8-2012

Effects of Interaction with an Immersive Virtual Environment on Near-field Distance Estimates

Bliss Altenhoff
Clemson University, blisswilson1178@gmail.com

EFFECTS OF INTERACTION WITH AN IMMERSIVE VIRTUAL ENVIRONMENT ON NEAR-FIELD DISTANCE ESTIMATES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Applied Psychology

---

by
Bliss Altenhoff
August 2012

Accepted by:
Dr. Chris Pagano, Committee Chair
Dr. Sabarish Babu
Dr. Richard Tyrrell

ABSTRACT

Distances are regularly underestimated in immersive virtual environments (IVEs) (Witmer & Kline, 1998; Loomis & Knapp, 2003). Few experiments, however, have examined the ability of calibration to overcome distortions of depth perception in IVEs. This experiment is designed to examine the effect of calibration via haptic and visual feedback on distance estimates in an IVE. Participants provided verbal and reaching distance estimates during three sessions; a baseline measure without feedback, a calibration session with visual and haptic feedback, and finally a post-calibration session without feedback. Feedback was shown to calibrate distance estimates within an IVE. Discussion focused on the possibility that costly solutions and research endeavors seeking to remedy the compression of distances may become less necessary if users are simply given the opportunity to use manual activity to calibrate to the IVE.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

Virtual environments (VE's) are a common means for providing communication (Biocca, 1992), education (Winn et al., 1999), social interaction (Blascovich et al., 2002), virtual reality therapy (Hodges, Anderson, Burdea, Hoffman, & Rothbaum, 2001), and training for situations that are dangerous, expensive, rare, or remote, such as laparoscopic surgery training (Bliss, Tidwell, & Guest, 1997; Darby, 2000; Peters et al., 2008). A main advantage of virtual environments is that they provide a controlled scenario so users can repeatedly and safely interact with situations. Immersive virtual environments (IVEs) are an important class of VE's that may use a head-mounted display (HMD) to surround the user with visual information, allowing them to interact with the VE using their physical body (Loomis, Blascovich, & Beall, 1999).

Distance estimates are typically found to be less accurate in virtual environments than in real environments. Based on experiences with rescue robots at the World Trade Center during the aftermath of September 11, 2001, Murphy (2004) concluded that one of the biggest problems with using teleoperated cameras is the lack of depth perception and ability to accurately perceive sizes of elements in the remote environment. Tittle, Roesler, and Woods (2002) have termed these difficulties "the remote perception problem." Robot operators at the September 11th clean up also had difficulty identifying objects and determining whether the robots could pass over obstacles and through apertures (Casper & Murphy, 2003).

Differences between impassability boundaries using direct line of sight versus teleoperation have been quantified using three different sized robots (48.5cm, 39.5 cm, and 30.5 cm wide). Moore, Gomer, Pagano, and Moore (2009) asked participants to judge the smallest passable aperture width of each robot based on an ascending or descending series of presented apertures, each differing by 3 cm. As predicted, although novice teleoperators tend to overestimate impassability boundaries using direct line of sight, they barely underestimate impassability boundaries (they would judge that robots could pass through apertures when they actually could not), using teleoperation. The actual average impassability boundary of the three robots was 38 cm, but participants judged the mean impassability boundary for direct line of sight to be 42.5 cm and only 35.5 cm for teleoperation. Underestimations of the impassability boundary increased with robot size in the teleoperation condition. Thus the subjects often judged as passable apertures that were too small for the robot to fit through.

To improve depth perception during teleoperation, Gomer, Dash, Moore, and Pagano (2009) suggest training with familiar objects (e.g. playing cards, compact discs, 12 oz. soda cans, etc.) and using passive front-to-back camera motions to produce radial outflow. When using passive front-to-back camera motions, participants were presented with video that was fed via remote camera that moved with a consistent forward and backward sinusoidal velocity profile. After a training session in which the subjects judged the depths to familiar objects and received feedback about their performance, subjects were able to judge the distances to uniform white squares which lacked a familiar size. These viewing conditions demonstrated participants' abilities to use radial outflow to perceive distances in a remote environment.

Users find it difficult to provide accurate distance estimates while wearing HMDs, consistently underestimating distances between themselves and other objects in the IVE (Witmer & Kline, 1998; Loomis & Knapp, 2003). For example, Grechkin, Nguyen, Plumert, Cremer, and Kearney (2010) compared real world viewing with and without a HMD to virtual world viewing conditions with HMD, augmented reality (AR) with a HMD, and a large-screen immersive display (LSID). Distances were similarly underestimated in VR, AR, and LSID conditions. Specifically, estimates of egocentric distances (0m - 30m) can be underestimated by as much as 50% (Loomis & Knapp, 2003; Napieralski et al., 2011; Richardson & Waller, 2005; Thompson et al., 2004; Witmer & Kline, 1998).

Although causes of this compression are not fully understood, one suggested solution is to allow users to interact with the environment before making distance judgments (Richardson & Waller, 2007). Interaction with the environment would allow the user to experience a training period with visual and/or haptic feedback regarding their actions within the IVE. This solution would be ideal for improving the accuracy of distance underestimations because it would not require significant time or money to implement. If closed-loop interaction with an IVE can significantly reduce distance estimation errors, then researchers need not be as concerned with alternative, more expensive solutions.

If distance estimations become more accurate with the closed-loop interaction between the user and the IVE, this change is likely caused by a visuomotor recalibration (Bingham & Pagano, 1998; Durgin et al., 2005; Mohler, Creem-Regehr, & Thompson., 2006; Richardson & Waller, 2007, 2008; Rieser, Pick, Ashmead, & Garing, 1995). For example, most people have experienced some sort of recalibration when performing regular activities under irregular circumstances, such as a baseball player who must decide how hard to throw the ball during a windy game. People's ability to use perceptual information to coordinate their actions implies that motor and perceptual systems are mutually calibrated (Rieser et al., 1995). Practice and experience allow us to adjust existing calibrations that represent conditions we may be most comfortable or familiar with to adjust to changes in circumstances.

When interacting with one's environment (e.g. walking to a destination), if there are inconsistencies between one's intended actions and the resulting sensory information (e.g. the amount of optic flow resulting from one's walking), actions will likely be adapted to reach one's goals (Rieser et al., 1995; Waller & Richardson, 2008). When provided with closed-loop interaction, visuomotor recalibrations can occur after only brief exposures to feedback. For example, after walking on a treadmill being towed to create an optic flow that was either faster or slower than actual walking speed, participants were asked to view a target and then walk to it while blindfolded. Those that experienced optic flow faster than would be produced by their walking speed, underestimated the distance to the target although they believed the opposite to be true, while those with optic flow slower than their actual walking speed walked past the target and also believed the opposite to be true (Rieser et al., 1995).

Similarly, Bingham and Romack (1999) examined the rate of calibration with displacement prisms over a three day period. Targeted reaches showed an initial increase in movement time (MT) and path length when prism goggles were donned, then they decreased over successive trials. And although the rate of decrease in MT remained constant, MT for the first trial decreased each day. Fewer trials were required each day to reach a set criterion MT and calibration was near immediate on the third day.

Bingham and Pagano (1998) also studied effects of feedback on targeted reaches performed with monocular and binocular vision. Participants viewed a floating, luminous disk at 50 to 90 percent of their maximum arm reach using a head-mounted camera and made targeted reaches with and without feedback. Without feedback, underestimation of distances increased using monocular viewing with restricted field of view (FOV). However, with feedback, this compression in depth due to the restricted FOV was calibrated away, although compression due to monocular viewing alone (with unrestricted FOV) was not. Feedback also improved distance compression with binocular viewing. It seems likely that distance estimation can be accurate in different viewing conditions (such as an IVE) when provided with feedback, as long as enough perceptual information is available. However, it is possible that feedback-induced recalibration may compensate for some distortions (e.g. restricted FOV) but not others (e.g. monocular viewing), thus it is important to study the effects of calibration.

After one has recalibrated in a new environment, aftereffects are likely to occur (Durgin & Pelah, 2004; Durgin, Fox, Lewis, & Walley, 2002, Durgin et al., 2005; Mohler et al., 2006; Rieser et al., 1995). Just as one requires several trials with feedback to recalibrate to an IVE, he or she would likely have to recalibrate back to the physical world after leaving the IVE. After a period of recalibration in an IVE that visually compresses distances, participants' distance estimates may be biased toward overestimation when immediately returned to the physical world.

Previous research has shown that a brief interaction period in an IVE can improve egocentric distance estimates within that IVE from approximately 56% of the intended distance to 94% using blindfolded and triangulated walking (Richardson & Waller, 2007). Because both walking tasks improved equivalently, it is likely that a visuomotor recalibration affected distance estimates, rather than a cognitive strategy. Additionally, participants have demonstrated aftereffects of interacting in an IVE once exposed to the natural physical environment by overestimating distances by approximately 10%. Participants were also shown to have improved distance estimates after interacting with an IVE when they were provided with body-based senses such as vestibular, proprioceptive, and efferent information, but no improvements were found when provided with visual optic flow when body-based information was not available (Waller & Richardson, 2008). Such research demonstrates that exposure to a normal IVE can result in visuomotor recalibration that even carries over when first reintroduced to a natural physical environment.

Distance estimation in an IVE has been widely studied in action space (approximately 0 to 30 meters from the body) using techniques such as imagined timed walking (Grechkin et al., 2010), verbal reports (Klein, Swan, Schmidt, Livingston, & Staadt, 2009), triangulation by pointing (Loomis & Knapp, 2003), blind-walking (Messing & Durgin, 2005; Loomis & Knapp 2003), triangulated walking (Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, & Beall, 2004), and throwing an object toward the viewed target with the eyes closed (Sahm, Creem-Regehr, Thompson, & Willemsen, 2005). For the proposed experiment, action measures are preferred to verbal distance estimates because it has been suggested that action measures and verbal judgments reflect two distinct perceptual processes that may be affected differently by the context within which they are made and which may react differently to calibration (Pagano & Bingham, 1998; Pagano, Grutzmacher & Jenkins, 2001; Pagano & Isenhower, 2008).

When directly compared in IVE and real world viewing conditions, both verbal and reach estimates show distance compression when made to near-field targets (Napieralski et al., 2011). For the reaches, underestimation was shown to increase as target distance increased, while underestimation decreased with increased distance for verbal reports. Compared to the direct, real world viewing condition, viewing in the IVE was observed to have larger effects on verbal judgments, but small effects on concurrent manual reaches to egocentric distances in personal space. Overall, the difference between reaches and verbal estimates accounted for a large proportion of the variance in the participants' responses, 9.6% in IVE and 22.1% in the real world. Reaches generally tended to be more accurate and more consistent (see also Pagano & Bingham, 1998; Pagano et al., 2001; Pagano & Isenhower, 2008).

Multiple regression analyses on response mode (verbal vs reach) confirmed that reaches and verbal reports were different (Napieralski et al., 2011). Although reaches were very similar in the IVE and RW, they were slightly farther in the RW (only 1.8 cm farther on average). As actual target distance increased, so did underestimation in participant reaches. A simple regression predicting the reaches from actual target distance indicated that the difference between viewing in RW or IVE accounted for only 1.2% of the variances in the reaches. However, even though verbal reports were made concurrently with reaches, they varied significantly in both the IVE and RW environment. Overall, the verbal reports increased at a much higher rate as actual distance increased in the virtual world than in the RW (see Figure 1). A simple regression predicting the verbal reports from actual target distance indicated that the difference between viewing in the RW or IVE accounted for 2.7% of the variance in the verbal reports. Multiple regression analyses also revealed that although verbal reports were made concurrently with reaches, they varied significantly from reaches and were highly variable in both viewing conditions.

