Investigating the Effects of Anthropomorphic Fidelity of Self-Avatars on Near Field Depth Perception in Immersive Virtual Environments

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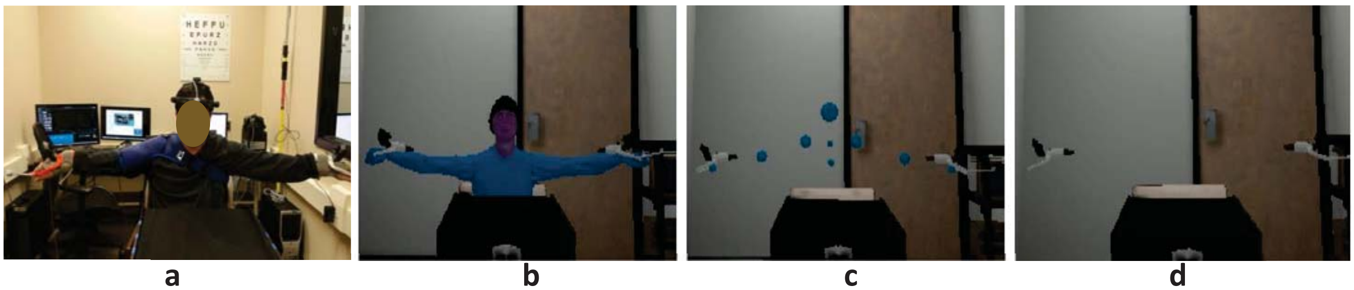

Figure 1: Left to right: a) Real-World condition and a digital illustration of b) Immersive Self-Avatar, c) Low-Fidelity Self-Avatar, and d) End-Effector (no avatar). Prior to the experiment, participants were instructed to make a T-Pose to measure the distance between the two controllers using the HTC Vive positions. This distance was then used to calculate the arm length of the participant to generate a custom avatar. The position of the head was also logged and was used to calculate the height of the participants.

Abstract

Immersive Virtual Environments (IVEs) are becoming more accessible and more widely utilized for training. Previous research has shown that the matching of visual and proprioceptive information is important for calibration. While research has demonstrated that self-avatars can enhance ones' sense of presence and improve distance perception, the effects of self-avatar fidelity on near field distance estimations has yet to be investigated. This study tested the effect of avatar fidelity on the accuracy of distance estimations in the near-field. Performance with a virtual avatar was also compared to real-world performance. Three levels of fidelity were tested; 1) an immersive self-avatar with realistic limbs, 2) a low-fidelity self-avatar showing only joint locations, and 3) end-effector only. The results suggest that reach estimations become more accurate as the visual fidelity of the avatar increases, with accuracy for high fidelity avatars approaching real-world performance as compared to low-fidelity and end-effector conditions. In all conditions reach estimations became more accurate after receiving feedback during a calibration phase.

Index Terms: Human-centered computing—Visualization—Empirical studies in visualization—; Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI

1 Introduction

Immersive virtual environments are widely used to replicate real-world scenarios that are rare, expensive and dangerous [4, 32]. Some of these IVEs allow users to interact with the environment for the purpose of training and education [32] and are aimed to transfer skills to the real-world. Unfortunately, depth perception in virtual environments has consistently been shown to be distorted [10, 27]. This distortion can potentially degrade training outcomes linked to depth perception. Worse, depth perception is related to size, height, scale and speed perceptions [20, 29], increasing the potential that inaccuracies in depth perception could affect users' overall experience and perception in virtual environments.

