualization*, pages 37–44. ACM, 2011.

[45] Ross Messing and Frank H. Durgin. Distance perception and the visual horizon in head-mounted displays. *ACM Transactions on Applied Perception (TAP)*, 2(3):234–250, 2005.

[46] A David Milner and Melvyn A Goodale. *The visual brain in action*, volume 2. Oxford University Press Oxford, 2006.

[47] Betty J Mohler, Sarah H Creem-Regehr, and William B Thompson. The influence of feedback on egocentric distance judgments in real and virtual environments. In *Proceedings of the 3rd symposium on Applied perception in graphics and visualization*, pages 9–14. ACM, 2006.

[48] Betty J Mohler, Sarah H Creem-Regehr, William B Thompson, and Heinrich H Bülthoff. The effect of viewing a self-avatar on distance judgments in an hmd-based virtual environment. *Presence: Teleoperators and Virtual Environments*, 19(3):230–242, 2010.

[49] Phillip E Napieralski, Bliss M Altenhoff, Jeffrey W Bertrand, Lindsay O Long, Sabarish V Babu, Christopher C Pagano, Justin Kern, and Timothy A Davis. Near-field distance perception in real and virtual environments using both verbal and action responses. *ACM Transactions on Applied Perception (TAP)*, 8(3):18, 2011.

[50] Tien Dat Nguyen, Christine J Ziemer, Timofey Grechkin, Benjamin Chihak, Jodie M Plumert, James F Cremer, and Joseph K Kearney. Effects of scale change on distance perception in virtual environments. *ACM Transactions on Applied Perception (TAP)*, 8(4):26, 2011.

[51] Christopher C Pagano and Geoffrey P Bingham. Comparing measures of monocular distance perception: Verbal and reaching errors are not correlated. *Journal of Experimental Psychology: Human Perception and Performance*, 24(4):1037, 1998.

[52] Christopher C Pagano, Richard P Grutzmacher, and Joseph C Jenkins. Comparing verbal and reaching responses to visually perceived egocentric distances. *Ecological Psychology*, 13(3):197–226, 2001.

[53] Christopher C Pagano and Robert W Isenhower. Expectation affects verbal judgments but not reaches to visually perceived egocentric distances. *Psychonomic bulletin & review*, 15(2):437–442, 2008.

[54] Dennis R Proffitt, Jeanine Stefanucci, Tom Banton, and William Epstein. The role of effort in perceiving distance. *Psychological Science*, 14(2):106–112, 2003.

[55] Luc Proteau, Karine Boivin, Stéphane Linossier, and Khémais Abahnini. Exploring the limits of peripheral vision for the control of movement. *Journal of Motor Behavior*, 32(3):277–286, 2000.

[56] Rebekka S Renner, Boris M Velichkovsky, and Jens R Helmert. The perception of egocentric distances in virtual environments-a review. *ACM Computing Surveys (CSUR)*, 46(2):23, 2013.

[57] Adam R. Richardson and David Waller. The effect of feedback training on distance estimation in virtual environments. *Applied Cognitive Psychology*, 19(8):1089–1108, 2005.

[58] Adam R. Richardson and David Waller. Interaction with an immersive virtual environment corrects users' distance estimates. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(3):507–517, 2007.

[59] Brian Ries, Victoria Interrante, Michael Kaeding, and Lee Anderson. The effect of self-embodiment on distance perception in immersive virtual environments. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, pages 167–170. ACM, 2008.

[60] Brian Ries, Victoria Interrante, Michael Kaeding, and Lane Phillips. Analyzing the effect of a virtual avatar's geometric and motion fidelity on ego-centric spatial perception in immersive virtual environments. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, pages 59–66. ACM, 2009.

[61] John J. Rieser, Herbert L. Pick, Daniel H. Ashmead, and Anne E Garing. Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology: Human Perception and Performance*, 21(3):480–497, 1995.

[62] Jannick P Rolland, Christina A Burbeck, William Gibson, and Dan Ariely. Towards quantifying depth and size perception in 3d virtual environments. *Presence: Teleoperators and Virtual Environments*, 4(1):24–48, 1995.

[63] Sverker Runeson and Gunilla Frykholm. Kinematic specification of dynamics as an informational basis for person-and-action perception: Expectation, gender recognition, and deceptive intention. *Journal of experimental psychology: general*, 112(4):585, 1983.