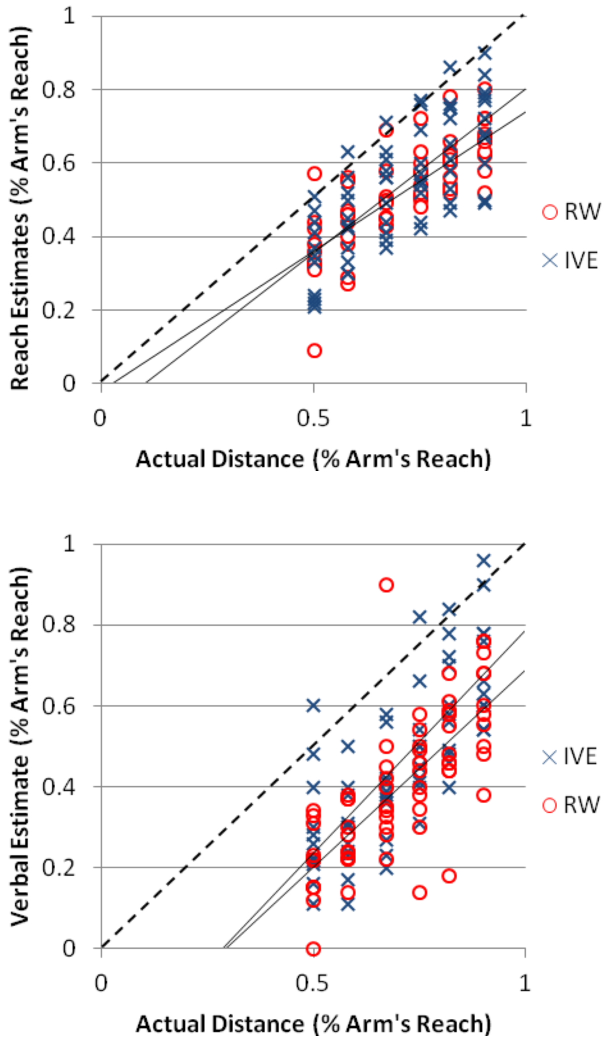
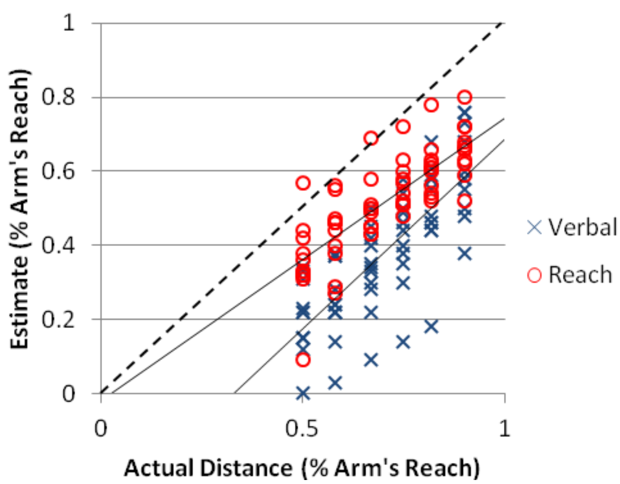


Figure 1: Physical reaches (top) and verbal estimates (bottom) as a function of the actual target distances for IVE and RW viewing (Napieralski et al., 2011)

Overall in the RW viewing condition, as the actual distances increased, the verbal reports increased at a higher rate than the reaches (Napieralski et al., 2011). This was a very large effect, and indicated by the large difference in intercepts (see Figure 2). A simple regression predicting indicated target distance from actual target distance indicated that the difference between the reaches and the verbal reports accounted for 22.1% of the variance in the responses. By restricting the field of view in the real world viewing condition to match that of the IVE, it is likely that this restricted view contributed to underestimation in both viewing conditions (Bingham & Pagano, 1998).

Although both response measures displayed an underestimation of distances in both viewing conditions, distances were underestimated more in the IVE than in RW. Similar to the RW, in IVE the verbal judgments and reaches were different from each other despite being performed within the same trial. And like the RW, as the actual distances increased, the verbal reports increased at a higher rate than the reaches. A simple regression predicting indicated target distance from actual target distance indicated that the difference between the reaches and the verbal reports accounted for 9.6% of the variance in the responses. While viewing in the IVE had a small effect on reaches, the effect was larger for verbal reports.



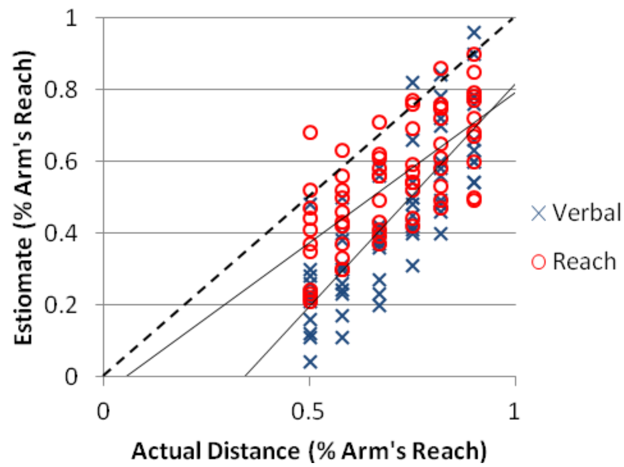


Figure 2: Interaction between actual target distance and verbal/reach estimates for RW (top) and IVE (bottom) (Napieralski et al., 2011)

In sum, the verbal reports were very different from the reaches in both the IVE and the RW. The verbal reports, however, were affected by the viewing condition to a greater extent than the reaches. The effect of response mode was much greater than the effect of viewing condition, with the reaches remaining more consistent between the viewing conditions than the verbal reports. Based on these findings, the next step in our research was to investigate the effects of distance estimation training with feedback within an IVE to see if this distance compression can be calibrated away.

Pagano and Isenhower (2008) investigated the accuracy of verbal and reach distance estimates by instructing participants to judge distances between 25 and 90 percent of their maximum arm reach in one condition, and between 50 and 100 percent in another, although targets presented to both groups were actually between 50 and 90 percent. Participants' verbal estimates were significantly affected and made based on the expected range, while reaches remained accurate and unaffected. While reaches appear to represent absolute metric distances, verbal estimates seem to only represent relative distances and are easily influenced by the expected range of distances. Therefore, many researchers find verbal responses inappropriate for examining absolute distance estimates. Although previous research has demonstrated a visuomotor recalibration of egocentric distances in an IVE by utilizing blind and triangulated walking, reaching estimates to near space have not been so thoroughly tested. However, verbal estimates are still a popular form of reporting size and distance estimates. Differences between verbal and action measures will also be interesting to compare because it is possible that verbal and action measures may be calibrated differently.

The materials, apparatus, and procedure were very similar to those used in Napieralski et al. (2011). To test for recalibration, a pretest measure in an IVE in which participants complete distance estimates without feedback was compared to IVE estimates made after visual and haptic feedback. Thus, participants completed a second set of distance estimates in the IVE without feedback. Here we compared the accuracy of the distance estimates in the final posttest session to those of the initial pretest. It was hypothesized that recalibration to the IVE from feedback via manual activity would be evidenced by improved distance estimates in the posttest.

CHAPTER TWO

METHODS

Participants

15 Clemson University students with normal or corrected-to-normal visual acuity and stereo vision participated in the study after providing informed consent. They received credit toward a requirement in their psychology course for participating.

Materials and Apparatus

General Setup. Figure 3 depicts the apparatus that was used. Participants were seated in a wooden chair with their shoulders loosely strapped to the back of a chair to allow freedom of movement of the head and arm while restricting motions of the trunk. Participants reached with a wooden stylus that is 26.5cm long, and 0.9 cm in diameter and weighing 65g, held in their right hand so that it extends approximately 3 cm in front and 12 cm behind their closed fist. Each trial began with the back end of the stylus inserted in a 0.5 cm groove on top of the launch platform, which was located next to the participant's right hip.

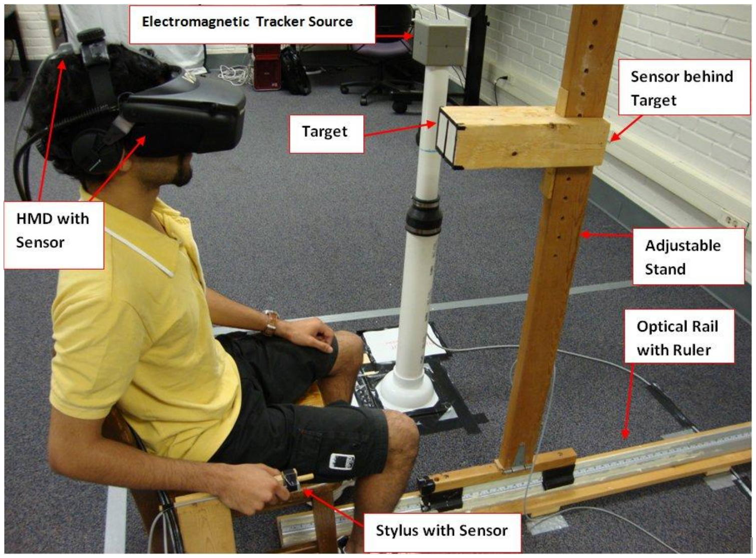


Figure 3: Shows our near-field distance estimation apparatus. The target, participant's head, and stylus are tracked in order to record actual and perceived distances of physical reach in the IVE

The target consists of a 0.5 cm deep vertical 8.0 cm x 1.2 cm groove extending from the center to the base of a 8.0 cm wide x 16 cm tall white rectangle (Figure 4). The edges of the target are covered by a 0.5 cm thick black tape, so that the participant can distinguish the target from the background of the wall. The target was positioned in front of the participant along the optical axis, approximately midway between the participant's midline and right shoulder (Figure 3). Therefore, the target was positioned such that the distance from the shoulder to the target will be as close as possible to the distance from the eyes to the target. The egocentric distance to the target was adjusted by the experimenter using mounts attached to a 200 cm optical rail extending parallel to the participant's optical axis. The target was attached to the optical rail via an adjustable hinged stand. The target, stand and stylus are made of wood and the aluminum optical rail will be mounted on a wooden base.

Figure 4: Image on the left shows a screen shot of the virtual target as perceived by participants in the IVE, and image on the right shows the real target.

Visual Aspects. Participants wore a Virtual Research VR 1280 HMD weighing 880g. 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 is determined to be 48 degrees horizontal and 36 degrees vertical. The field of view was determined by rendering a carefully registered virtual model of a physical object, and asking users to repetitively report the relative size of the virtual object against the physical counterpart through a forced choice method (see Napieralski et al., 2011).

The virtual model of the experimental room and apparatus developed by Napieralski et al. (2011) was employed in this experiment. In Napieralski et al. (2011) we strove to model and render the virtual setting to be similar to the physical setting. An accurate virtual replica of the experiment apparatus and surrounding environment were modeled using Blender. The virtual replica of the apparatus and surrounding environment included the target, stand, chair, room, tracking system, stylus and a virtual body representing the participant. The gender neutral model of a virtual body seated in the participant's chair was meant to provide the participant with an egocentric representation of the self whenever the participant glances down (see Figure 5).

Figure 5: The left shows a screenshot of the avatar as seen from the participant's first person perspective through the HMD. The right shows the avatar with the virtual apparatus in the testing environment.

We have attempted to achieve this level of realism by not only matching the size and placement of objects located in the real-world environment exactly, but by matching the textures and lighting as well (Napieralski et al., 2011). The accuracy of the scale and size of the virtual objects in the IVE was ensured by careful hand measurements of each of the physical objects in the real world room setup. Many of the textures of the synthetic world are simply photographs of the real-world objects. Great care was taken to match the objects exactly, especially those that were involved in the experiment, such as the virtual target, as shown in Figure 4. We also employed state of the art rendering techniques such as radiosity and render to texture, to match as close as possible the visual quality of the virtual environment and apparatus to the physical experiment setting. These efforts were largely undertaken to prevent any adverse effects on perception in the virtual world, which can occur in non-photorealistic virtual environments (Phillips et al., 2009).

The computational environment that hosted the distance estimation system consists of a Dell Precision workstation with a quad core processor and dual NVIDIA Quadro FX 5600 SLI graphics cards. The distance estimation system that rendered the IVE in HMD stereo, ran the tracking system, and measured and recorded the perceived physical reaches in tracker coordinates was developed in OpenGL and the Simple Virtual Environment toolkit (SVE) (Kessler et al., 2000). The distance estimation experiment system runs at an application frame rate of 45Hz.

Tracking of the Physical Reaches. A 6 degree of freedom Polhemus Liberty electromagnetic tracking system tracked the position and orientation of the participant's head, the stylus, and the target (Polhemus/Colchester, VT). Prior to conducting the experiment, the Polhemus tracking system was calibrated to minimize any interference due to metallic objects in the physical environment, through the creation of a distortion map, using a calibration apparatus and proprietary software from the manufacturers of the tracking system. This calibration step ensured that the sensor position reported by the tracking system was accurate to 0.1cm, and the sensor orientation was accurate to 0.15 degrees. Measurements of the participant's physical reach was measured from the position of the target face to the origin of the optical rail as reported by the tracking system in centimeters (cm) in both conditions. Raw position and orientation values of the tracked sensors as well as the measured perceived and actual distances for each trial were logged in a text file by the experiment system for each participant.