One potential explanation for this kind of distortion could be accommodation-convergence mismatch and/or limited field of view [37] as a result of the 3D displays. However, allowing users to interact with the environment can help to reduce distance distortion [3]. Previous work showed that visuo-motor calibration alters the use of visual and proprioceptive information so that actions are properly scaled. Research has demonstrated that visual and proprioceptive sensory channels are highly tied together and constantly calibrated to accommodate for new circumstances. This kind of interaction has been shown to be effective in increasing the accuracy of the reach estimates and enhancing users' experience [9, 18]. Recent perception research suggests the presence of avatars influence how users perceive and interact with their surroundings [13, 33]. Virtual self-avatars are life-size visual representations of the user, seen from a first-person perspective and co-located with users' actual body. Presence of a self-avatar has been shown to have an effect on users' spatial perception in medium field in IVEs [21, 25, 38]. Furthermore, visual fidelity of self-avatar could also alter the users' spatial perception in IVEs [28]. However, it is not well understood how the visual fidelity of self-avatars affects the perception of ones' environment in VR. Thus, we explore how the anthropometric characteristics of the arm and hand during 3D interaction affect users' near-field depth perception in IVEs.

2 Related Work

The space around us can be categorized into three main regions: 1) near field (or personal space/interaction space: the area within a typical user's arm reach), 2) medium field (or action space: the area beyond personal space up to roughly 30m), and vista space (or far field: distances beyond 30 m) [7]. Although distance can be accurately estimated in real-world, it is mostly underestimated in IVEs in medium field [22]. Similarly, distance is distorted in near-field, where users perform fine motor tasks within their personal space, but it is mostly *overestimated* in VEs, unlike distance underestimation in medium-field [9, 29]. Different methods on how to improve users'

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space perception in VR have been studied. One method to improve distance distortion is to create VEs that replicate real environments which provides a high degree of situational awareness. Steinicke et al. [35] showed that gradual transition from familiar to unfamiliar environments significantly improve distance estimation in VE. Another method to overcome distance distortion is by employing feedback during interaction stimulating visuo-motor calibration [36]. Previous research demonstrated that users' interaction within a virtual environment could potentially improve distance estimation in a relatively short amount of time [18, 27]. Kelly et al. [18] showed only five closed-loop interactions with VEs significantly improved users' distance estimation. Another widely studied approach on enhancing space perception in VR is the presence of self-avatars.

Research has shown the presence of self-avatars in the IVE affects how people perceive their environment [13, 33]. Mohler et al. [25] showed that accuracy of users' distance estimation was altered via the self-avatar representation; fully-articulated and tracked self-avatars that animated corresponding to the users' movements produced the highest improvement, as compared to no self-avatar on users' space perception through blind walking for distances greater than 1m. Similarly, Ries et al. [28] investigated the effect of self-avatar visual fidelity on users' spatial perception via direct blind walking. They provided users with either a fully tracked, high-fidelity self-avatar or a fully tracked but simplified self-avatar (only the tracking marker locations were presented using small spheres). They then compared their results with no avatar condition and found that participants with low-fidelity avatars showed greater improvement on medium field distance estimation as compared to no avatar. However, participants' distance estimation with a high-fidelity avatar was significantly more accurate than the low-fidelity and no avatar conditions. They concluded that a minimal level of avatar visual fidelity may be required to improve users' distance judgments.

Runeson and Frykholm [30] studied the effect of the real-world joint position representation on medium field distance estimation. They attached retroreflective material to the ankles, knees, wrists, elbows, hips, shoulders, and forehead of two actors. They then recorded the throwing action of those actors towards 6 target distances at various locations from 1.75 m to 8 m. Runeson and Frykholm demonstrated that by showing the joint positions only to the participants, the participants could accurately estimate the distance from the actor to the targets. Based on Runeson [30], we created a low-fidelity self-avatar viewing condition in which the main joints (ankles, knees, wrists, elbows, hips, shoulders, neck and forehead) were illustrated using blue spheres. The radius of each of the spheres representing the joints was extracted from the Anthropometric source book [5] to create custom low-fidelity self-avatars. The use of this low-fidelity self-avatar was compared to two other conditions; the use of a faithful high-fidelity self-avatar and the rendering of only the end-effector at the hand. The same inverse kinematic system was employed in all three conditions to calculate the position of the joints with HTC Vive trackers to accurately track user's upper body and arm motion (figure 1).

