Enhancing Spatial Perception via Visuo-Motor Recalibration in Immersive Virtual Environments

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Abstract

Research in visuo-motor coupling has shown that the matching of visual and proprioceptive information is important for calibrating. 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 [23, 35]. 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. 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 also 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.

Previous research has demonstrated that self-avatar representation of the user enhances the sense of presence [27] and even a static notion of an avatar can improve distance estimation in far distances [48, 36]. In the present study, we will investigate the effect of visual fidelity of the self-avatar in enhancing the user's depth judgments. Participants will be randomly assigned to one of the three conditions: i) high-fidelity self-avatar (realistic limb matching the size and scale of the participants limbs), ii) medium-fidelity (abstract rendering of joint and limb location only), and iii) low-fidelity (abstract rendering of joint locations only). It is expected that participant depth judgments will improve regardless of the calibration condition. Further, it is expected that the high-fidelity self-avatar of the participants arm will significantly enhance depth perception in the IVE by providing a more realistic proprioceptive cue as compared to medium and low-fidelity avatar.

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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 [13], therapy [19], and surgery training [54]. 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 [33, 46] which has the potential to adversely affect task performance, training effectiveness, 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 transfer 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, 28, 6]. 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 one's perception of the environment. This fact has been shown by some research that our physical action is actually influenced by the presence of information from multiple sensory inputs such as visual, proprioceptive, auditory, and tactile channels [16]. For instance, some research indicates that the visual and proprioceptive sensory channels are highly tied together and constantly calibrated based on sensory inputs from the real world [4]. Distortion in human spatial perception could potentially degrade training outcomes, experience and performance. Also, it has been shown that in the real world visuo-motor calibration rapidly alters one's actions to accommodate new circumstances [4, 5].

2. *Evaluate the effect of visual and haptic feedback on overcoming distance mis-perception by training the motor component of perception motor activities and illustrate that the users' notion of space could be affected by motor component.* Haptic feedback provides a sense of limb position and movement as well as an apprehension of object properties such as hardness, extent, orientation, weight and inertia [42, 43]. Haptic feedback and its role on precise perception has drawn more attention to it in VR [9].

3. *Characterize the physical reach motions 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 to 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 [59]. 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 [53]. 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 [29]. It is not well understood how these limitations affect reaching motions during 3D interaction in the IVE.

4. **Proposed Study**: *Study the impact of animation fidelity on spatial perception in action space in IVE.* The interaction with the IVE could be through an immersive self-avatar which is life-size digital representation of the user. Existing of self-avatar requires some degrees of tracking and animation depending on accuracy of the rendered environment and the scenario. To generate high-fidelity immersive self-avatars in IVE one needs the higher level of real-time rending and animations which could be computationally expensive. However, there are some studies suggesting just the perception of a self-representation in IVE could increase the sense of presence [27]. Other studies found the present of even a static self-avatar in the environment improved distance judgment via blind walking [48, 36]. 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 far distance and less is known about the impact of animation fidelity on spatial perception in IVE in action space.

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) [12]. 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) [29, 66, 46, 60]. Similarly, distance estimation is distorted but overestimated in personal space (or near field) in VEs as compared to the real world [14, 50] which may have implications on physical reaching behavior of participants in the near field. Willemsen et al. [63] illustrated that the mechanical properties of the HMD can potentially contribute to distance underestimation as measured using blind walking. However, Grechkin et al. [17] pointed out that mechanical properties of the HMD cannot be the only reason for the distance underestimation in VE. Grechkin et al. [17] 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 [66] 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 [62]. 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. [44] showed that wearing a heavy backpack caused distance overestimation. In another study Willemsen et al. [63] 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 [26]. For instance, Linkenauger et al. [26] 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, 5, 68]. The rate of calibration (aka adaptation) has been shown to be constant despite the immediate calibration wearing displacement prisms [3]. Ziemer et al. [68] 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. [38] 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 [5] 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 [49, 4] as well as in VE's [35, 23]. 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 [46, 1, 21, 20]. In another study, Kelly et al. [21] 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 [45]. For instance, Kunz et al. [24] 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 [34], they suggested that verbal report and action-based responses use different neurological streams and may involve two distinct perceptual processes [37, 40, 15]. 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 [41, 39]. For instance, Pagano and Isenhower [41] 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 [51]. 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 [51, 11, 8]. Similarly, in VR applications, such as rehabilitation [13] and surgical training simulations [54], 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. [48] and Mohler et al. [36] 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 [58, 57]. For instance, by having a visual-tactile synchrony, Slater et al. showed that the rubber hand illusion could be replicated in virtual reality

[57]. 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, 31].

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. [36] 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. [27] 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. [65] 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 present of self-avatar has been shown to have an effect on user's spatial perception. However, to what degree 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. [61] 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. [27] 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. [32] 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 [25] showed participants to a degree 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 one was one of the main factors on inducing the sense of presence and the ownership of the virtual hand. Similarly, Ma and Hommel [30] 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. Overall, the visual fidelity or the rendering style of the avatar and also active operation of the self-avatar 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.

Chapter 3

Initial Study 1

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 [23, 35]. 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 [37]). 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 seated on the chair was also presented to provide an egocentric representation of self whether the participant looked down [Figure 3.2].

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

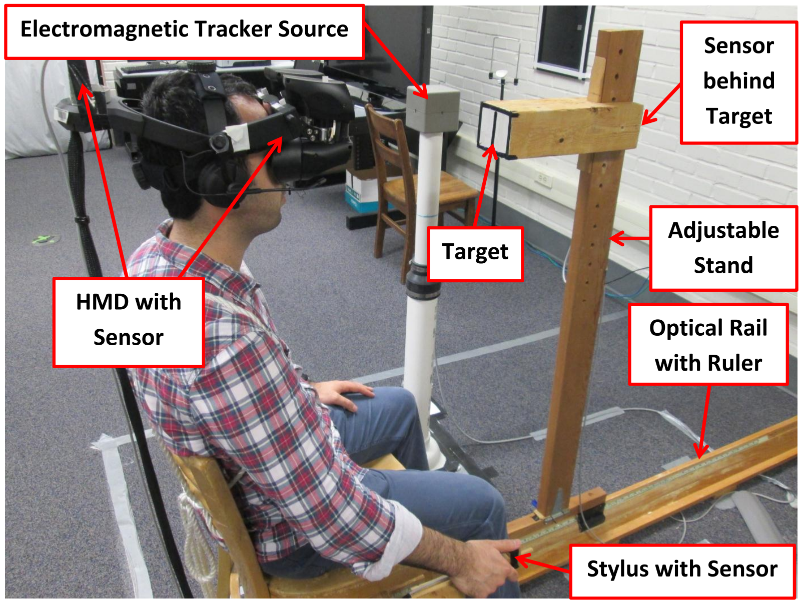


Figure 3.1: Shows the near-field distance estimation apparatus. The target, participant's head, and stylus are tracked in order to record actual and perceived distances of physical reach in the IVE.