To ensure proper registration of the virtual target and stylus with their real counterparts, we carefully aligned the virtual object's coordinate system with that of the tracking sensor's coordinate system. We also determined the relationship between the coordinate system of the tracking sensor on the participant's head (on top of the HMD) and the coordinate system of the HMD's display screen (computer graphics view plane), to ensure proper registration of the virtual environment to the physical environment as perceived by the participant.

Procedure

Upon arrival, participants completed a standard consent form and demographic survey before visual acuity and stereo vision testing. All participants' acuity measured better than 20/40 and based on the Titmus Fly Stereotest, all were able to perceive stereo when viewing an image with a disparity of 3600 sec of arc. Interpupillary distance of each participant was measured manually with a ruler. Participants were asked to fixate on the visual acuity chart while they remain standing 20 feet away so their pupils will be parallel to each other, as they would be if set to optical infinity. After passing the necessary vision tests, the participant was loosely strapped in a chair to restrict movement of the trunk but to allow free movement of the arm. The height of the target was adjusted so it best matched the participant's sitting eye height. Participants' maximum arm reach was then measured by adjusting the target so the participant could place the stylus in the groove of the target with their arm fully extended but without moving their shoulders forward off the back of the chair. This maximum arm reach distance was used to generate the trial distances at which the apparatus was placed during the experiment.

The participant was also instructed on how to make physical reach estimates, with swift, ballistic reaches and verbal reports based on percentage of the participant's maximum arm reach. By using a more natural, intrinsic body scaled unit for verbal reports rather than an extrinsic scale such as inches or centimeters, unconscious transformation from an intrinsic scale will be reduced (Bingham & Stassen, 1994; Warren, 1995). The experimenter then adjusted two knobs on the HMD to adjust the distance between the two displays to match the interpupillary distance of the participant before placing it on their head.

Once the HMD was fastened to the head, an IVE training environment was presented to help the participant adjust to using the device and the head-coupled motion. The environment was a near perfect replica of the real-world environment except that the testing apparatus was not seen. Additionally, the training environment included a few objects not present in the actual, real world room, such as a television and a poster. The participant was asked to take a minute to move their head around in order to view the objects in the environment. Then the participant was asked simple questions to ensure they had properly adjusted to the head motions and the viewing conditions of the IVE (e.g. What is on the television? What time is on the clock?). See figure 6 for screenshots of this training environment. After this training phase one of the experimenters pressed a keyboard key to initiate the testing environment. The testing environment consisted of a photorealistic virtual representation of the real environment surrounding the participant.

Figure 6: The figures left and right show screenshots of the training environment that participants viewed in order to gain familiarization with use of the IVE experiment apparatus. For instance, the HMD viewing condition and head-coupled motion.

Following Napieralski et al. (2011), each participant began with a baseline session of distance estimates with no feedback. They first completed two practice trials followed by 30 recorded distance estimates. For each trial, with the HMD display turned off, the target distance was adjusted. The participant then viewed the target and once they notified the experimenter that they are ready, the HMD video was turned off via a key press. The target was then immediately swung out of the way to prevent any haptic feedback during the participant's reach. The experimenter at the keyboard then pressed a key to record all of the sensor data from the tracking system pertaining to the position of the stylus (hand), target face, and head to a log file. To reduce aural cues about the target position during adjustment on the optical rail for the next trial, white noise was played in the participant's headphones. This sound also cued to the participants to return their hand back on the stylus loading dock in preparation for the next trial. The next trial distance was then adjusted with the HMD display turned off.

Two days after the pretest measure was completed, participants completed 20 distance estimates in the IVE with visual and haptic feedback, leaving the display on and not swinging the target out of the way during reaches. Participants then immediately provided 30 distance estimates in the IVE without feedback, as in the pretest session, to test for aftereffects. In the pretest and posttest phases without feedback, participants were presented with five random permutations of six target distances corresponding to 50, 58, 67, 75, 82 and 90 percent of the participant's maximum reach. For the feedback session, participants were presented with five random permutations of four target distances corresponding to 50, 58, 67, and 75 percent of the participant's maximum reach for a total of 80 trial distances. At the end of any session, some participants were asked to repeat particular trials if, for instance, they made a slow, calculated reach.

RESULTS

The slopes and intercepts of the functions predicting indicated target distance from actual target distance for the individual subjects in each session are presented in Tables 1 and 2. Multiple regression techniques were used to determine if the slopes and intercepts differed between the two viewing sessions and between the two response measures. Multiple regression analyses are preferable to *ANOVA*s 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. 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 you from the actual target distances to the perceived target distances.

Table 1

R^2, Slopes, and Intercepts of Simple Regressions Predicting Reach Estimates from Actual Distance (In Arm Length Units) for Each Participant

	Reach Estimates					
	Pre			**Post**		
Subject	**R^2**	**Slope**	**Intercept**	**R^2**	**Slope**	**Intercept**
1	0.458	1.38	-45.67	0.617	0.96	-7.234
2	0.555	1.11	8.56	0.851	1.17	-14.18
3	0.275	0.59	11.41	0.397	0.524	4.59
4	0.48	0.37	56.26	0.731	0.773	14.56
5	0.497	0.74	7.82	0.752	0.689	20.02
6	0.219	0.37	39.09	0.669	0.418	32.3
7	0.151	0.33	64.3	0.728	0.79	14.47
8	0.739	1.26	-17.45	0.809	1.1	-26.54
9	0.401	0.96	-12.24	0.66	0.98	-19.91
10	0.37	0.96	-13.11	0.703	1.19	-27.31
11	0.374	0.97	-6.14	0.709	0.83	1.93
12	0.38	0.56	41.57	0.658	0.72	21.09
13	0.336	1.07	-13.25	0.468	0.89	-7.73
14	0.335	0.32	71.07	0.361	0.67	24.42
15	0.493	0.79	22.41	0.677	0.89	3.86
Overall	**.404**	**0.79**	**14.31**	**.653**	**0.84**	**2.29**

Table 2

R^2, Slopes, and Intercepts of Simple Regressions Predicting Verbal Estimates from Actual Distance (In Arm Length Units) for Each Participant

	Verbal Estimates					
	Pre			Post		
Subject	**R^2**	**Slope**	**Intercept**	**R^2**	**Slope**	**Intercept**
1	0.604	1.73	-75.68	0.788	1.81	-87.12
2	0.703	1.39	-41.16	0.926	1.39	-55.53
3	0.568	1.04	-39.81	0.637	0.36	-15.21
4	0.495	0.67	-2.73	0.792	0.52	-6.39
5	0.44	0.56	12.13	0.767	1.05	-10.79
6	0.749	1.18	-21.51	0.894	1.01	-23.89
7	0.466	1.55	-63.89	0.776	1.65	-61.07
8	0.758	1.97	-83.39	0.826	1.68	-66.6
9	0.436	1.02	-41.33	0.815	1.22	-56.38
10	0.334	1.24	-34.26	0.75	0.82	-26.61
11	0.617	0.99	-11.8	0.724	1.03	-9.48
12	0.688	1.16	-18.57	0.799	1.2	-20.67
13	0.343	1.04	-19.16	0.641	0.92	-12.63
14	0.504	0.69	8.96	0.781	0.83	-16.06
15	0.65	1.14	-32.23	0.714	1.2	-40.24
Overall	**.557**	**1.16**	**-30.96**	**.775**	**1.11**	**-33.91**

Comparing Pretest & Posttest

Reaches. Overall, the slopes for the reaches were .79 and .84 for the Pretest and Posttest sessions, respectively. The intercepts were 14.31% and 2.29% (in arm length units), respectively. Figure 7 depicts the relation between actual target distance and the distances reported via reaches for the two sessions. Each point in Figure 7 represents average judgments 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 sessions (coded orthogonally) to predict the reach distances. The multiple regression was first performed with an actual target distance X session interaction term, yielding an $r^2 = .336$ (n = 896), with a partial F of 380.25 for actual target distance ($p < .0001$). The partial F for session was 3.06 ($p = .081$) and the interaction term .13 ($p = .72$), with the partial F for viewing session increasing to 52.27 ($p < .0001$) after the removal of the interaction term.

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 variation due to the other terms (viewing session and the interaction) having 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 viewing session assesses the degree to which the intercepts for the two sessions differ from each other and thus test for a main effect of viewing 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, as well as a main effect for viewing session (reaches made in the pretest vs. reaches made in the posttest), but did not reveal an interaction. Therefore, the slopes of the functions predicting reached distance from actual distance did not differ for the two viewing sessions, while their intercepts did. Overall, the reaches were 4.25 cm farther in the pretest than in the posttest A simple regression predicting the reaches from actual target distance resulted in an $r^2 = 0.297$ (n = 896), indicating that the difference between viewing in the pretest or posttest accounted for only 3.9% of the variances in the reaches. A Repeated Measures *ANOVA* confirmed that average reach estimates for each presented distance were different between pretest and posttest $F(1) = 14.23$, $p < .05$ (Table 4). See Figure 8 for individual participant regression plots for reaches.

When this analysis was conducted for individual participants, the partial *F* for session was $p < .05$ for 10 out of the 15 participants after the removal of the interaction term (see Table 3). A paired t-test shows that the increase in R^2 values from a mean of 0.404 ($SD = 0.143$) in the pretest to a mean of 0.653 ($SD = 0.141$) for the posttest was significant for the reaches, $t(14) = -6.692$, $p < .0001$.

Table 3

Values of R^2, n, and Partial F for Multiple Regression Analyses Predicting Reach Distance Estimates From Actual Target Distance (In Arm Length Units), Session (Pretest Versus Posttest), and the Target Distance × Session Interaction

			Partial *F*		
Subject	**R Square**	**n**	**Target Distance**	**Session**	**Interaction**
1	0.512	60	56.03**	2.94*	1.82
2	0.772	60	125.44**	2.55*	0.1
3	0.463	60	26.69**	0.18*	0.09
4	0.79	60	97.81**	24.7**	12.43**
5	0.632	60	81.5**	1.22*	0.09
6	0.395	60	30.18**	0.43	0.11
7	0.681	60	43.31**	16.02**	7.38**
8	0.816	60	184.42**	0.55*	0.83
9	0.497	60	54.88**	0.16	0.01
10	0.54	57	58.92**	0.48	0.65
11	0.467	60	48.72**	0.2	0.27
12	0.61	60	58.09**	2.86*	0.89
13	0.647	59	34.08**	0.05	0.27
14	0.644	60	27.52**	12.48**	3.58
15	0.639	60	77.81**	1.96*	0.25
Overall	**0.607**	**896**	**67.03**	**4.45**	**1.92**

*$p < .05$ without Interaction term included in the regression analysis
**$p < .05$ with Interaction term included in the regression analysis

Table 4

Average Reach Estimates for Each Distance Presented in Pretest and Posttest

Distance Presented	Pretest	Posttest
50%	53.21	41.07
58%	60.71	52.01
67%	67.92	58.5
75%	73.3	64.69
82%	79.36	71.26
90%	83.78	76.73
Overall	**69.71**	**60.71**