Most of the previous research investigating the effect of self-avatars in distance perception was conducted in medium field, where distance is estimated via blind walking. The main visual contributors during walking are the eye level and a fixation point on the ground which is approximately two steps ahead [12]. Unlike medium field, the primary distance perception task in near field is reaching, which has different affordances. The two main visual contributors in on-line control of hand movements while reaching are a) the position of the hand and b) the hand motion [31]. Generally, walking and reaching use two distinct mechanisms which can affect distance estimation quite differently in the presence of the self-avatars. It has been shown that reaches become more accurate when users can see their arm while reaching in the real-world [14, 26]. McManus et al. [24] showed that the users' performance in terms of accuracy and time to complete was improved in the presence of self-avatars when users could interact with the environment. Moreover, it is not well understood if the anthropometric similarity of self-avatar with its real-world representation has any effect on users' distance estimation via reaching tasks in IVE. Additionally, the presence of self-avatar and its visual fidelity may have a greater impact on users' distance estimation in reaching activities when the fixation point is at the end-effector (hand) as compared to walking tasks as the fixation point is somewhere in front of legs [12, 31]. Data regarding the alteration of depth perception measured via pre- and post-test phases straddling a calibration phase in which users receive information from their self-avatar regarding their activates in VR is missing. Also, the perception of self-representation is mostly studied in medium field distance and less is known about the impact of visual fidelity of self-avatar on space perception in near-field in IVEs.

3 Hypothesis

There is little or no research on the visuo-motor calibration effects of visual fidelity of immersive self-avatars on distance estimation in near-field in IVE. This study has three primary hypotheses.

- **H1**: We hypothesize that the mere existence of a self-avatar or end-effector position will calibrate users' near-field depth perception in an IVE. Therefore, participants' distance judgments will be improved after the calibration phase regardless of self-avatar's visual fidelity.
- **H2**: The magnitude of the changes from pre-test to post-test will be significantly different based on the visual details of the self-avatar presented to the participants during the calibration phase.
- **H3**: We predict distance estimation accuracy will be the highest in visually realistic self-avatar condition and the lowest in end-effector only condition.

4 Experiment Methodology

4.1 Participants

Forty-one undergraduate students (26 females and 15 males) from the student population of a Clemson University were recruited and received course credit for their participations in the study. In this experiment, all participants were required to be right-handed as all equipment to be used was designed for right-handed participants. As participants entered the testing area, they were given a brief overview of the purpose of the experiment and informed consent was obtained. All participants were asked to sit on a wooden chair at one end of a wooden table. Various motion sensors were placed on the participant through the use of a long-sleeve shirt and a shoulder strap support (Figure 3). All participants were tested for visual stereo acuity. Participants were randomly assigned to one the three conditions 1) Immersive Self-Avatar, 2) Low-Fidelity Self-Avatar and 3) End-Effector (described in Section 4.5). Real-world data was gathered from a separate set of eleven undergraduate students and was used as the reference group (Figure 2).

4.2 Apparatus and Material

Figure 3 depicts the experiment apparatus which consists of a custom table and a chair, HTC Vive HMD and two controllers, and five Polhemus electromagnetic sensors. The table was 50 cm wide and 130 cm long, and 76.2 cm tall (a standard table height). An array of 125 red LED lights was lined up along the center of the table and was situated under a glass surface at 1 cm interval as visual targets for the reaching task. Participants were asked to sit with their backs against the chair. The chair was placed approximately 20 cm from the table and aligned midway between participants' eyes and right shoulder in order to keep the distance from the center of the eyes to the LED target line the same as the distance from the right shoulder.

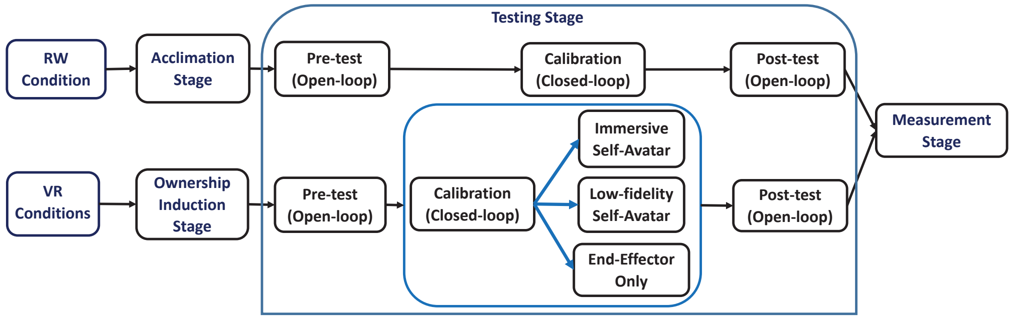

Figure 2: Experiment design.