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.

to participants, they visually detected when the stylus intersected a groove in the target's face in the IVE.

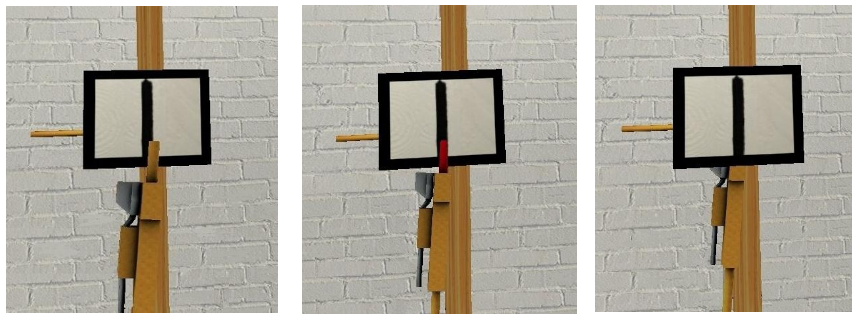


Figure 3.3: Image on the left shows a screen shot of the virtual target as perceived by participants in the IVE with the stylus in front of the target. Image on the middle shows that the tip of the stylus turned red when it was placed in the groove of the target, and on the right shows stylus passed 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. [64]. 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. [37] 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).

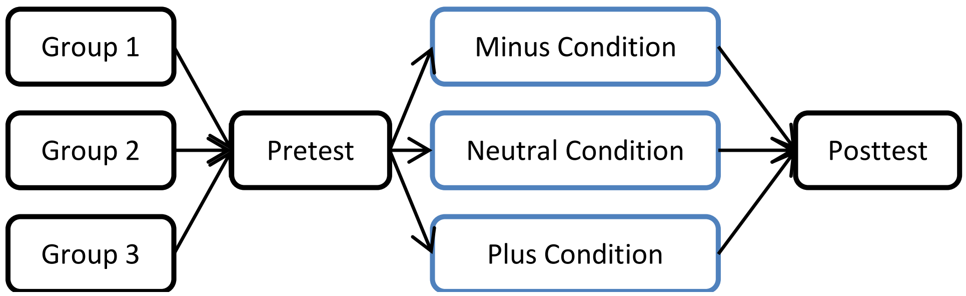


Figure 3.4: Experiment design.

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.

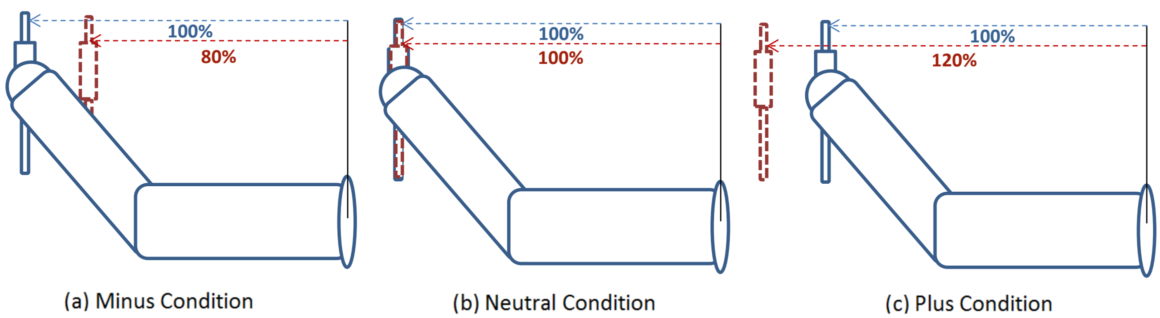


Figure 3.5: (a) Minus Condition: the virtual stylus (red lines) appears 20% closer than its physical position (blue lines). (b) Neutral Condition: physical (blue line) and virtual (red lines) stylus are co-located. (c) Plus Condition: the virtual stylus (red lines) appears 20% farther than its physical 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, 39, 40, 41]. 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.

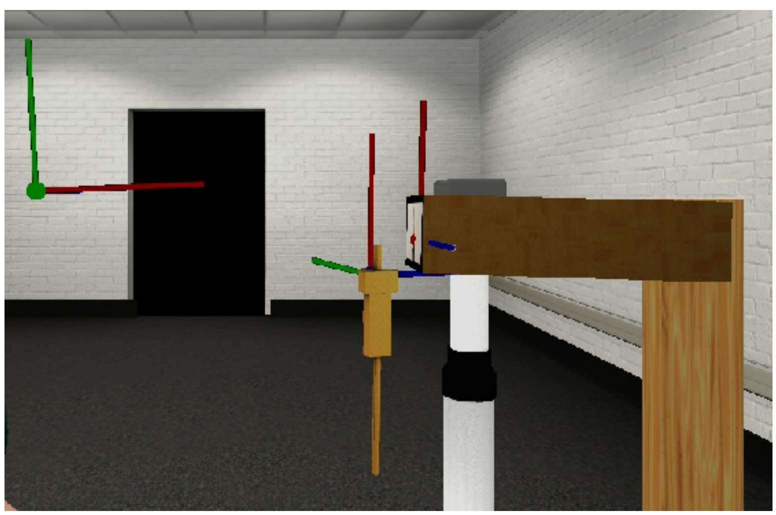


Figure 3.6: A screen shot of the visualizer that was used to tag the approximate location of the end of the ballistic reach. In this image, the coordinate system attached to the stylus, target, and user's eye centered point also can be seen.

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.