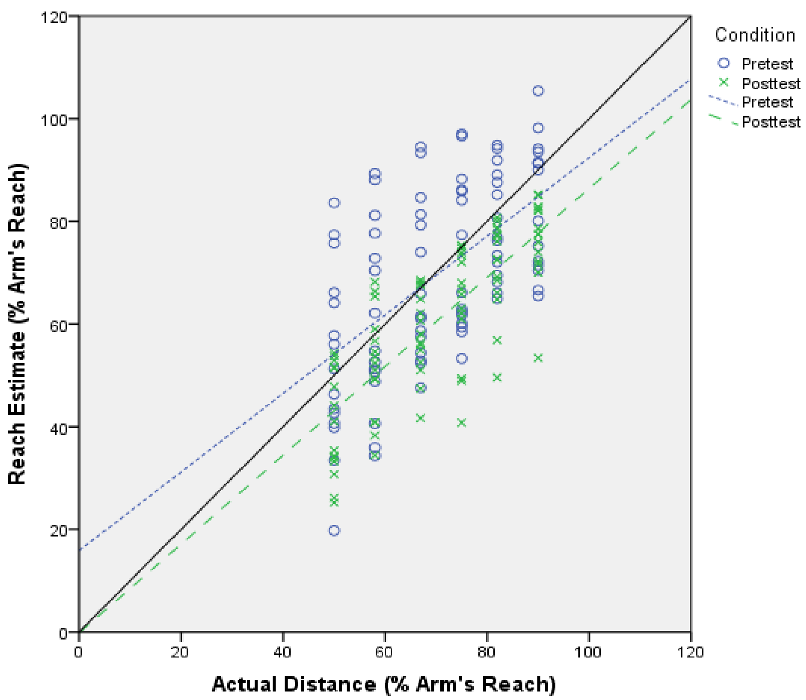
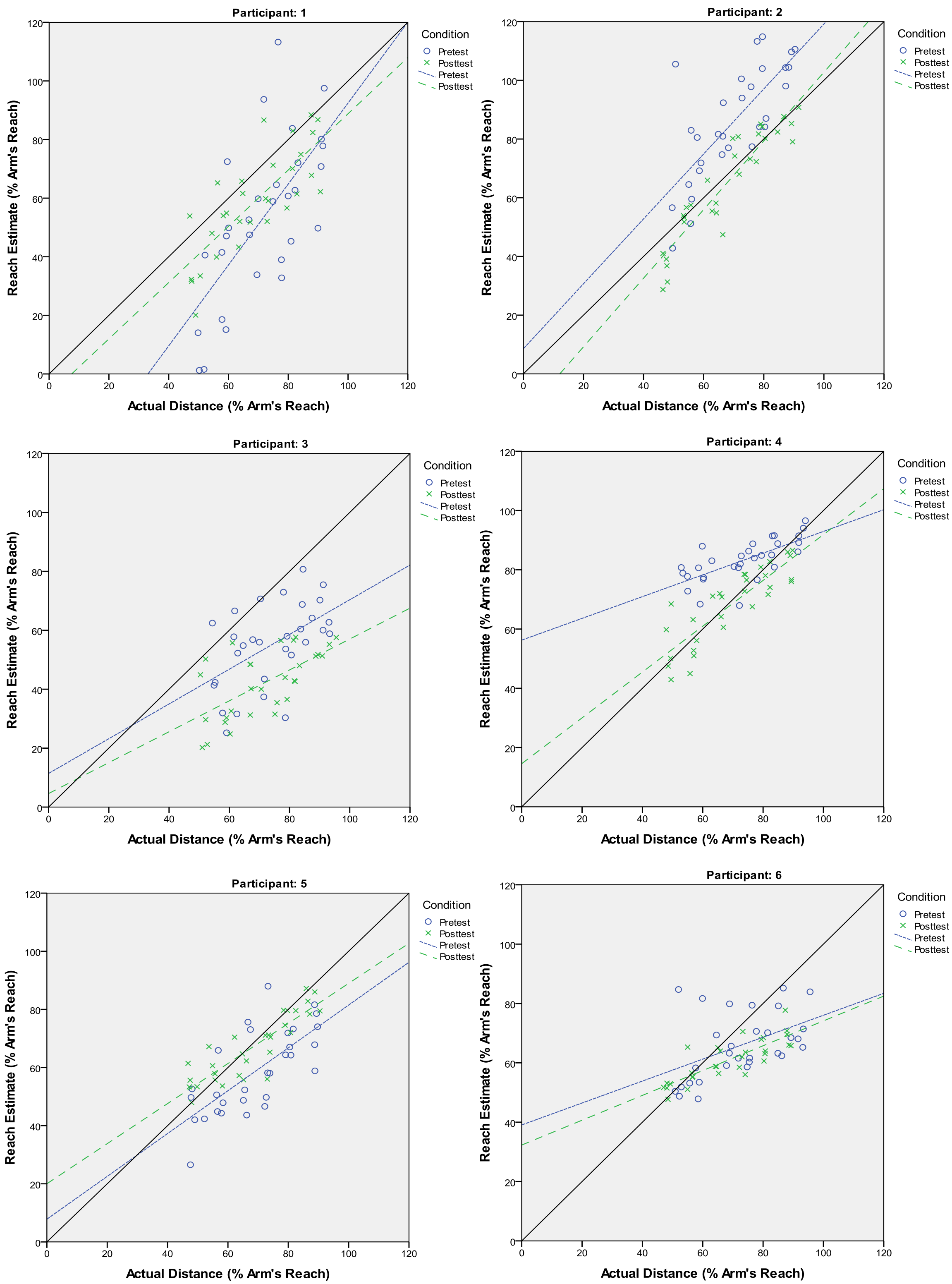
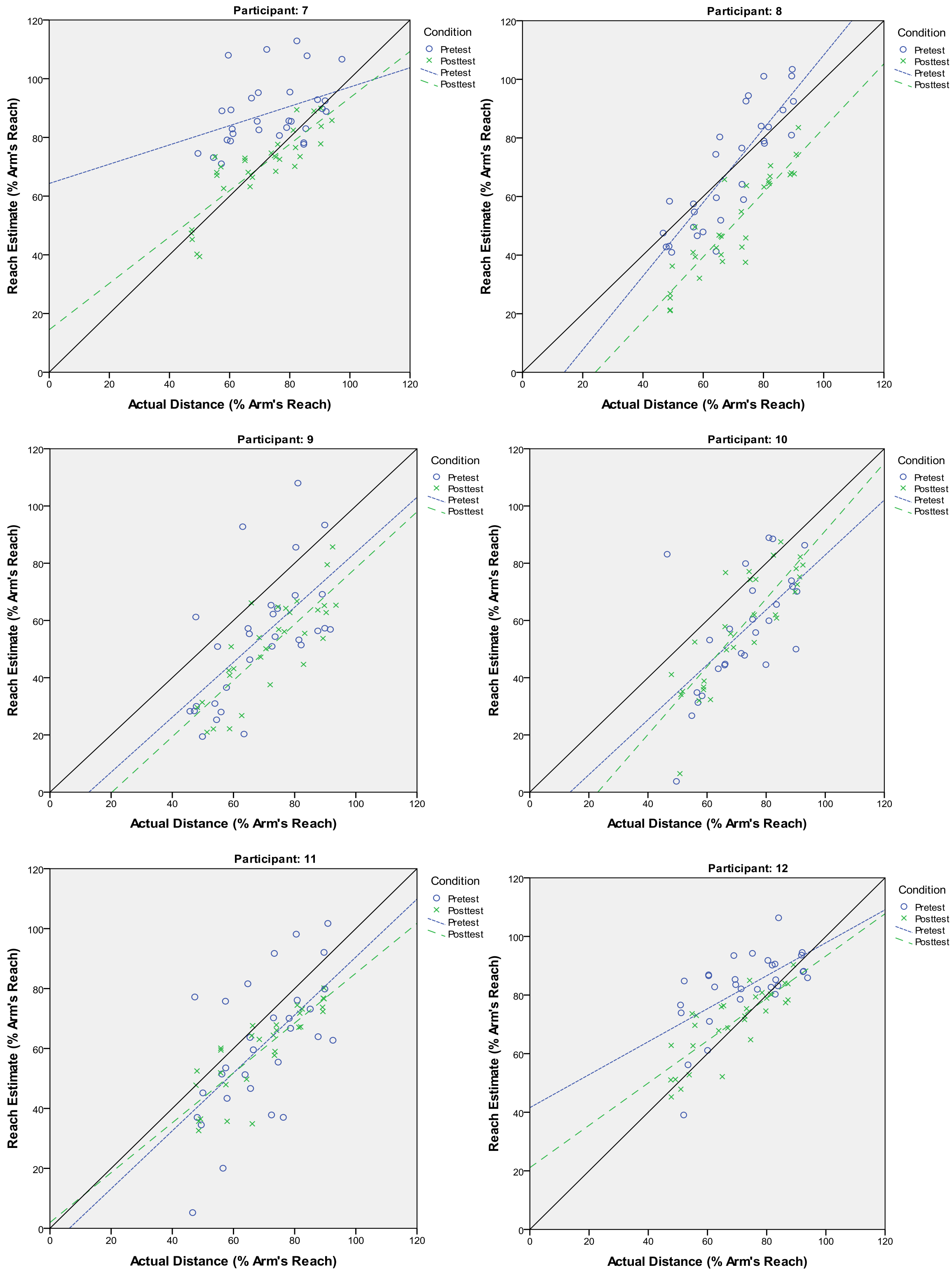


Figure 7: Physical reaches as a function of the actual target distances for Pretest and Posttest viewing.


Participant: 1
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest
Participant: 2
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest
Participant: 3
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest
Participant: 4
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest
Participant: 5
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest
Participant: 6
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest


Participant: 7
Participant: 8
Participant: 9
Participant: 10
Participant: 11
Participant: 12
Reach Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
Condition
Pretest
Posttest
Pretest
Posttest

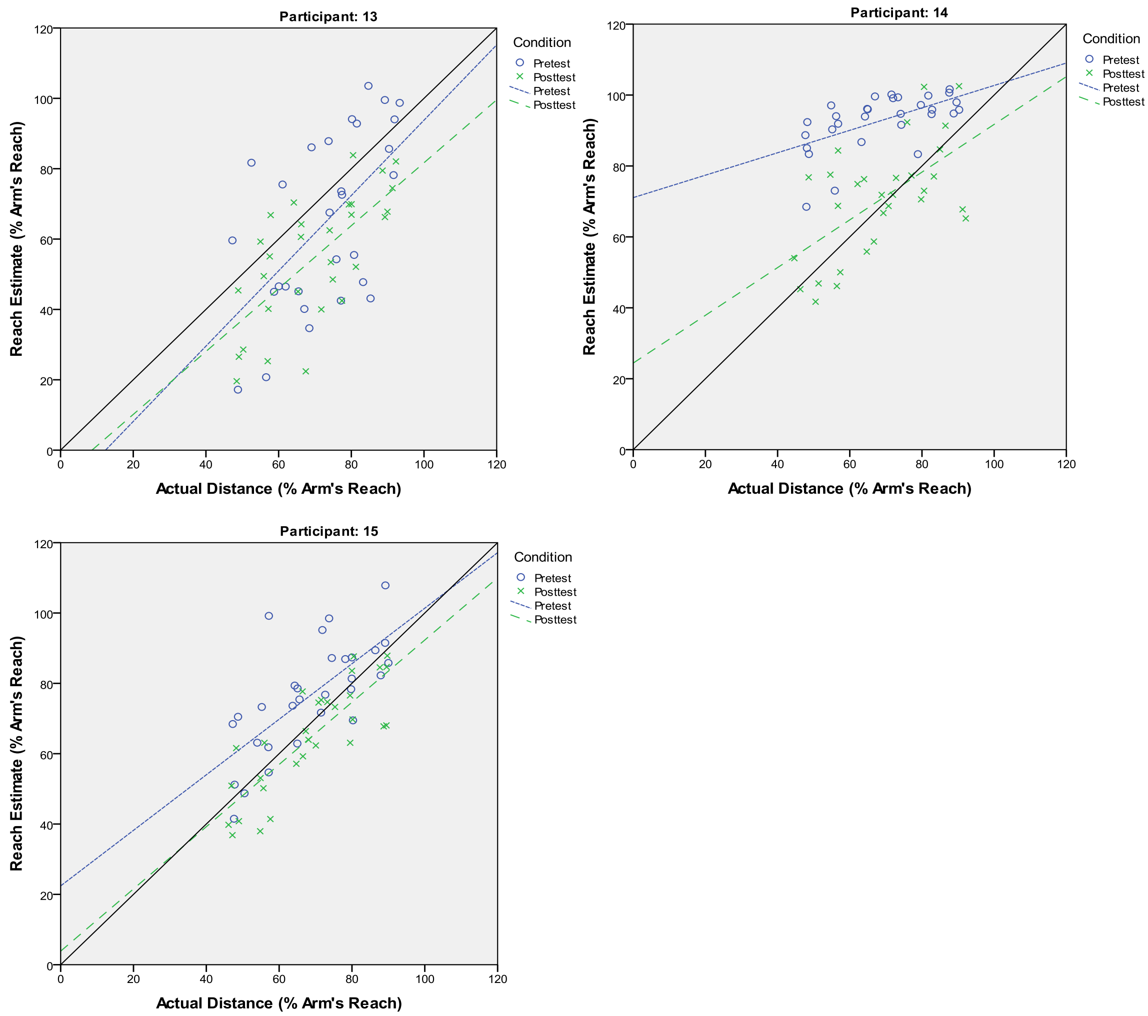


Figure 8: Physical reaches as a function of the actual target distances for Pretest and Posttest viewing for individual participants.