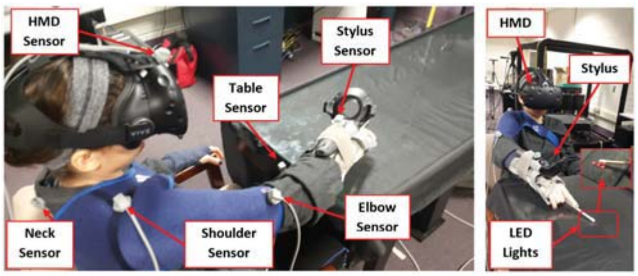

Figure 3: Shows the near-field distance estimation apparatus. The participant's head, neck, shoulder, elbow and stylus are tracked in order to record perceived distances of physical reach in the IVE.

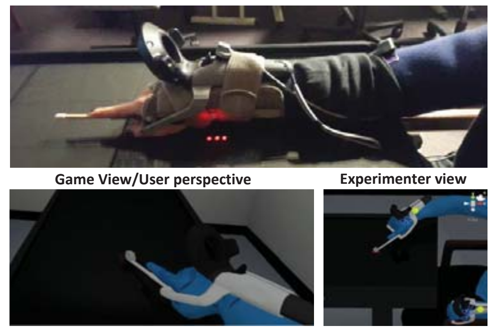

Figure 4: Top image: LED lights illuminated on the table for each trial. Bottom left image: shows participant's view in self-avatar condition. Bottom right image: experimenter view.

Each target consisted of a set of three neighboring LED-lights that could be turned on or off via an Arduino controller interfaced with the simulation. This LED configuration made the target area easier to see and it also provided visual cues for binocular depth perception as well as the motion parallax (Figure 4). Participants were instructed that the middle-LED light corresponded to the target distance on the table. All three lights spanned a length of 3 cm. Blender and Unity3D were used to model the visual replica of the experiment apparatus and surrounding environment. All these visual components were carefully registered to be co-located with the corresponding physical apparatus and experiment room.

The HTC Vive controllers were mounted using a wrist brace and a 3D-printed plastic mold on top of the participants' wrists. This configuration helped to provide a consistent orientation of HTC Vive controllers across all trials and all participants, which allowed experimenters to accurately model their wrist and hand position and orientation in the IVE. A plastic rod with a rubber tip was inserted in a 3D printed plastic mold. Participants were instructed to place their index finger on the rod and reach to the target with the tip of the tool on their right hand in natural manner (Figure 4). Rubber tip extended participants' reach by approximately 4 cm in all of the experimental conditions. Before any trials occurred, the distance between two controllers attached to the hands and wrists (while making a T-pose) as well as the eye height were measured and recorded using the HTC Vive controllers (Figure 1).

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

4.3 Procedure

Participants were instructed on how to reach as quickly and accurately as possible to the target (demonstrated by experimenter). Before physical reaches, participants were asked to make a verbal judgment on the reachability of the target by saying yes or no, indicating if the target was reachable or unreachable, respectively. During the experiment participants were instructed that they must remain seated (i.e. stay on the seat pan) during any attempted reach. Each trial started and ended from the same resting position with their right arm on the right armrest and their backs against the back of the chair. This ensured uniformity in starting positions across participants.

In pre- and post-test phases, 13 target distances were randomly presented 5 times corresponding to LED numbers (14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, 91, and 98; total of 65 trials). The LED target distances ranged from 20.5 cm to 121.5 cm with approximately 8 cm interval between neighboring targets. In calibration phase, 5 random permutations of 9 target distances (45 total trials) corresponding to LED numbers (10, 20, 30, 40, 50, 60, 70, 80, and 90; note these are different than pre- and post-test distances as the calibration should happen regardless of the distances.) ranged from 15.7 cm to 107.65 cm with approximately 11.5 cm interval between neighboring targets.