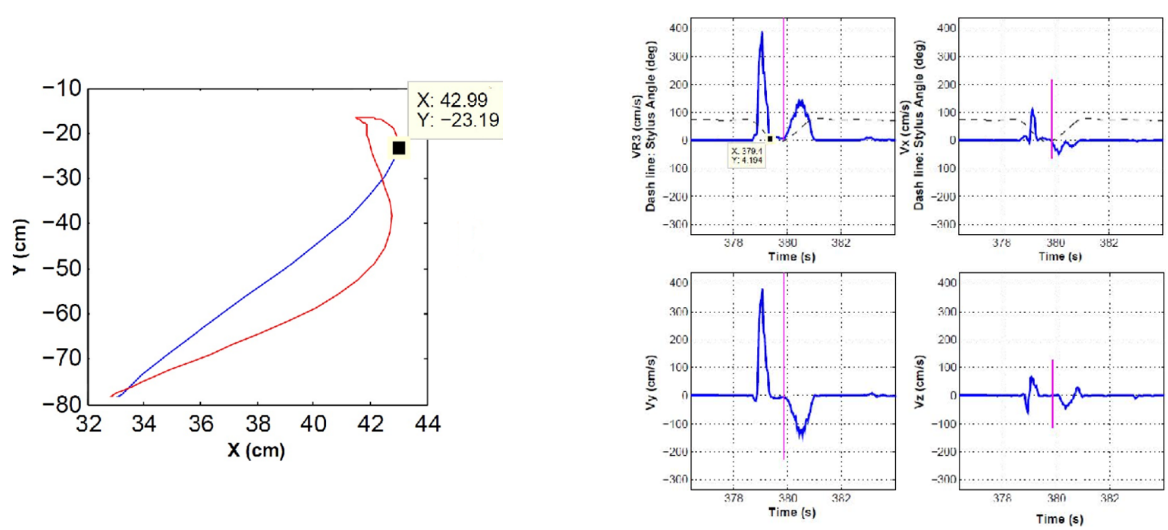


Figure 3.7: **Left**: An example of XY trajectory for a single trial. The black square is the tagged data point denoting the end of the ballistic reach. **Right**: An example of speed and velocity profiles (solid blue line). The magenta line denotes the time instance at the end of the ballistic reach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

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 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.

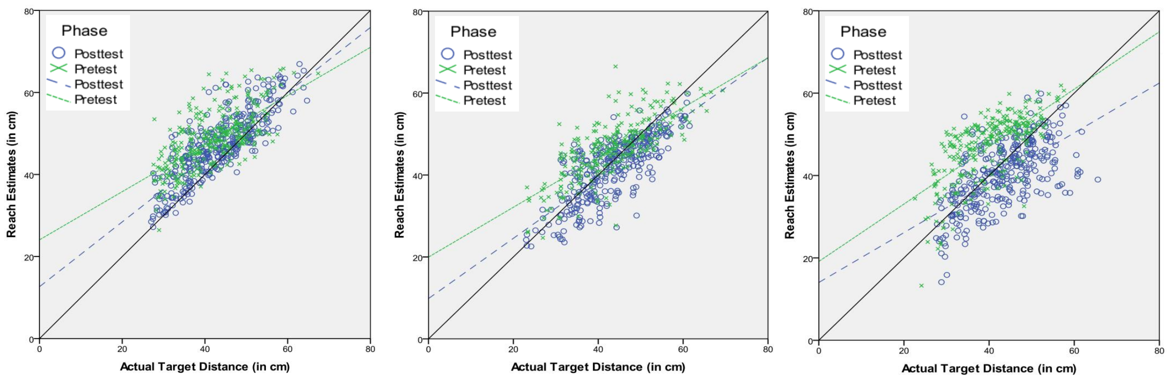
Next, multiple regression techniques were used to determine if the slopes and intercepts differed between the pretest and posttest sessions within each of the calibration conditions. Multiple regression analyses are preferable to ANOVAs and t-tests because they allow us to predict a continuous dependent 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, 39, 40, 41]). 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.



(a) Minus (b) Neutral (c) Plus

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.

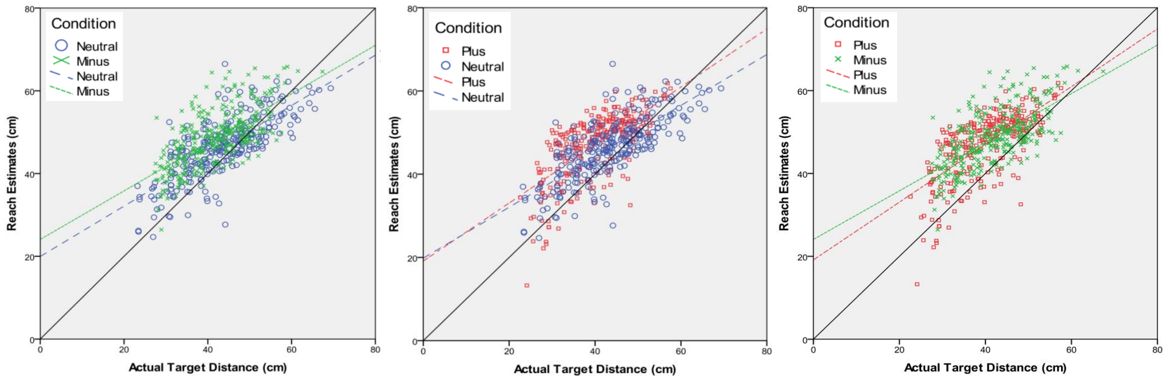
Our findings suggest that participants generally overestimated distances when reaching to the perceived location of the target without visual guidance. The tendency towards overestimation of reached distance observed in this study is consistent with a similar pattern observed by Rolland et al. [1995] 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).

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 $r^2 = .522$



(a) Minus and Neutral (b) Neutral and Plus (c) Minus and Plus

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.

(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).

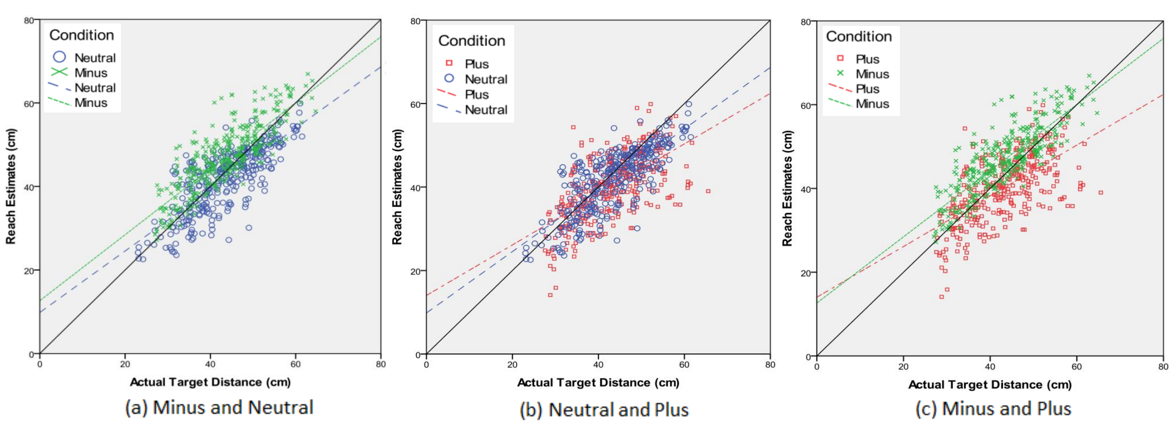


Figure 3.10: Reach estimates in (a) Minus and Neutral conditions, (b) Neutral and Plus conditions and (c) Minus and Plus conditions as a function of the actual target distances for the posttest.