Verbal Reports. The slopes of the functions predicting indicated target distance from actual target distance for the verbal judgments were 1.16 and 1.11 for the Pre and Post viewing sessions, respectively (see figure 9). The intercepts were -30.96 and -33.91 (in arm length units), respectively. A multiple regression analysis predicting the verbal judgments from actual target distance and session was first performed with an actual target distance X session interaction term, yielding an r^2 = .438 (n = 896), with partial Fs of 648.06 for actual target distance (*p*< .0001), 0.006 for session (*p* = .939), and 0.93 for the interaction term (*p* = .336), with the partial *F* for viewing session increasing to 28.05 (*p* < .0001) after the removal of the interaction term. This multiple regression confirmed that like the reaches, the verbal judgments changed in intercept but not in slope as a function of session. Overall, as the actual distances increased the verbal reports increased at the same rate in the pretest and the posttest. A simple regression predicting the verbal reports from actual target distance resulted in an r^2 = .420 (n = 896), indicating that the difference between viewing in pretest or posttest accounted for 1.8% of the variance in the verbal reports. In sum, the verbal reports were very similar in the pretest compared to the posttest. When this analysis was conducted for individual participants, the partial *F* for session was $p < .05$ for 8 out of the 15 participants after the removal of the interaction term (see Table 5). A paired t-test shows that the increase in R^2 values from a mean of 0.557 (*SD* = 0.138) in the pretest to a mean of 0.775 (*SD* = 0.078) in the posttest was significant for the verbal estimates, *t* (14) = -7.07, *p* < .0001. See Figure 10 for individual participant regression plots for verbal reports.

Table 5

Values of R^2, n, and Partial F for Multiple Regression Analyses Predicting Verbal Distance Estimates From Actual Target Distance (In Arm Length Units), Session (Pretest Versus Posttest), and the Target Distance × Session Interaction

			Partial *F*		
Subject	**R Square**	**n**	**Target Distance**	**Session**	**Interaction**
1	0.703	60	125.84**	0.26	0.06
2	0.84	60	238.05**	1.29*	0.0003
3	0.792	60	65.53**	3.69*	15.14**
4	0.746	60	78.55**	0.14*	1.21
5	0.702	60	99.26**	4.13**	9.46**
6	0.85	60	227.35**	0.05*	1.37
7	0.61	60	85.23**	0.01*	0.09
8	0.785	60	203.55**	0.86	1.3
9	0.594	60	80.91**	0.7	0.65
10	0.55	57	37.63**	0.1*	1.58
11	0.675	60	112.36**	0.03	0.04
12	0.744	60	158.48**	0.02	0.03
13	0.448	59	42.95**	0.09	0.14
14	0.729	60	97.26**	5.36**	0.79
15	0.686	60	120.08**	0.29	0.06
Overall	**0.697**	**896**	**118.2**	**1.13**	**2.13**

*$p < .05$ without Interaction term included in the regression analysis
**$p < .05$ with Interaction term included in the regression analysis

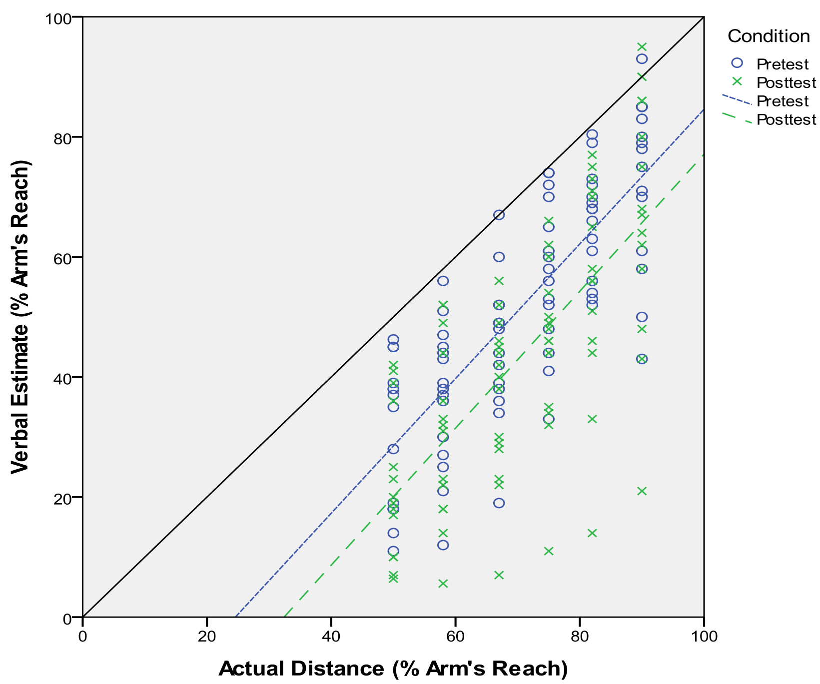
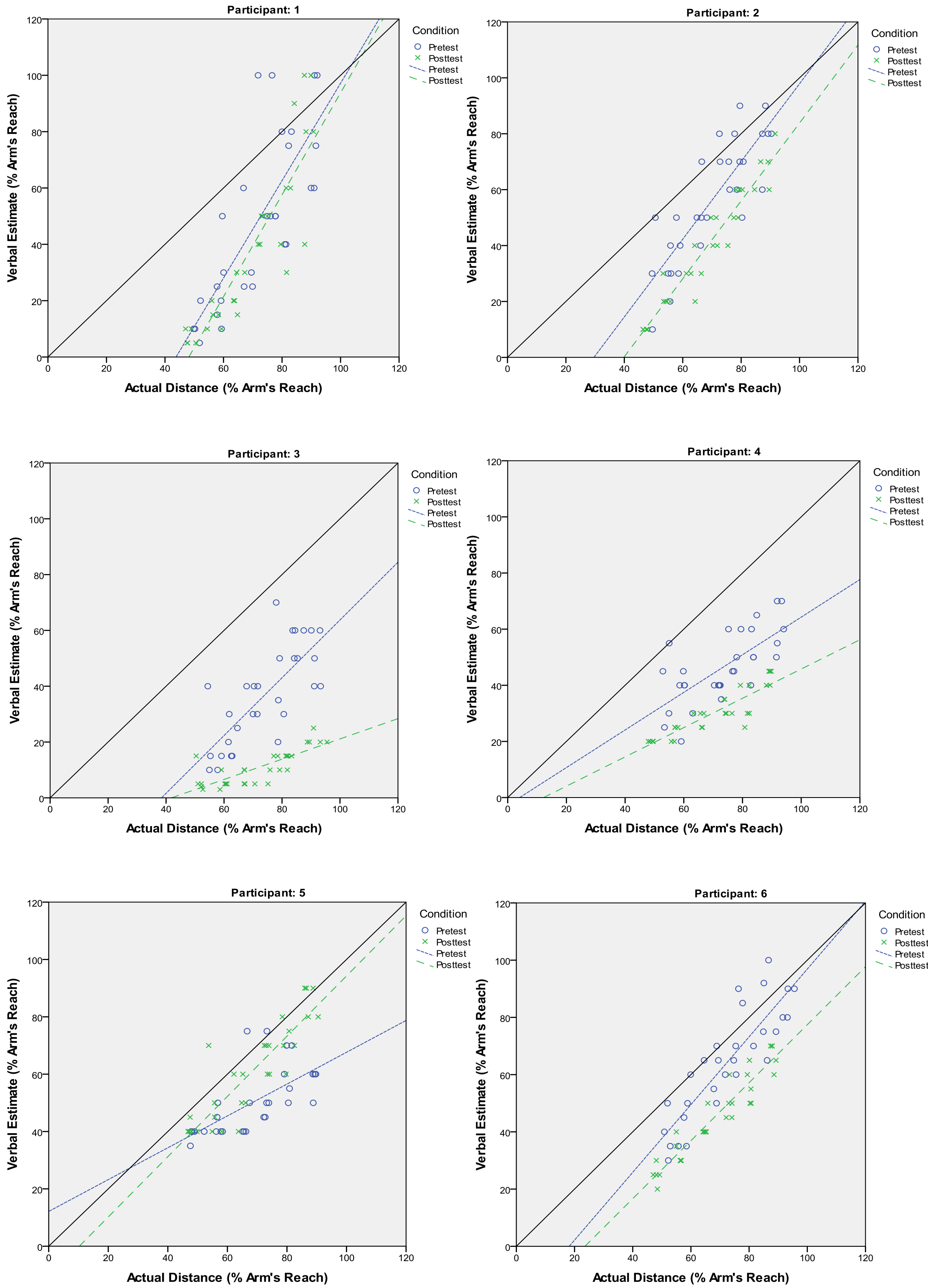
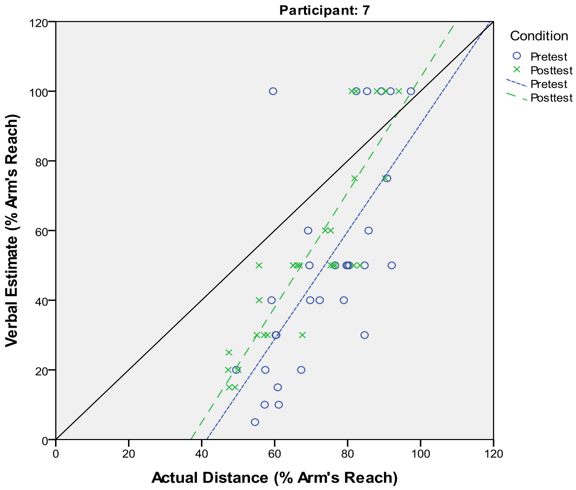
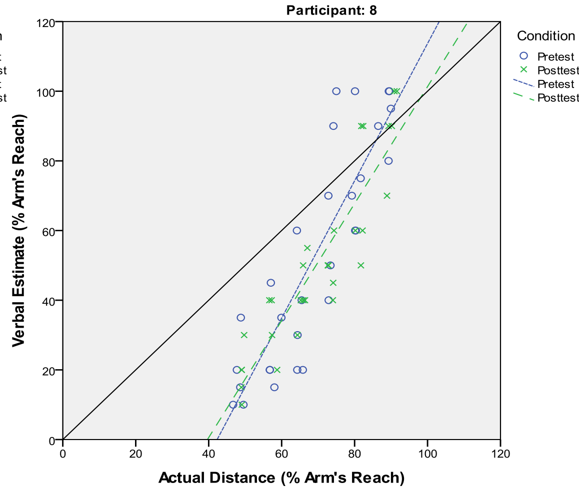
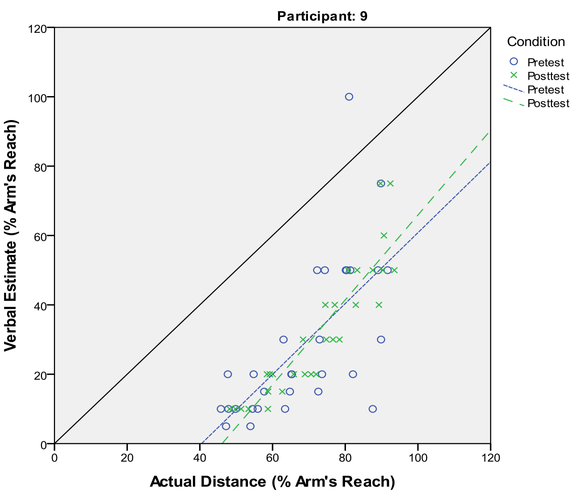


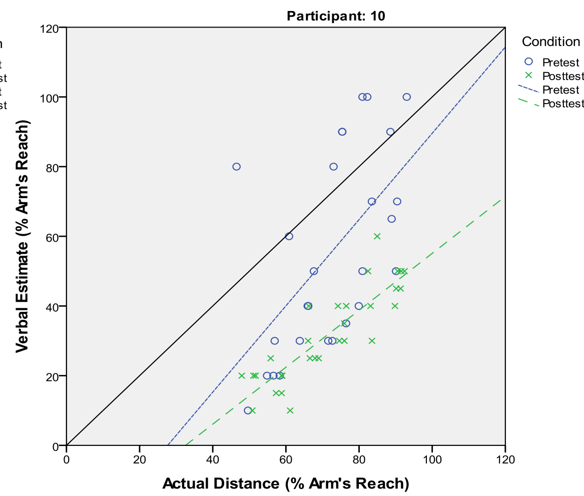
Figure 9: Verbal estimates as a function of the actual target distances for Pretest and Posttest viewing.