4.4 Visual aspects

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

4.5 Experiment Design

This experiment utilized a 4 (Condition: Real-world reference group, Immersive Self-Avatar, Low-Fidelity Self-Avatar, and End-Effector only) by 3 (Phase: Pretest, Calibration, Posttest) mixed groups design (Figure 2). Participants were assigned to one of the experiment conditions. Condition was a between-subjects variable and phase was a within-subjects variable. All participants completed three successive stages (1) induction/acclimation stage, 2) testing stage 3) measurement stage) depicted in Figure 2.

- **Real World *(RW)*** - *Reference group*: Participants completed all three stages (Figure 2) in the real-world (all other conditions were conducted in the virtual environment). The acclimation phase was performed only to get participants used to the equipment that they were outfitted with described in 4.2.

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

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

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

As discussed previously, the experiment consisted of three stages (Induction, Testing, and Measurement) depicted in Figure 2.

- ***Induction Stage*** To get participants acclimated to the new environment (mainly for VR conditions) and be well grounded in the IVE, they spent a few minutes interacting with the environment immediately after they were outfitted with all the equipment described in section 4.2. The virtual experiment room in the induction stage was decorated with several objects such as a poster, clock, lamp, bookshelf, and a mirror. In this stage, participants were asked to extend their arms to the sides of their body, above their head and in front of them, respectively, and move them around while looking at themselves in the mirror to enforce self-embodiment. Participants were then instructed to complete some additional tasks to adopt the self-avatar as their own suggested in previous work [1, 19, 23].

  - *Pointing to Environment:* Pointing to different objects in the room with the tip of the stylus.
  - *Pointing to Self:* Touching their shoulders, elbows and wrists using the right and left controllers, respectively.
  - *Peripheral Stimulation:* Touching the inner part of their forearm and moving one of the controllers from their elbow to wrist and back several times. Then repeating the same task with the other hand.

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

- ***Testing Stage*** All participants completed three successive phases; 1) Pre-test phase, 2) Calibration phase 3) Post-test phase) depicted in Figure 2.

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

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

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

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

5 Results

As discussed in section 4.2, five electromagnetic sensors were utilized to track movements of participants' head, neck, right shoulder, right elbow and tip of the tool. The start and the end points of the ballistic were extracted by analyzing the XY position trajectories and speed profile associated with the physical reach motions for the sensors attached to the users. An initial analysis showed that there was a high correlation between the data from different sensors. Therefore, to eliminate suppression with our data analysis model, only the data collected from the tool, which was the strongest predictor, was used in the model. Participants' maximum arm reach, measured by the tracking system in the measurement stage, was utilized in the analysis instead of participants' arm length since it is a better measurement variable of action capabilities for the affordance of physical reaching.

5.1 Transformed Variables

More informative variables were created from manipulated and collected variables for analysis. These new variables are as follows:

$$Error = EstimatedDistance - PresentedDistance \qquad (1)$$

This is the linear error term (i.e. signed error) where negative and positive values indicate underestimation and overestimation respectively. Figure 5 demonstrates the signed error as a function of presented distance with all conditions in pre- and post-test phases. Perfect performance would result in an absolute error of 0 cm and is designated with a black line.

The error term was then broken down into two separate variables named *directionality* and *absolute error*. Directionality is a binary variable indicating whether the participant over- or underestimated distances. For the data analysis, overestimation (also known as positive error) was used as reference group and coded as 0 while

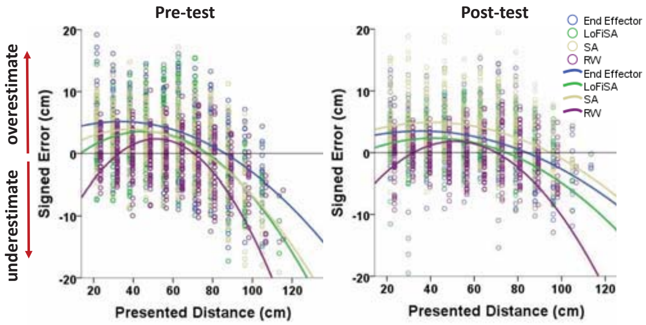

Figure 5: Signed Error as a function of presented distance a) pre-test b) post-test. The solid black line in each graph represents perfect performance (y = 0).