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. 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 decoupling 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, 46, 47].

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 [5]. While Bourgeois and Coello [5] 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 [52], 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

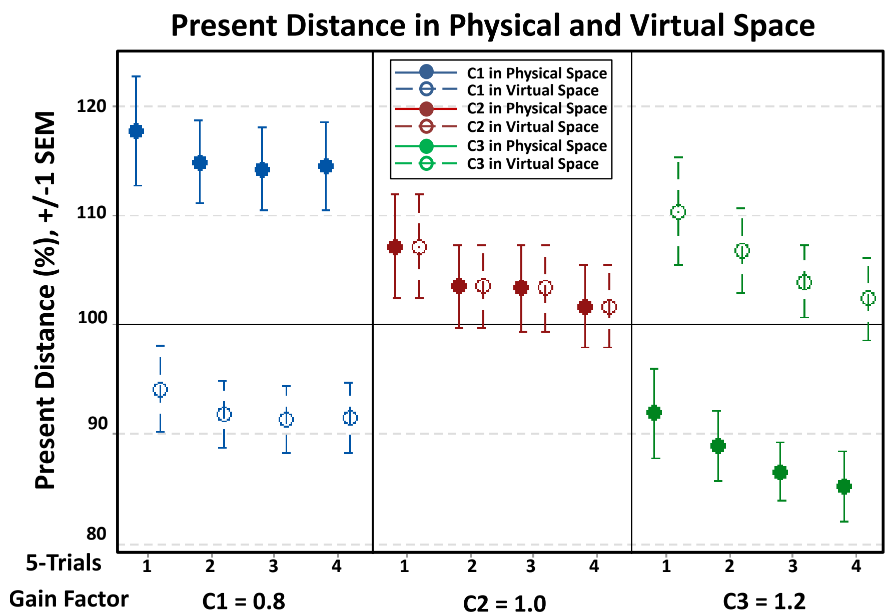


Figure 3.11: Physical and visual stylus location for all closed-loop conditions (C1 (Minus) = 0.8, C2 (Neutral) = 1.0, C3 (Plus) = 1.2)

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 [50] in the AR. However, others have reported underestimation when performing similar tasks [1, 55, 37]. 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

Initial Study 2

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) [22], 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 [37]. 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.

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) $\times$ (Environment - Real vs Virtual)] utilizing four of five different conditions in the experiment (Table 4.1). We analyzed the data using a 2×2

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)

Table 4.2: Step2 - Effect of Feedback in Virtual Environment

	Feedback		
	Visually Guided		*Non-Visually Guided*
Environment	*Haptic Feedback*	*No Haptic Feedback*	*No Haptic Feedback*
Virtual	n=14 (V&H)	n=13 (V&NH)	n=12 (NV&NH)

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.

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

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, $F(1, 1455) =$

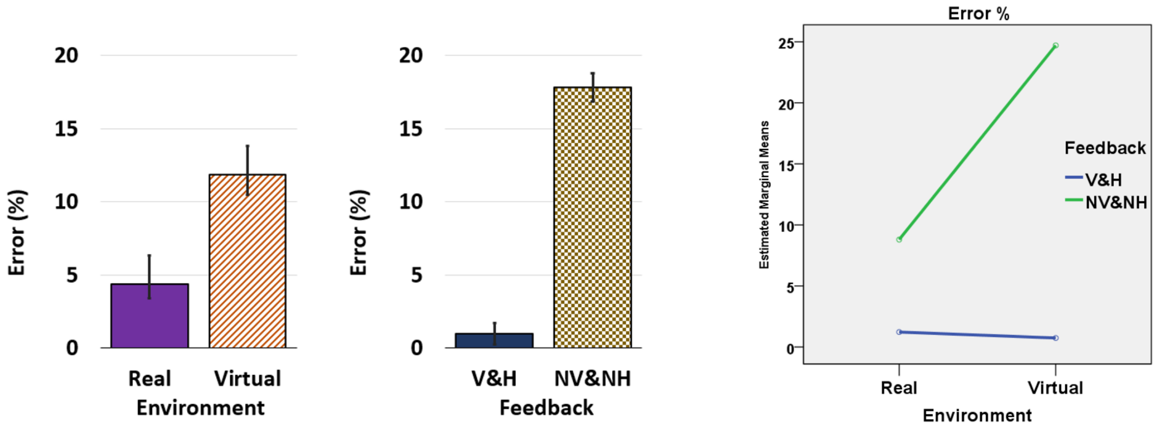


Figure 4.1: % Error for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

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 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 ($M = .72, SD = .24$) 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

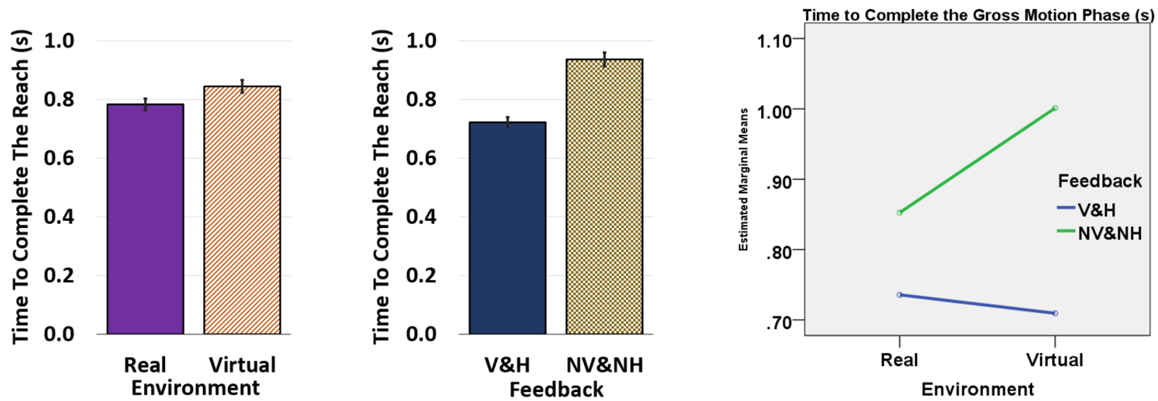


Figure 4.2: Time (s) to complete the task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