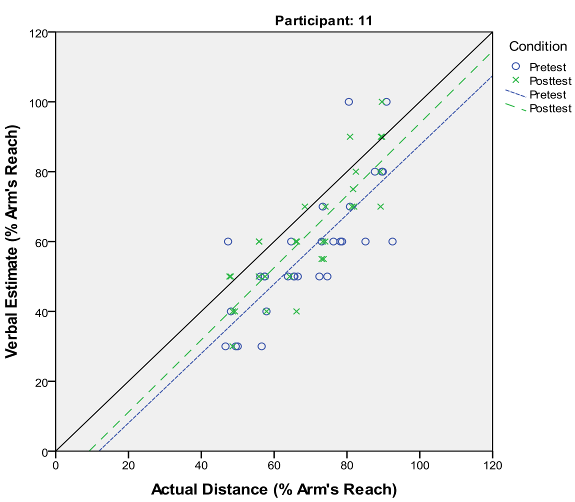

Participant: 1
Participant: 2
Participant: 3
Participant: 4
Participant: 5
Participant: 6
Condition
Pretest
Posttest
Pretest
Posttest
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120

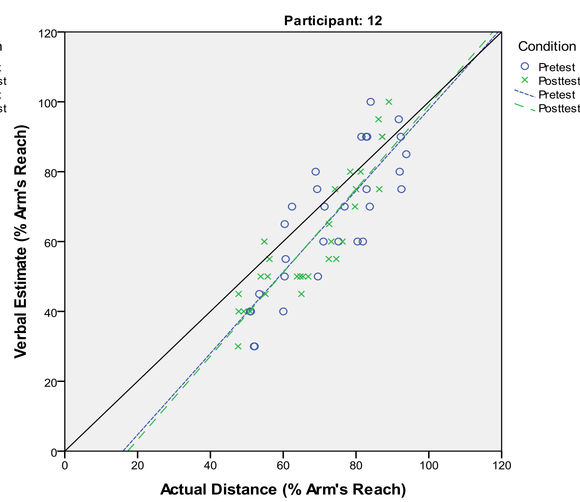

Participant: 7
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120
Condition
Pretest
Posttest
Pretest
Posttest


Participant: 8
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120
Condition
Pretest
Posttest
Pretest
Posttest


Participant: 9
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120
Condition
Pretest
Posttest
Pretest
Posttest


Participant: 10
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120
Condition
Pretest
Posttest
Pretest
Posttest


Participant: 11
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120
Condition
Pretest
Posttest
Pretest
Posttest


Participant: 12
Verbal Estimate (% Arm's Reach)
Actual Distance (% Arm's Reach)
0
20
40
60
80
100
120
Condition
Pretest
Posttest
Pretest
Posttest

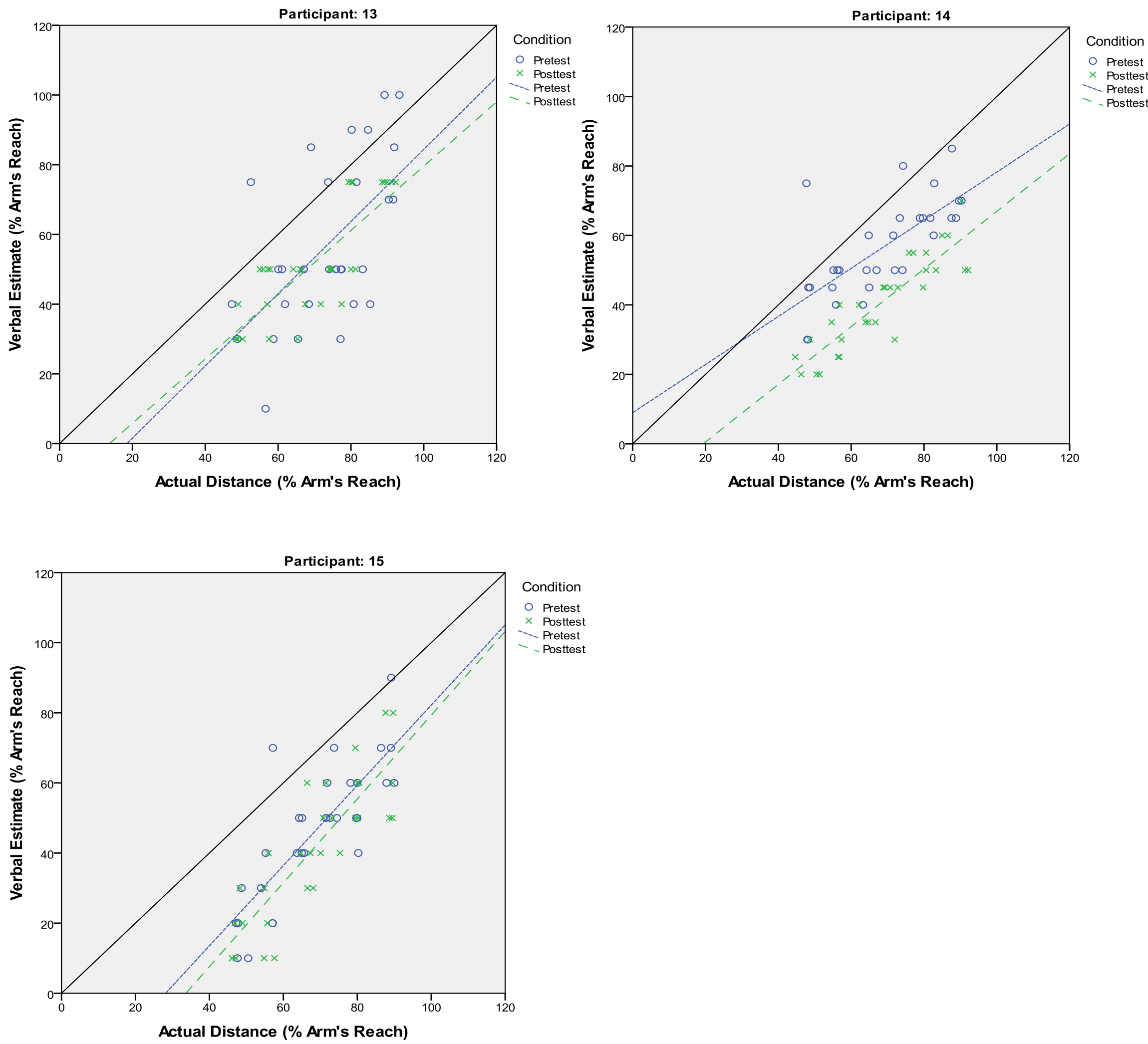


Figure 10: Verbal estimates as a function of the actual target distances for Pretest and Posttest viewing for individual participants.

Accuracy Measures.

Absolute Error. As a second measure of distance estimate accuracy, absolute error was also examined for each participant by computing the absolute value of difference scores (actual distance – estimated distance). Absolute error (Table 6) for reaches decreased from 16.16% of arm length in the pretest to 12.15% in the posttest, showing an improvement after the calibration phase of 4.01% of the arm length. In sum, the reaches improved after the feedback phase, $t(14) = 2.212$, $p = 044$. Absolute error for verbal estimates actually increased from 22.85% of arm length in the pretest to 27.22% in the posttest, showing verbal estimates worsened after the calibration phase by 4.37% of the arm length. However, this change in absolute error was not significant, $t(14) = -1.682$, $p = .115$. This reduction of verbal estimate accuracy is also reflected in the intercept change from -30.96 to -33.91 after the calibration phase.

Table 6

Absolute Error (Absolute Value of Actual Distance – Estimated Distance) for Each Participant in Percentage of Arm Length

Subject	**Pretest Reaches**	**Posttest Reaches**	**Pretest Verbal Estimates**	**Posttest Verbal Estimates**
1	23.65	12.24	28.05	33.2
2	16.73	6.02	15.56	29.01
3	19.91	29.51	37.18	60.86
4	10.87	5.84	26.97	39.58
5	13.38	5.47	19.31	9.13
6	11.61	9.37	11.02	22.98
7	16.22	6.12	30.06	20.57
8	8.84	19.64	22.47	21.37
9	20.19	21.21	41.12	40.28
10	20.27	15.07	25.56	39.69
11	16.09	10.63	14.97	9.47
12	11.86	6.22	11.33	9.49
13	18.36	16.63	21.52	18.06
14	24.16	10.49	14.32	27.73
15	10.33	7.74	23.28	26.84
Overall	**16.16**	**12.15**	**22.85**	**27.22**

***Total Variability*.** However, comparing total variability among reaches rather than absolute error reveals somewhat different results. According to Schmidt (1988), absolute error (which measures overall accuracy without regard to direction) is the most commonly used accuracy measure, although total variability is often considered to be the best measure of overall accuracy in responses because it combines both constant error (a measure of signed average error) and variable error (a measure of inconsistency in responses by comparing each response to a respective participant's average reach response to a specific distance). Total variability can be computed by setting the square of constant error plus the square of variable error equal to the square of total variability, where zero represents perfect performance. However, a Repeated Measures *ANOVA* revealed that although the overall total variability was less in the posttest (18.53) than the pretest (21.5), this difference was not significant $F(1) = 4.52$, $p = .052$ (Table 7).

Table 7

Total Variability (√(∑(Reach Estimate – Actual Distance)^2 / number of trials)) for Each Participant in Percentage of Arm Length

Subject	Pretest Total Variability	Posttest Total Variability
1	32.65	19.83
2	24.73	18.17
3	23.63	31.58
4	11.91	12.57
5	17.58	11.05
6	12.80	10.31
7	18.57	13.55
8	20.05	25.87
9	26.54	26.92
10	26.00	24.22
11	23.92	16.94
12	15.86	12.13
13	25.63	23.38
14	25.35	15.77
15	17.36	15.61
Overall	**21.5**	**18.53**

Comparing Reaches and Verbal Reports

Pretest. Next the verbal reports to the reaches made within each of the two sessions were compared (see Figure 11). In the pretest the slopes of the functions predicting indicated target distance from actual target distance were 1.16 and .79 for the verbal reports and the reaches, respectively. The intercepts were -30.96 and 14.31 (in arm length units), respectively. A multiple regression predicting the judgments from actual target distance and response mode (verbal or reach) was first performed with an actual target distance X session interaction term, yielding an r^2 = .428 (n = 892), with partial *F*s of 429.11 for actual target distance ($p < .0001$), 46.27 for session ($p < .0001$), and 16.74 for the interaction term ($p < .0001$). See Table 8 for partial *F*s for individual participants. This multiple regression confirmed that in the pretest the verbal judgments were very different from the reaches that were made within the same trial and which were thus directed at the same target distance. Overall, as the actual distances increased the verbal reports increased at a higher rate than the reaches and this was accompanied by a large intercept difference. A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.276$ (n = 892), indicating that the difference between the reaches and the verbal reports accounted for 15.2% of the variance in the responses. In sum, in the pretest the verbal reports and the reaches were different.

Table 8

Values of R^2, n, and Partial F for Multiple Regression Analyses Predicting Indicated Target Distance from Actual Target Distance (In Arm Length Units), Response Measure (Verbal Versus Reach), and the Target Distance × Response Measure Interaction during Pretest

			Partial *F*		
Subject	**R Square**	**n**	**Target Distance**	**Response Type**	**Interaction**
1	.514	60	64.32**	1.13	0.8
2	.767	60	96.96**	7.62**	1.26
3	.589	60	42.65**	7.49**	3.21
4	.884	60	49.82**	28.98**	4.26**
5	.524	60	49.63**	0.11*	0.98
6	.617	60	70.56**	19.67**	19.4**
7	.671	60	5.42**	24.61**	12.39**
8	.775	60	161.95**	13.68**	7.92**
9	.559	60	40.32**	1.77*	0.04
10	.347	54	26.08**	0.45	0.42
11	.473	60	49.38**	0.08	0.01
12	.677	60	73.7**	16.22**	8.93**
13	.359	58	27.69**	0.04	0.008
14	.853	60	42.58**	32.88**	5.93**
15	.766	60	77.7**	12.76**	2.61
Overall	**.625**	**892**	**58.58**	**11.17**	**4.23**

*$p < .05$ without Interaction term included in the regression analysis
**$p < .05$ with Interaction term included in the regression analysis

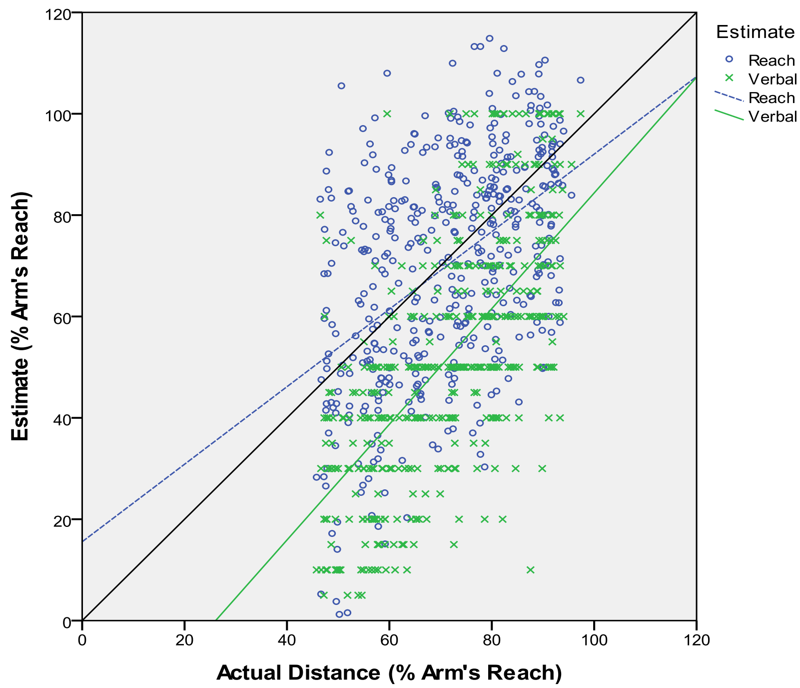


Figure 11: Verbal and reach estimates as a function of the actual target distances for Pretest viewing.