underestimation (also known as negative error) was coded as 1. Extracting the directionality from the error term leaves the absolute error (measured in cm). The de-conflating of these two variables from the signed error allows for a more precise and comprehensive analysis.

A quadratic presented distance term was also created. Previous research has demonstrated that participants actions for target distances are dependent on the different distances [8]. This quadratic trend in the data can also be seen in Figure 5 thereby justifying the creation of a quadratic term [6]. Essentially, the quadratic presented distance term is an interaction term of the presented distance where the effect of the target distance on error depends on the target distance (i.e. the effect does not remain constant across all distances). Additionally, there are three categorical variables within the analyses listed below:

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

5.2 Outlier Analysis

A full model was conducted in order to obtain residuals. These were then standardized and potential outliers were identified. Trials with excessive standardized residuals outside of a normal distribution of 3 SD were removed from the analysis [6]. Overall, less than 1% of the data was eliminated from the data analysis.

5.3 Hierarchical Linear Modeling (*HLM*)

The repeated-measure design of this experiment created some challenges for traditional repeated measures analysis of variance. A multilevel modeling approach is a more flexible and accommodating alternative to repeated measures ANOVA. Predictor variables can be within person variables, called Level 1 in HLM, or between person variables, called Level 2 in HLM. Additionally, predictor variables at either level can be nominal or quantitative. HLM uses all available data for each participant where as repeated measures ANOVA requires complete data for each participant. HLM is essentially a general linear model designed to analyze variance at multiple levels. For more comprehensive overviews on multilevel modeling see for example Hoffman [16] and Snijders and Bosker. [34].

The design of this experiment also created natural nesting of the data. To determine the amount of nesting, the intraclass correlation (ICC) of the null model (i.e. the intercept only model) was calculated for absolute error (ICC= 23% for the absolute error). A multilevel modeling approach is required for an ICC greater than 2-3% [2, 15]. One of the great advantages of HLM is that all levels of variance across all trials and within participants could be used and not be reduced to just the mean value similar to mean based analysis. Unlike repeated measure ANOVAs, HLM allows for a within-subjects scale variable (e.g. target distances) to be analyzed. This type of approach is more flexible and allows for the estimates, errors, and effect sizes to be more accurately modeled than traditional approaches such as repeated-measures ANOVA [6].

For HLM, variables are categorized as level 1 (L1) when they vary within-subjects or level 2 (L2) when they vary between-subjects. Level 1 variables change within a participant and they are collected at each measurement occasion (e.g. presented distance, quadratic presented distance, phase, and directionality). These variables are going to carry the residual variance. Thus, error variance for L1 predictors and intra-level interactions (L1*L1) is indexed by a reduction in residual variance. Level 2 variables do not change within a participant (i.e. condition) and represent intercept variance. Lastly, cross-level interactions (L1*L2) are indexed by the reduction in Level 1 slope variance. In multilevel modeling, the effect sizes are known as pseudo-R^2 and are the percent of reduction in error variance to the corresponding variance (e.g. residual for L1 predictor and intercept for L2 variance). Pseudo-R^2 (also known as R^2) is only calculated for significant effects with all other predictors remaining within the model to control the unique effects.

For the data analyses, only the pre- and post-test data were included due the different task constraints in the calibration phase (e.g. participants were forced to reach to presented targets even if they perceived the target to be outside of their reach envelope). Comparison of pre- and post-test data to determine the effect of calibration phase is common practice (e.g. [8, 10, 11]).