(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,

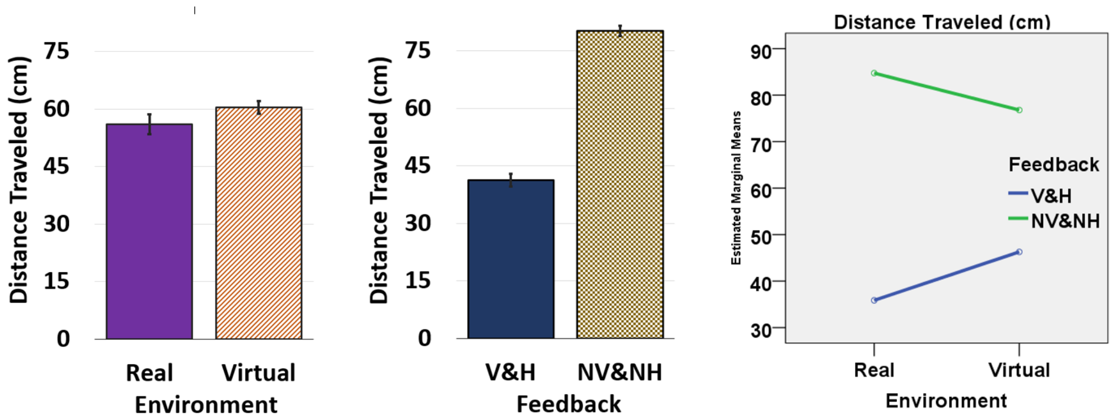


Figure 4.3: Distance traveled (cm) to complete the task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

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 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.

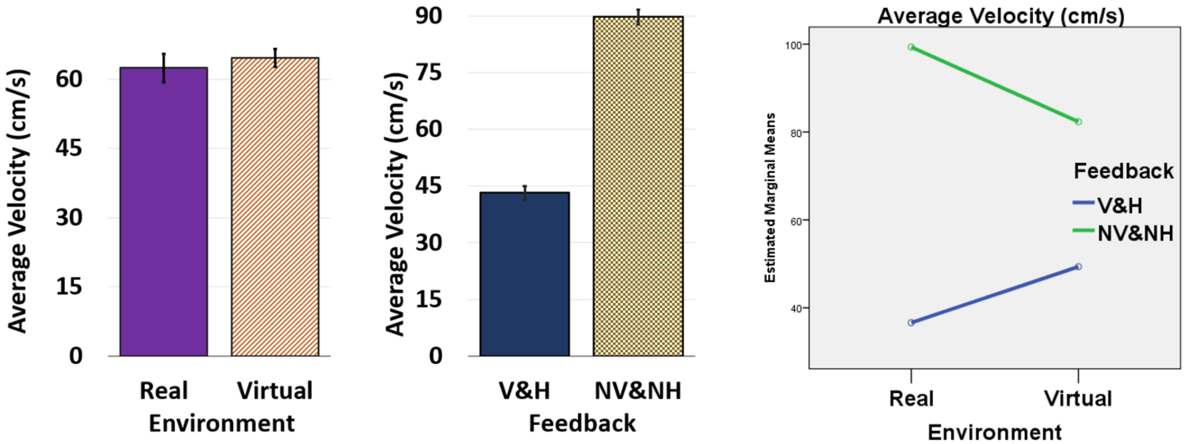


Figure 4.4: Average velocity (cm/s) during the physical reach task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

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).

$$\Delta V_i = \frac{\Delta D_i}{\Delta t_i}, where \begin{cases} \Delta t_i = t_{i+1} - t_i \end{cases} \tag{4.4}$$

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

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 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 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 [37]. On the contrary, in the virtual world, the distances are usually misjudged [14]. 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

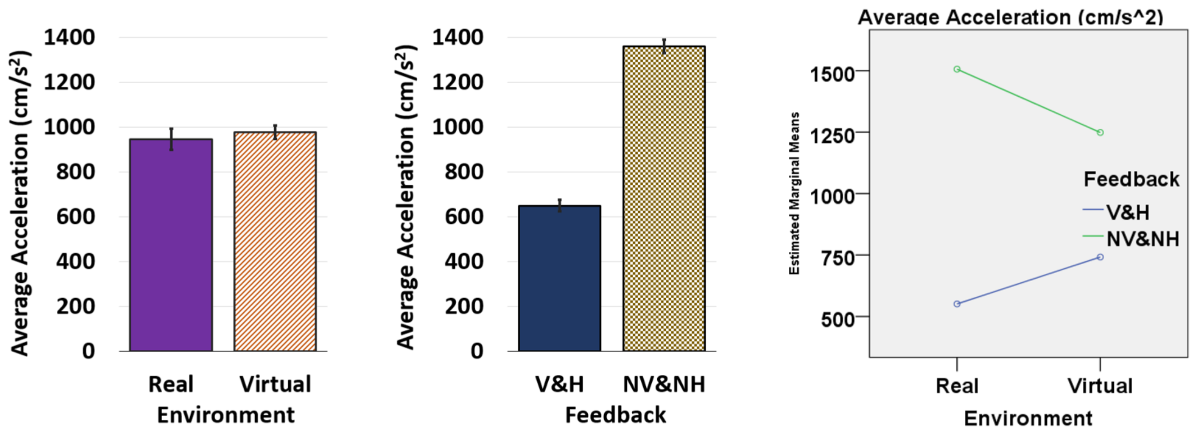


Figure 4.5: Average acceleration (cm/s^2) during the physical reach task for "Real vs Virtual Environment" and "Visuo-haptic Feedback (V&H) vs No Visuo-haptic Feedback (NV&NH)"

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 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