Posttest. Verbal reports were also compared to the simultaneous reaches made within the posttest (see Figure 12). The slopes of the functions predicting indicated target distance from actual target distance were 1.11 and 0.84 for the verbal reports and the reaches, respectively. The intercepts were -33.91 and 2.29 (in arm length units), respectively. A multiple regression predicting the judgments from actual target distance and response mode (verbal or reach) was performed with an actual target distance X session interaction term, yielding an $r^2 = .508$ (n = 900), with partial *F*s of 626.60 for actual target distance ($p < .0001$), 46.62 for session ($p < .0001$), and 12.79 for the interaction term ($p < .0001$). See Table 9 for partial *F*s for individual participants. This multiple regression confirmed that in posttest the verbal judgments and reaches were different from each other despite being performed within the same trial. Overall, as the actual distances increased, the verbal reports increased at a higher rate than the reaches and this was accompanied by a large intercept difference. A simple regression predicting indicated target distance from actual target distance resulted in an $r^2 = 0.344$ (n = 900), indicating that the difference between the reaches and the verbal reports accounted for 16.4% of the variance in the responses. In sum, the differences between the response modes (verbal and reach) within each session were greater than the differences between sessions (pretest and posttest) within each response mode.

Table 9

Values of R^2, n, and Partial F for Multiple Regression Analyses Predicting Indicated Target Distance from Actual Target Distance (In Arm Length Units), Response Measure (Verbal Versus Reach), and the Target Distance × Response Measure Interaction during Posttest

			Partial *F*		
Subject	**R Square**	**N**	**Target Distance**	**Response Type**	**Interaction**
1	.786	60	147.62**	24.79**	13.86**
2	.927	60	465.39**	25.57**	3.67
3	.863	60	44.78**	4.19**	1.48
4	.942	60	161.29**	8.42**	6.08**
5	.773	60	172.19**	11.16**	7.41**
6	.898	60	275.19**	30.97**	47.55**
7	.793	60	163.64**	30.81**	20.33**
8	.821	60	245.8**	10.06**	10.74**
9	.804	60	163.1**	8.24**	1.94
10	.822	60	137.69**	0.003*	4.67**
11	.720	60	140.9**	1.05	1.64
12	.777	60	162.92**	16.02**	9.96**
13	.547	60	66.68**	0.1	0.02
14	.774	60	63.46**	9.4**	0.69
15	.789	60	128.05**	11.76**	2.86
Overall	**.802**	**900**	**169.25**	**12.84**	**8.86**

*$p < .05$ without Interaction term included in the regression analysis
**$p < .05$ with Interaction term included in the regression analysis

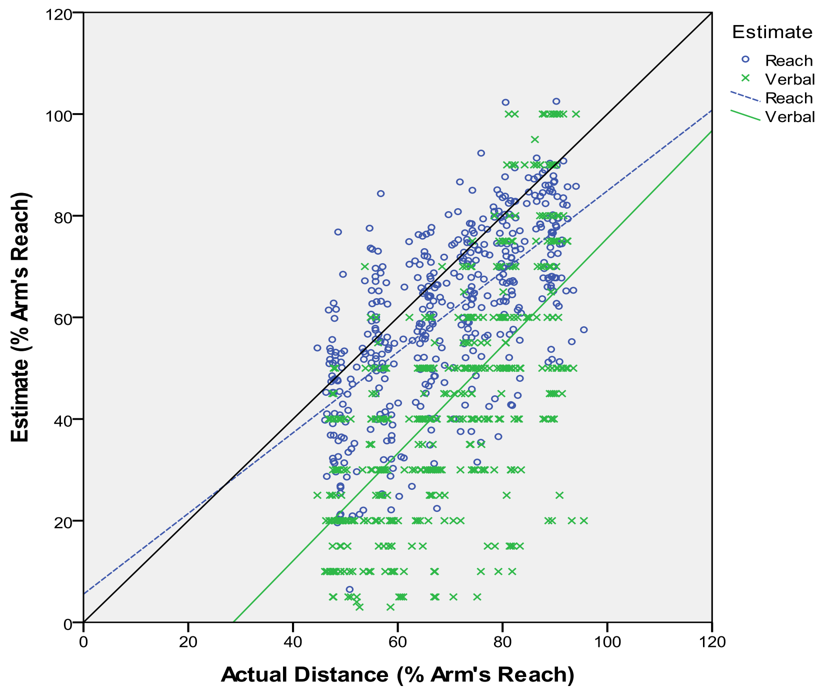


Figure 12: Verbal and reach estimates as a function of the actual target distances for Posttest viewing.

Comparing Posttest and Real World Viewing

Reaches. Because the methods and apparatus used to collect distance estimates in Napieralski et al. (2011) were identical to those used in this experiment, distance estimates in the posttest were compared to the real world viewing condition of the previous study. Because distance estimates made in the real world condition were not perfect, resulting in a regression with an intercept of -29.55 and slope of 1.03 for verbal reports and intercept of 1.74 and slope of .77 for reaches, it should not be assumed that distance estimates made in an IVE with current technologies, would be any more accurate than viewing in the RW. If distance estimates made in an IVE after visual and haptic feedback recalibrate to that of RW viewing, estimates would be very similar between the two viewing conditions. The slopes of the functions predicting indicated target distance from actual target distance for the reach estimates were 0.77 and 0.84 for the RW and Posttest viewing conditions, respectively (Figure 13). The intercepts were 1.74 and 2.29 (in arm length units), respectively. A multiple regression predicting the reach estimates from actual target distance and condition was first performed with an actual target distance X session interaction term, yielding an $r^2 = .412$ (n = 779), with partial *F*s of 496.22 for actual target distance ($p < .0001$), 0.29 for viewing condition ($p = .59$), and 0.003 for the interaction term ($p = .956$), with the partial *F* for viewing condition increasing to 5.2 ($p = .016$) after the removal of the interaction term. This multiple regression confirmed that the reaches differed in intercept but not in slope as a function of changes in the viewing conditions. Overall, as the actual distances increased the reaches increased at the same rate in the RW and the posttest. A simple regression predicting the verbal reports from actual target distance resulted in an $r^2 = .407$ (n = 779), indicating that the difference between viewing in RW without feedback and in the posttest after receiving feedback accounted for only 0.5% of the variance in the reaches. In sum, the reaches were very similar in the RW compared to the posttest.

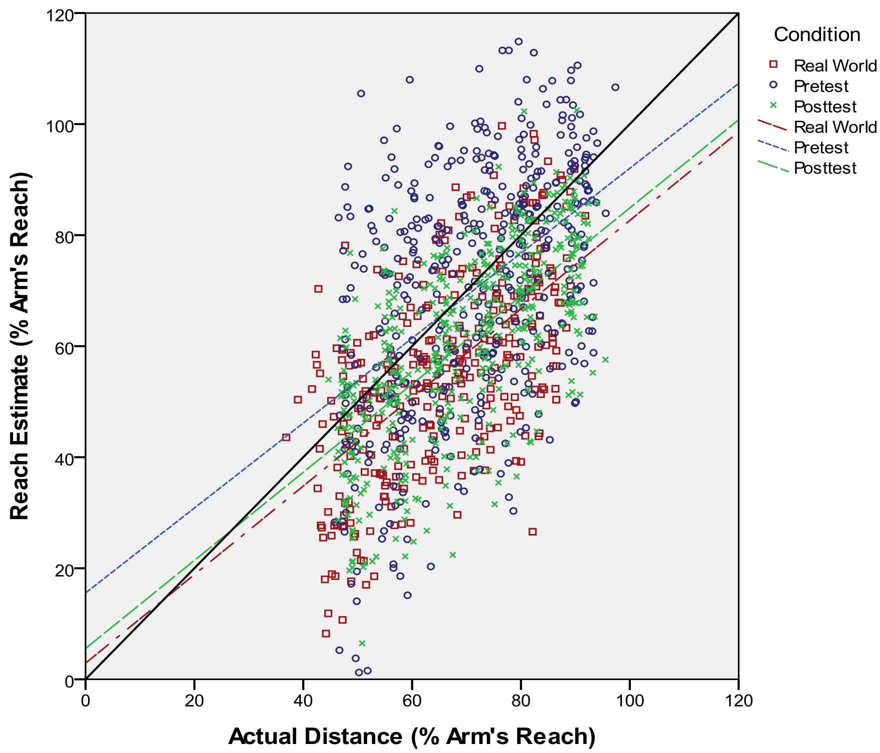


Figure 13: Physical reaches as a function of the actual target distances for Pretest IVE, Posttest IVE, and Real World viewing.

In sum, in both the pretest and the posttest the verbal reports were different from the reaches. Also, the differences between the verbal reports and the reaches made within each session were greater than the differences between the reaches made in the pretest and posttest. The verbal reports, however, were affected by the session to a greater extent than the reaches. Thus the effect of response mode was much greater than the effect of session, with the reaches remaining more consistent between the sessions than the verbal reports.

DISCUSSION

We investigated the effects of visual and haptic feedback on egocentric distance perception in an IVE using pretest, calibration, and posttest viewing sessions. Within each session and for each trial, both manual reaches and verbal reports were given by participants to indicate perceived distance. Our findings show that participants' reach estimates improved after the calibration session, becoming more similar to distance estimates made by participants in a real world viewing condition. For both reaches and verbal reports, estimates were farther in the pretest than the posttest. Consistent with previous research (Napieralski et al., 2011; Pagano & Bingham, 1998; Pagano et al. 2001; Pagano & Isenhower, 2008), we also found that verbal reports and reach estimates of egocentric differences differed. Specifically, verbal reaches were underestimated more in both pretest and posttest for nearer distances than farther distances. In general the reaches tended to be more accurate and more consistent. In sum, compared to the pretest, viewing in the posttest had a large effect on manual reaches to egocentric distances in personal space and the effect of response mode (verbal vs. reach) was much greater than the effect of session.

Similar to previous research (Bingham & Pagano, 1998; Bingham & Romack, 1999; Richardson & Waller, 2005; Richardson & Waller, 2007; Waller & Richardson, 2008), our study showed that distance estimates improved after a period of interaction with the environment, with reaches improving from pretest to posttest (as revealed by the change in intercept in Table 1 and change in difference scores in Table 5). However, unlike previous research that demonstrates underestimations in VR compared to RW

(Witmer and Kline 1998; Loomis and Knapp 2003; Grechkin et al., 2010), our participants overestimated more in the RW, with participants reaching farther in the pretest than the posttest and farther in the posttest than RW. For example, Richardson and Waller (2007) demonstrated that a brief interaction period in an IVE improved egocentric distance estimates within that IVE from approximately 56% of the intended distance to 94% using blindfolded and triangulated walking. The only noticeable differences between our studies which could be responsible for these different findings include the methods used of making distance estimates and the distances presented to participants. In Richardson and Waller's study (2007), the closest distance presented to these participants was at 75 cm, whereas a participant in our study with an arm length of 35 cm (average arm length across the 15 participants), would not see the target at a distance farther than 31.5 cm. FOV differed by 2° horizontally and number of interaction trials were only two fewer compared to the current study.