5.4 Absolute Error

A multilevel model was conducted with absolute error as the dependent variable and presented distance (PD), quadratic presented distance (QPD), phase (pre-test used as reference), directionality (overestimation used as reference), and condition (real-world used as reference) as independent variables. All of the independent variables and appropriate interactions were included into the model as predictors. The appropriate F-tests, fixed effect coefficients, and effect sizes can be found in Table 1. Main effects were included in an initial conservative model. The two-way interactions were then included individually with the main effects to obtain unique effect sizes for the three-way interaction. All main effects and appropriate two-way interactions were held constant within the model.

In terms of predicting absolute error, a significant main effect of presented distance was found which indicates a linear relationship between the presented distance and absolute error. However, a significant main effect of quadratic presented distance showed a non-linear relationship between the absolute error. This indicates that distance judgments were not consistent across all target distances. Thus, error would increase as the target distance gets farther from participants. The other two Level 1 predictors, phase and directionality had significant main effects and a significant two-way interaction (Figure 6).

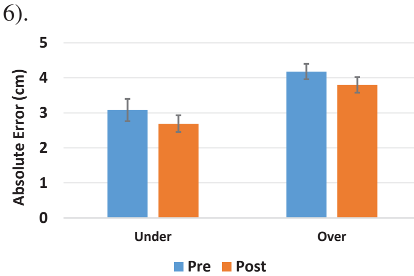

Figure 6: Directionality moderated by phase.

Overall, participants performed better in post-test phase (M = 3.25, SE = 0.19) as compared to pre-test phase (M = 3.63, SE = 0.21) suggesting that calibration phase improved the accuracy of reach estimates. Participants tended to have larger errors when they overestimated distance with a higher overestimation in pre-test as compared to post-test. The amount of underestimation was smaller

Table 1: Multi-level Model Results for Absolute Error: F-tests, Coefficients, Standard Error (SE) and pseudo-R^2 (effect sizes) for significant variables.