[64] Ferran Argelaguet Sanz, Anne-Hélène Olivier, Gerd Bruder, Julien Pettré, and Anatole Lécuyer. Virtual proxemics: Locomotion in the presence of obstacles in large immersive projection environments. In *IEEE Virtual Reality*, pages 75–80, 2015.

[65] Jeffrey A Saunders and David C Knill. Visual feedback control of hand movements. *The Journal of neuroscience*, 24(13):3223–3234, 2004.

[66] Richard A Schmidt and Tim Lee. *Motor Control and Learning, 5E.* Human kinetics, 1988.

[67] Lauren E Sergio and Stephen H Scott. Hand and joint paths during reaching movements with and without vision. *Experimental brain research*, 122(2):157–164, 1998.

[68] Neal E Seymour. Vr to or: a review of the evidence that virtual reality simulation improves operating room performance. *World journal of surgery*, 32(2):182–188, 2008.

[69] Gurjot Singh, J Edward Swan II, J Adam Jones, and Stephen R Ellis. Depth judgment measures and occluding surfaces in near-field augmented reality. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, pages 149–156. ACM, 2010.

[70] Mel Slater, Angus Antley, Adam Davison, David Swapp, Christoph Guger, Chris Barker, Nancy Pistrang, and Maria V Sanchez-Vives. A virtual reprise of the stanley milgram obedience experiments. *PloS one*, 1(1):e39, 2006.

[71] Mel Slater, Daniel Pérez Marcos, Henrik Ehrsson, and Maria V Sanchez-Vives. Towards a digital body: the virtual arm illusion. *Frontiers in human neuroscience*, 2:6, 2008.

[72] Mel Slater, Daniel Pérez Marcos, Henrik Ehrsson, and Maria V Sanchez-Vives. Inducing illusory ownership of a virtual body. *Frontiers in neuroscience*, 3:29, 2009.

[73] Craig L Taylor and Robert J Schwarz. The anatomy and mechanics of the human hand. *Artificial limbs*, 2(2):22–35, 1955.

[74] William B Thompson, Peter Willemsen, Amy A Gooch, Sarah H Creem-Regehr, Jack M Loomis, and Andrew C Beall. Does the quality of the computer graphics matter when judging distances in visually immersive environments? *Presence: Teleoperators and Virtual Environments*, 13(5):560–571, 2004.

[75] Matias Volante, Sabarish V Babu, Himanshu Chaturvedi, Nathan Newsome, Elham Ebrahimi, Tania Roy, Shaundra B Daily, and Tracy Fasolino. Effects of virtual human appearance fidelity on emotion contagion in affective inter-personal simulations. *IEEE transactions on visualization and computer graphics*, 22(4):1326–1335, 2016.

[76] Mark Wexler and Jeroen JA Van Boxtel. Depth perception by the active observer. *Trends in cognitive sciences*, 9(9):431–438, 2005.

[77] Peter Willemsen, Mark B. Coltona, Sarah H. Creem-Regehr, and William B. Thompson. The effects of head-mounted display mechanical properties and field of view on distance judgments in virtual environments. *ACM Transactions on Applied Perception (TAP)*, 6(2):1–14, 2009.

[78] Peter Willemsen, Amy A Gooch, William B Thompson, and Sarah H Creem-Regehr. Effects of stereo viewing conditions on distance perception in virtual environments. *Presence: Teleoperators and Virtual Environments*, 17(1):91–101, 2008.

[79] Betsy Williams, Derek Johnson, Lucy Shores, and Gayathri Narasimham. Distance perception in virtual environments. In *Proceedings of the 5th symposium on Applied perception in graphics and visualization*, pages 193–193. ACM, 2008.

[80] Bob G Witmer and Paul B Kline. Judging perceived and traversed distance in virtual environments. *Presence: Teleoperators and Virtual Environments*, 7(2):144–167, 1998.

[81] Catherine Amine Zanbaka, Amy Catherine Ulinski, Paula Goolkasian, and Larry F Hodges. Social responses to virtual humans: implications for future interface design. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1561–1570. ACM, 2007.

[82] Christine J Ziemer, Mia J Branson, Benjamin J Chihak, Joseph K Kearney, James F Cremer, and Jodie M Plumert. Manipulating perception versus action in recalibration tasks. *Attention, Perception, & Psychophysics*, 75(6):1260–1274, 2013.