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			

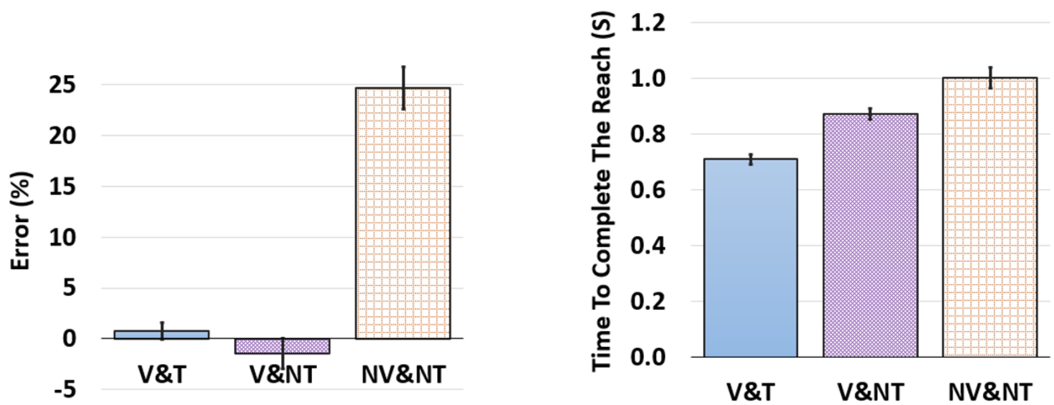


Figure 4.6: **Left:** % Error. **Right:** Time to complete a reach for three virtual conditions (Visual and Haptic Feedback (V&H), Visual and No Haptic Feedback (V&NH), and No Visual and No Haptic Feedback (NV&NH)

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.

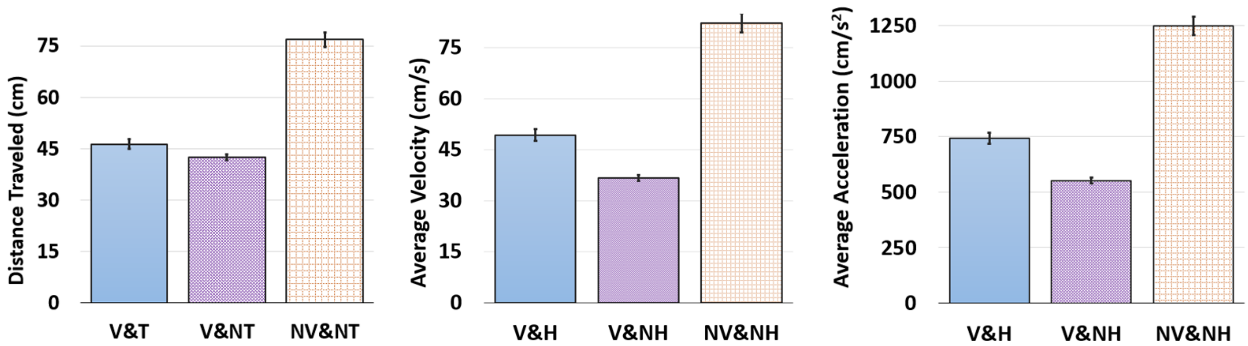


Figure 4.7: **Left**: Distance traveled. **Middle**: Average velocity **Right**: Average acceleration for three virtual conditions (Visual and Haptic Feedback (V&H), Visual and No Haptic Feedback (V&NH), and No Visual and No Haptic Feedback (NV&NH))

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 [22, 7]. 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 [22], 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):

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

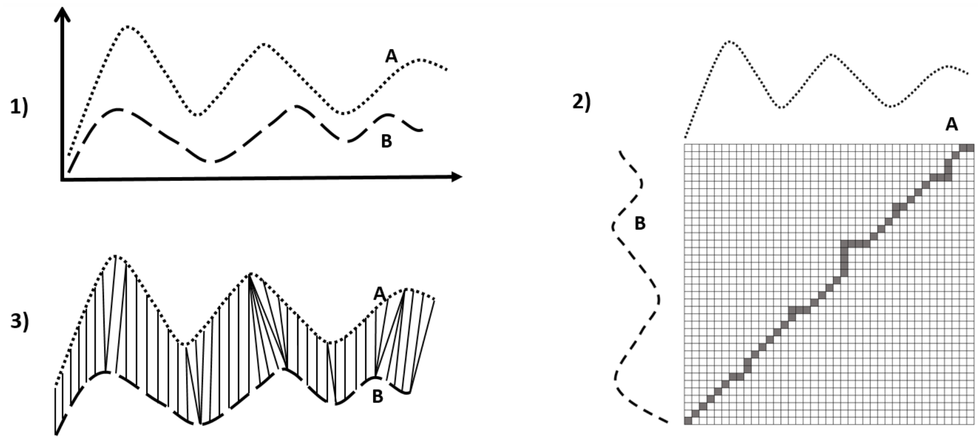


Figure 4.8: **1)** Two paths each representing a physical reach. Time is represented on the horizontal axis and one of the spatial dimensions is represented on the vertical axis **2)** Optimal warping path shown with gray squares. **3)** Time alignment of the two sequences. Aligned points are indicated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

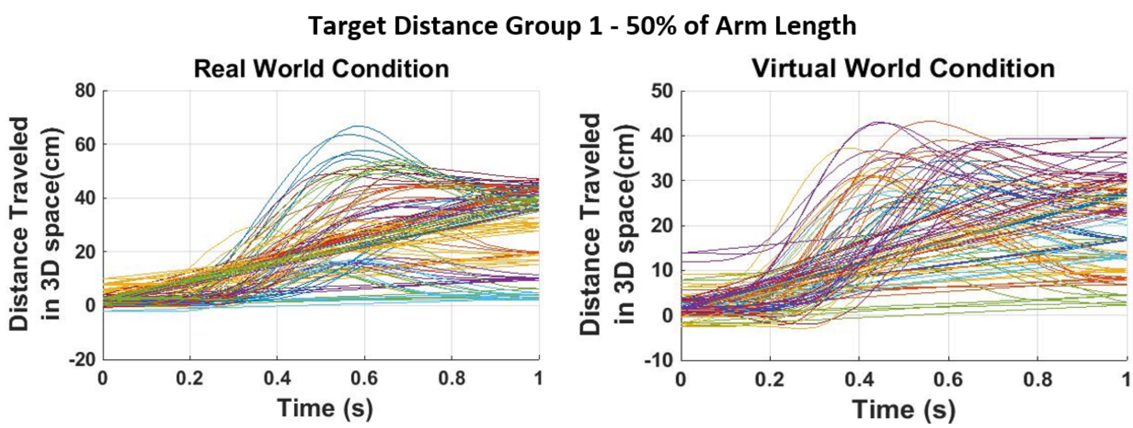


Figure 4.9: Spaghetti plots of physical reach motion in real environment (Left Image) and virtual environment (Right Image) for target distances corresponding to 50% of participants' maximum arm length. The variability between the paths when reaching to close distances was significantly more in virtual 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 [35]. 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

Proposed Study: Enhancing Proprioception via Self-Avatars Calibration on Spatial Perception in IVE

The interaction with the IVE could be through an immersive self-avatar which is life-size digital representation of the user.