Regarding verbal reports overall, as the actual distances increased estimates increased at a higher rate than the reaches. Verbal reports were very similar between the pretest and posttest, but were less accurate, although they were given concurrent to reaches. These findings are similar to previous research (Pagano & Bingham, 1998; Pagano et al., 2001; Pagano & Isenhower, 2008) showing that verbal estimates appear to be less accurate and more variable than reaches. Verbal estimates are less stable than reaching or pointing, with errors changing dramatically between experimental sessions (such as pretest and posttest) and between participants within a single condition. For example, in a distance estimate study that also used concurrent verbal reports and physical reaches, reach estimates remained stable, while the slopes of the functions predicting verbal judgments from actual target distances increased when a 6 second delay occurred between the target presentation and the responses, and it increased again with a delay of 12 seconds (Pagano, Grutzmacher, & Jenkins, 2001). Because verbal reports can be at least twice as variable as reaching or pointing, they are also considered to be less reliable (Foley, 1977; Pagano & Bingham, 1998; Pagano & Isenhower, 2008; Pagano et al., 2001). Similar to our study, Pagano and Bingham (1998) found that although reaches became more accurate after feedback, verbal judgments did not become more accurate and remained twice as variable as the reaches. Pagano and Isenhower (2008) investigated this further when they manipulated participants' expectations of the possible target distances. Participants' verbal estimates were significantly affected and made based on the expected range, while reaches remained accurate and unaffected. While reaches appear to represent absolute metric distances, verbal estimates seem to only represent relative distances and are easily influenced by the expected range of distances. Therefore, many researchers find verbal responses inappropriate for examining absolute distance estimates.

There is debate whether a single perceived depth is produced, which generates separate output functions for different response modes (Brunswick, 1956; Foley, 1977, 1985; Gogel 1993; Philbeck & Loomis 1997), or whether neurologically distinct visual systems underlie different responses such as "cognitive" verbal estimates (perception-for-cognition) versus motor reach estimates (perception-for-action) (Bridgeman, Kirch, & Sperling, 1981; Milner & Goodale, 1995, 2008). Although verbal reports in our experiment were made in arm length units, with 100 corresponding to maximum reach, they still remained distinct from the reaches, supporting the theory of two distinct visual systems. Perception-for-cognition may be a different perceptual process than perception-for-action, with observers attuning to different information depending on what type of responses they will make. A virtual environment must support the responses that will be executed within it by supporting both perception-for-cognition and perception-for-action and each of the calibration processes.

Future work will examine the effects of perturbation of the virtually presented target by comparing estimates made when participants are given accurate feedback regarding distance estimates and a systematic perturbation of the target. For example participants will be presented with visual feedback that is biased to show the hand at a fixed percentage closer to or farther from its actual location during the reach. We will also examine the effects of visual feedback alone compared to haptic feedback alone, as well as examine the carryover effects of calibration in an IVE to a RW viewing environment.

Our work is one of the first studies to investigate calibration of egocentric distance estimation in IVEs in the near field. It is also one of few studies that use both verbal responses and physical reaches in an IVE for each trial. The implications of this research for VR application developers and consumers could be significant. Although designers of complex systems may be using research supporting compression of depth perception in IVEs compared to RW viewing to enhance performance by automatically accounting for such systematic underestimations, these efforts could be less necessary if users of IVEs instead produce more accurate distance estimates after calibration via manual activity. For example, if a user is simply given an opportunity to practice operating in the IVE before performing actual tasks, visual and/or haptic feedback could calibrate their visuomotor system to the new environment. Future research will examine differences between visual and haptic feedback to see if one is more effective at calibrating distance estimates compared to the other.

REFERENCES

Bingham, G., & Pagano, C. (1998). The necessity of a perception - action approach to definite distance perception: monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance, 24(1)*, 145-167.

Bingham, G.P., & Romack, J.L. (1999). The rate of adaptation to displacement prisms remains constant despite acquisition of rapid calibration. *Journal of Experimental Psychology: Human Perception and Performance, 25(5)*, 1131-1346.

Bingham, G., & Stassen, M. (1994). Monocular egocentric distance information generated by head movement. *Ecological Psychology, 6(3)*, 219-238.

Biocca, F. (1992). Communication within virtual reality: Creating a space for research. *Journal of Communication, 42*, 5–22.

Blascovich, J., Loomis, J., Beall, A. C., Swinth, K. R., Hoyt, C. L., & Bailenson, J. N. (2002). Immersive virtual environment technology as a methodological tool for social psychology. *Psychological Inquiry, 13,*103–124.

Bliss, J. P., Tidwell, P. D., & Guest, M. A. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence: Teleoperators and Virtual Environments, 6,* 73–86.

Bridgeman, B., Kirch, M., & Sperling, A. (1981). Segregation of cognitive and motor aspects of visual function using induced motion. *Attention, Perception and Psychophysics, 29(4)*, 336-342.

Brunswik, E. (1956). Perception and the representative design of psychological experiments, 2nd ed. Berkeley, University of California Press.

Casper, J., & Murphy, R.R. (2003). Human-robot interactions during the robot-assisted urban search and rescue response at the World Trade Center. *IEEE Transactions on Systems, Man, and Cybernetics-Part B: Cybernetics, 33*, 367-385.

Darby, M. L. (2000). Battlefield simulation: Building virtual environments. *Journal of Battlefield Technology, 3,* 35–43.

Durgin, F. H., Fox, L. F., Lewis, J., & Walley, E. K. (2002, November). *Perceptuomotor adaptation: More than meets the eye.* Paper presented at the 43rd Annual Meeting of the Psychonomic Society, Kansas City, MO.

Durgin, F. H., & Pelah, A. (2004). Visuomotor adaptation without vision? *Experimental Brain Research, 127*, 12–18.

Durgin, F. H., Pelah, A., Fox, L. F., Lewis, J., Kane, R., & Walley, K. A. (2005). Self motion perception during locomotor recalibration: More than meets the eye. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 398–419.

Foley, J. M. (1977). Effect of distance information and range on two indices of visually perceived distance. *Perception, 6(4),* 449-460.

Grechkin, T., Nguyen, T., Plumert, J., Cremer, J., & Kearnew, J. (2010). How does presentation method and measurement protocol affect distance estimation in real and virtual environments? *ACM Transactions on Applied Perception, 7(4),* 1-18.

Gogel, W.C. (1993). The analysis of perceived space. *Advances in Psychology, 99*, 113-182.

Gomer, J.A., Dash, C.A., Moore, K.S., & Pagano, C.C. (2009). Using radial outflow to provide depth information during teleoperation. *Presence, 18(4)*, 304-320.

Goodale, M.A., & Milner, A.D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*, 20-25.

Hodges, L., Anderson, P., Burdea, G., Hoffman, H., & Rothbaum, B. (2001). Treating psychological and physical disorders with VR. *IEEE Computer Graphics and Applications, 21(6)*, 25-33.

Kessler, G.D., Bowman, D., & Hodges, L. (2000). The simple virtual environment library, an extensible framework for building VE applications, *Presence: Teleoperation and Virtual Environments, 9(2)*, 187-208.

Klein, E., Swan, J., Schmidt, G., Livingston, M., & Staadt, O. (2009). Measurement protocols for medium-field distance perception in large-screen immersive displays. In *Proceedings of the IEEE Virtual Reality*, Lafayette, LA, 107-113.

Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers, 31*, 557–564.

Loomis, J., & Knapp, J. (2003). Visual perception of egocentric distance in real and virtual environments. In *Virtual and Adaptive Environments: Applications, Implications, and Human Performance Issues*, L.J. HETTINGER AND J.W. HAAS, Eds. Lawrence Erlbaum Associates, Mahwah, NJ, 21-46.

Messing, R., & Durgin, F. (2005). Distance perception and the visual horizon in head-mounted displays. *ACM Transactions on Applied Perception, 2(3),* 234-250.

Milner, A.D., & Goodale, M.A. (1995). The visual brain in action. Oxford: Oxford University Press.

Milner, A.D., & Goodale, M.A. (2008). Two visual systems reviewed. *Neuropsychologia, 46(3)*, 774-785.

Mohler, B. J., Creem-Regehr, S. H., & Thompson, W. B. (2006, July). The influence of feedback on egocentric distance judgments in real and virtual environments. In *ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization* (pp. 9–14).

Moore, K. S., Gomer, J. A., Pagano, C. C., & Moore, D. D. (2009). Perception of robot passability with direct line of sight and teleoperation. *Human Factors, 51(4)*, 557-570.

Murphy, R. (2004). Trial by fire: Activities of the rescue robots at the World Trade Center from 11-21 September 2001. *IEEE Robotics & Automation Magazine, 11(3),* 50-60.

Napieralski, P. E., Altenhoff, B. M., Bertrand, J. W., Long, L. O., Babu, S. V., Pagano, C. C., Kern, J., & Davis, T. A. (2011). Near-field distance perception in real and virtual environments using both verbal and action responses. *ACM Transactions on Applied Perception,8(3),* Article 18.

Pagano, C., & Bingham, G. (1998). Comparing measures of monocular distance perception: Verbal and reaching errors are not correlated. *Journal of Experimental Psychology: Human Perception and Performance, 24(4)*, 1037-1051.

Pagano, C., & Isenhower, R. (2008). Expectation affects verbal judgments but not reaches to visually perceived ego-centric distances. *Psychonomic Bulletin and Review, 15(2),* 437.

Pagano, C., Grutzmacher, R., & Jenkins, J. (2001). Comparing verbal and reaching responses to visually perceived ego-centric distances. *Ecological Psychology, 13(3)*, 197-226.

Peters, T. M., Linte, C.A., Moore, J., Bainbridge, D., Jones, D.L., & Guiraudon, G.M. (2008). Towards a medical virtual reality environment for minimally invasive cardiac surgery. *Medical Imaging and Augmented Reality*, 5128, 1-11.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance, 23(1)*, 72-85.

Phillips, L., Ries, B., Interrante, V., Kaeding, M., & Anderson, L. (2009). Distance perception in NPR immersive virtual environments, revisited. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization (APGV '09)*, 11-14.

Richardson, A. R., & Waller, D. (2005). The effect of feedback training on distance estimation in virtual environments. *Applied Cognitive Psychology, 19,* 1089–1108.

Richardson, A. R., & Waller, D. (2007). Interaction with an immersive virtual environment corrects users' distance estimates. *Human Factors, 49,* 507–517.

Rieser, J. J., Pick, H.L., Ashmead, D.H., & Garing, A.E. (1995). Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology: Human Perception and Performance, 21(3)*, 480–497.

Sahm, C., Creem-Regher, S., Thompson, W., & Willemsen, P. (2005). Throwing versus walking as indicators of distance perception in similar real and virtual environments. *ACM Transactions on Applied Perception, 2(1)*, 35-45.

Schmidt, R. A. (1988). *Motor control and learning: A behavioral emphasis*. Champaign, Illinois: Human Kinetics Publishers, Inc.

Thompson, W., Willemsen, P., Gooch, A., Creem-Regher, S., Loomis, J., & Beall, A. (2004). Does the quality of the computer graphics matter when judging distances in visually immersive environments? *Presence: Teleoperation and Virtual Environments, 13(5)*, 560-571.

Tittle, J.S., Roesler, A., & Woods, D.D. (2002). The remote perception problem. In *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting* (pp. 260-264). Santa Monica, CA: Human Factors and Ergonomics Society.

Waller, D., & Richardson, A.R. (2008). Correcting distance estimates by interacting with immersive virtual environments: Effects of task and available sensory information. *Journal of Experimental Psychology – Applied, 14(1)*, 61-72.

Warren, W.H. (1995). Constructing an econiche. In *Global Perspectives on the Ecology of Human-machine Systems*, Flach, J., Hancock, P., Caird, J. & Vicente, K., Eds. Lawrence Erlbaum Associates, Mahwah, NJ, 210-237.

Winn, W. D., Hoffman, H., Hollander, A., Osberg, K., Rose, H., & Char, P. (1999). Student-built virtual environments. *Presence: Teleoperators & Virtual Environments, 8,* 283–292.

Witmer, B.G., & Kline, P.B. (1998). Judging perceived and traversed distance in virtual environments. *Presence – Teleoperators and Virtual Environments, 7(2)*, 144-167.