Avatars are digital representations of human users in virtual environments. In most VR applications, avatars are the 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 knows 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 virtual environment affects how people perceive their environment. It also influences the user's behavior on the presence of the other virtual agents in IVE [18, 56, 67]. Recent perception research suggests the presence of an avatar influences the user's spatial perception in medium field in IVEs [36, 27, 65]. However, investigating the effect of self-avatar on user's spatial perception in near-field requires accurate body and hand tracking along with an realistic animation depicting user's motion. Many techniques have been developed to improve the real-time rendering and animation of an immersive self-avatar in IVEs.

The fidelity of the self-avatar has so induce the body ownership for it to be effective, recent research showed in the presence of specific types of synchronous multi-sensory and sensorimotor simulation [58, 57]

Research in inexpensive tracking technologies, such as the Microsoft Kinect, and rich animation techniques are required to produce high quality self-representations in IVE. While techniques are being developed for new and improved methods of real-time rendering and animation of immersive self-avatars in VR with high fidelity, there are some early results that suggest that just the perception of a self-representation via an avatar improves a sense of presence [86, 88]. Also research suggests that when presented with cue conflicts between visual and proprioceptive position of a persons hand in the VR, we have a strong tendency to resolve the conflict in favor of the visual position (even when the hand was not an articulated or animated realistic hand) [89, 90]. Recent perception research suggests that simply viewing a rendering of ones static feet in the VR decreases the depth compression of participants in a bisection task within a simulation with a HMD [91]. Researchers have found that the presence of a static self-avatar and the experience of walking around with a self-avatar have the effect of improving distance estimation when later measured via blind walking techniques [92, 93]. The limitations of the small number of related work investigating the impact of self-avatars on spatial perception are as follows: a) Self-avatars were generally experienced in an exploration phase which usually occurred in a different environment from the distance judgment phase of the experiment; therefore self-avatars were not involved in calibration of a complex manual fine motor tasks requiring depth estimation. b) The perception of the self-avatar has only been investigated in these recent studies in far distances (action space) [92, 93], which were measured using blind walking techniques. Typically when viewers see targets at these distances, the limited field-of-view of the HMD occludes the perception of the immersive self-avatars during the depth estimation task. c) Self-avatars were not involved in the viewers responses or actions to the visual stimuli; therefore, the calibration effect of the immersive self-avatar in scaling users responses in VR to depth perception is currently unknown.

Another body of research has looked at the visual fidelity of avatars in IVE. Volante et al. [61] 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. [27] 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. [32] 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 [25] showed participants to a degree 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 one was one of the main factors on inducing the sense of presence and the ownership of the virtual hand. Similarly, Ma and Hommel [30] 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. Overall, the visual fidelity or the rendering style of the avatar and also active operation of the self-avatar 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.

5.1 Hypothesis

There is little or no research on the visuo-motor calibration effects of immersive self-avatars on spatial judgments in interaction space in IVE. This study has four primary hypotheses. First, we predict that just the existing of the self-avatar will calibrate user's interaction space depth perception in an IVE. Therefore, participants spatial judgments will be improved after the calibration phase regardless of the visual fidelity. Second, the immersive self-avatar visual fidelity has an impact on user's spatial judgments in an IVE. We expect to observe different levels of improvement based on the self-avatar details presented to the participants. Third, we predict that participants in high-fidelity self-avatar condition have a significantly better spatial judgment as compared to medium and low-fidelity avatar conditions. Forth, we expect the adaptation happens fastest for high-fidelity avatar and slowest for low-fidelity avatar in calibration phase and reversion back to normal occurs fastest for low-fidelity avatar and slowest for high-fidelity avatar in posttest phase.

5.2 Experiment Methodology

5.2.1 Participants

Thirty-six undergraduate students will be recruited from the student population of Clemson University and received course credit for their participation. Participants will be required to be right handed as all equipment to be used is 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 described in Section 5.4.

5.2.2 General Setup

Figure 1 ??? (new figure) depicts the proposed apparatus to be used in the experiment which will be represented in VR. Participants will be seated in a wooden chair, which will be situated approximately 20 cm from the edge of the wooden table. The tabletop will be 50 cm wide by 130 cm long, and will be 76.2 cm tall (which is standard table height). Seat height will vary between 43 and 48 cm depending on the height of the participant. Shorter participants will be allowed to sit on a cushion if they desire. The center of the table will be aligned with the midpoint between the participants right eye and right shoulder. Participants will be outfitted with six Pohlemus sensors: 1. On their forehead. 2. On their neck. 3. On their shoulder. 4. On their elbow. 5. On their wrist. And 6. On their hand. Aside from the sensor on the forehead, the other five sensors will all be 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 will be a recreation of the room the experiment will be performed in, will be displayed using a HTC VIVE HMD.

As mentioned previously, three different avatars regarding different visual fidelities will be utilized in the experiment. In any given block of trials participants will be asked to reach for a target with their right arm and hand. In the real world, participants will be given a Vive controller to hold. The Vive controller is 26.5 cm 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 is 12 cm wide at its widest point. The Vive controller will allow the experimenters to accurately model participants wrist position in VR. The controller will be outfitted with a plastic mold that can hold a 10 cm wooden rod with a rubber tip. (add the brace description here)

Participants will be asked to reach for a visual target stimuli in IVE. For any trial, the target will consist of a virtual representation of three illuminated LED lights. The middle light in the target will correspond to the target distance, and with the other two lights illuminated the length of the target area will be three cm. Targets will be presented at 13 different distances, ranging from 20.5 cm to 121.5cm. The difference between each target will be approximately eight cm. Each target will be presented five times each for a total of 65 reaches per phase.

5.2.3 Visual aspects

An HTC Vive HMD weighing about 563 g will be used for the experiment. The HMD contains Fresnel lens with a resolution of 1200 x 1080 pixels for viewing a stereoscopic virtual environment with IPD adjustment. The field of view of the HMD was determined to be 110 degrees horizontal and 113 degrees vertical. The simulation will be consisted of the virtual model of the experimental room and apparatus created using Blender and Unity3D. The virtual replica of the apparatus include Table, chair, HTC Vive controllers with a plastic mold, and wooden rod. (Add a picture)

5.3 Procedure

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 asked to sit on the wooden chair at one end of the wooden table. Various motion sensors will be placed on the participant through the use of a long sleeve shirt.

Before any trials occur, various anthropometric measurements of the participant will be collected using the HTC Vive controller. The experimenter will measure participant standing height (floor to top of head) and various aspects of their arm, such as the length from acromion process to lateral epicondyle of the humerus (shoulder to elbow), and the length from the lateral epicondyle of the humerus to the end of the index finger (elbow to end of index finger). The experimenter will also measure various aspects of the participants arm relative to the positions of the sensors.

After these measurements have been collected, the participant will participate in three body ownership tasks in VR. The tasks are based upon those frequently used by Slater in his research on presence in VR. In the different conditions, participants will observe the self-avatar holding a tool. To induce a feeling of embodiment, participants will perform two tasks prior to the experiment. First, from a first-person viewpoint, participants will be able to see their movements in the mirror where the self-avatar movements are synchronized with their actual body movements. After five minutes of performing a set of predefined movements in front of mirror participants will progress to the second task. In the next task, participants will use the HTC Vive controllers to tap different parts of their body such as their shoulders, chest, hip, etc. with a synchronous visuo-tactile stimulus. In total, the body ownership tasks should last for about ten minutes.

Next, the experimenter will demonstrate the types of reaches that are appropriate in the experiment. Participants will be instructed to reach as quickly and as accurately as possible on each trial. The major restriction participants will have is 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 further).

Regardless of phase, each trial will begin with the participant resting their right arm on the armrest of the chair and their back against the back of the chair. Participants will be instructed that this is the starting point for each trial. To ensure uniformity in starting positions across participants, it will be emphasized to participants that their starting posture is critical for the study.

5.3.1 Pretest

In the pretest, participants will be instructed to reach to the target that will appear on the table at various distances from them. As part of each trial the participant will be asked to perform a reach if they believe they can reach the target. After viewing the target and at the initiation of their reach, participants will be shown a grey screen to simulate closing their eyes but maintaining the same overall illumination, and reach out with the stylus and place the tip of the stylus as close to the center of the target as possible. After attempting to reach the target, participants will be instructed to return their hand and arm to the starting point to begin the next trial. If they do not believe they can reach the target they will be instructed to say no. Regardless of condition, all participants will perform the pretest with a high-fidelity avatar. In this phase, participants will only receive haptic feedback from when the controller they are wielding in the real world contacts the surface of the table.

5.3.2 Calibration phase

After the pretest, participants will complete the calibration phase. The task in this phases will be the exact same as in the pretest, except they will perform less reaches to fewer distances. Participants will only be presented with nine different distances, and each distance will be presented five times. The first six distances presented in the calibration phase will all be reachable targets to encourage participants to engage in a reach. After the sixth trial, distances that are unreachable will be presented as well. None of the nine distances in the calibration phase will be identical to the 13 distances presented in the pre and posttest.

The primary manipulation of the experiment will occur in the calibration phase. Participants will experience one of the following conditions: a) high-fidelity avatar b) medium-fidelity avatar or c) low-fidelity avatar. Participants will not be informed about the changes in the visual fidelity. In this phase, participants will receive haptic feedback from when the controller they are wielding in the real world contacts the surface of the table. Then, once contact has been made participants will be allowed to open their eyes and adjust their reach so the end of the virtually presented hand is in the center of the target, thus receiving visual feedback as well.

5.3.3 Posttest

The posttest will be identical to the pretest. All participants will complete the exact same reaching task while using a high-fidelity avatar arm. In this phase, participants will only receive haptic feedback from when the controller they are wielding in the real world contacts the surface of the table. Importantly, the experimenters will ensure there is no delay between the calibration phase and the posttest. By doing so, we hope to preserve the just modified action capabilities of the avatar for the posttest, as a long delay between these two phases might cause the calibration to disappear.

5.3.4 Post Data Collection

After the conclusion of data collection, the experimenter will again measure various aspects of the participants arm to ensure that the positions of the sensors did not move over the course of the experiment. In addition, the participant will be asked to perform two maximum reaches with their arm only (reaching their arm straight out as far as they can without engaging their shoulder or back) and two maximum reaches with their entire upper body (by reaching as far as they can and touching the table with no restrictions other than remaining seated in the chair). Lastly, participants will be given a brief questionnaire designed to measure the degree of body ownership they felt over the avatar in VR. A manipulation check will also be administered to participants. They will be asked if they noticed anything odd that occurred during the course of the experiment.

5.4 Experiment Design

The proposed experiment will utilize a 3 (Condition: High-fidelity, Medium-Fidelity, Low-fidelity Avatar) by 3 (Phase: PreTest, Calibration, PostTest) mixed groups design. Condition will be a between subjects variable and phase will be a within subjects variable. All three conditions will involve use of an avatars arm that is directly proportional to the dimensions of the users own arm where the visual fidelity will be altered in the calibration phase.

5.5 Data Preprocessing

5.6 Expected Results

We will use HTC Vive and Polhemus electromagnetic tracking system to track and create accurately scaled articulated models of the users and animate the limbs to match the physical reaching activities in our perception apparatus described in previous section using the *Inverse Kinematic* (IK). We have plan to use a Synertial tracking suit as a confirmation to our IK system to more accurately animate the user's upper body movements. The anthropometric measurement prior to the experiment will ensure that the participants limbs are scaled accordingly. Together with a tracked stylus, participants can receive accurate visual feedback of their actions (proprioception) in a closed-loop condition via the immersive self-avatar in the IVE. In order to assess the impact of visuo-motor calibration to enhanced proprioception via the immersive self-avatar, participants will perform the closed-loop calibration phase in one of three visual fidelity conditions: 1) high-fidelity: realistic limb matching the size and scale of the participants limbs, 2) medium-fidelity: abstract rendering of joint and limb location only, and 3) low-fidelity: abstract rendering of joint locations only. We expect to find that the high-fidelity self-avatar of the participants arm will provide a more realistic proprioceptive cue as compared to medium and low-fidelity avatar, and will significantly enhance depth perception in the IVE.

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