Predictors	F-Test (p-value)	Coefficient (SE)	P-value	Pseudo-R^2		
				L1	**L2**	**Interaction**
Intercept		3.54 (0.44)	<0.001			
PD	12.64 (0.001)	0.03 (0.01)	0.001	1.4%		
QPD	9.53 (0.003)	<0.001 (<0.001)	0.003	0.5%		
Phase	7.88 (0.007)	-0.71 (0.25)	0.01	1.8%		
Directionality	5.63 (0.024)	-0.56 (0.24)	0.02	0.3%		
Condition	3.06 (0.039)				12.5%	
EE Condition		1.50 (0.54)	0.01			
LF-SA Condition		1.32 (0.56)	0.02			
SA Condition		1.23 (0.54)	0.03			
PD*Phase	6.62 (0.013)	-0.02 (0.01)	0.01	0.4%		
QPD*Phase	34.11 (<0.001)	<-0.001 (<0.001)	<0.001	0.3%		
PD*Directionality	74.63 (<0.001)	0.04 (0.004)	<0.001	2.8%		
QPD*Directionality	85.65 (<0.001)	0.002 (<0.001)	<0.001	1.4%		
Directionality*Phase	4.25 (0.045)	-0.79 (0.38)	0.05	0.3%		
PD*Condition	0.47 (0.708)					NA
PD EE Condition*		-0.02 (0.02)	0.45			
*PD*LF-SA Condition*		-0.002 (0.02)	0.93			
*PD*SA Condition*		-0.02 (0.02)	0.34			
QPD* Condition	0.56 (0.643)					
QPD EE Condition*		<-0.001 (<0.001)	0.94			NA
*QPD*LF-SA Condition*		<-0.001 (<0.001)	0.29			
*QPD*SA Condition*		<-0.001 (<0.001)	0.98			
Phase*Condition	2.42 (0.077)					
Phase EE Condition*		-0.98 (0.71)	0.17			NA
Phase LF-SA Condition*		-0.57 (0.72)	0.43			
Phase SA Condition*		0.71 (0.71)	0.32			
Directionality *Condition	1.46 (0.245)					
Directionality EE Condition*		-1.01 (0.69)	0.15			NA
Directionality LF-SA Condition*		-1.38 (0.72)	0.06			
Directionality SA Condition*		-0.48 (0.68)	0.49			
PD*Phase*Directionality	30.69 (<0.001)	-0.04 (0.01)	<0.001	0.6%		
QPD*Phase*Directionality	3.85 (0.050)	-0.04 (0.01)	<0.001	0.06%		
PD*Phase*Condition	1.85 (0.150)					NA
*PD*Phase* EE Condition*		0.01 (0.02)	0.68			
*PD*Phase*LF-SA Condition*		-0.04 (0.02)	0.1			
*PD*Phase* SA Condition*		-0.02 (0.02)	0.4			
QPD*Phase*Condition	3.16 (0.016)					<0.001 (trivial)
*QPD*Phase*EE Condition*		<0.001 (<0.001)	0.44			
*QPD*Phase*LF-SA Condition*		<-0.001 (<0.001)	0.37			
*QPD*Phase*SA Condition*		<-0.001 (<0.001)	0.03			
Directionality*Phase*Condition	1.94 (0.138)					NA
Directionality*Phase*EE Condition		0.25 (1.03)	0.81			
Directionality*Phase*LF-SA Condition		-0.32 (1.09)	0.77			
Directionality*Phase*SA Condition		-1.91 (1.01)	0.07			
PD*Directionality*Condition	1.60 (0.202)					NA
*PD*Directionality* EE Condition*		0.04 (0.02)	0.06			
*PD*Directionality* LF-SA Condition*		0.04 (0.02)	0.07			
*PD*Directionality* SA Condition*		0.04 (0.02)	0.2			
QPD*Directionality*Condition	0.34 (0.794)					NA
*QPD*Directionality* EE Condition*		<0.001 (0.001)	0.42			
*QPD*Directionality* LF-SA Condition*		<0.001 (0.001)	0.49			
*QPD*Directionality* SA Condition*		<0.001 (0.001)	0.92			
PD*Phase*Directionality*Condition	0.36 (0.790)					NA
*PD*Phase*Directionality*EE Condition*		-0.002 (0.04)	0.95			
*PD*Phase*Directionality*LF-SA Condition*		0.02 (0.04)	0.58			
*PD*Phase*Directionality*SA Condition*		-0.02 (0.04)	0.63			
QPD*Phase*Directionality*Condition	1.03 (0.38)					NA
*QPD*Phase*Directionality*EE Condition*		<-0.001 (0.002)	0.36			
*QPD*Phase*Directionality*LF-SA Condition*		-0.003 (0.002)	0.09			
*QPD*Phase*Directionality*SA Condition*		-0.002 (0.002)	0.24			
			TOTAL R^2:	**9.86%**	**12.5%**	**<0.001% (trivial)**

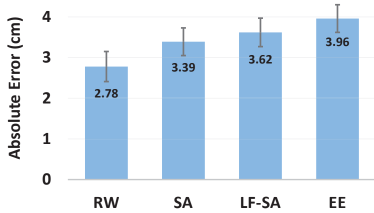

Figure 7: The mean and SE of all the conditions (in cm): RW: real-world, SA: self-avatar, LF-SA: low-fidelity self-avatar, and EE: end-effector conditions.

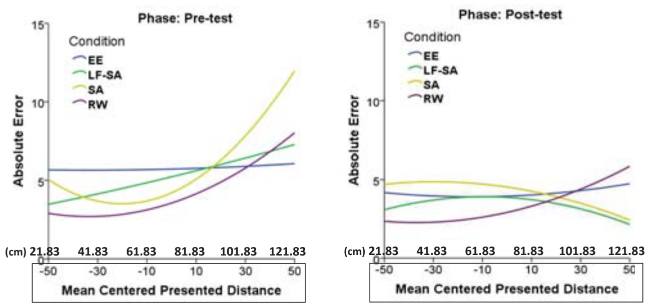

Figure 8: Interaction of quadratic presented distance and condition moderated by phase.

in post-test as compared to pre-test phase (Figure 6). There were two other Level 1 interactions. Quadratic presented distance moderated by phase indicates that the main effect of quadratic trend in absolute error decreased from pre- to post-test. The significant interaction of quadratic presented distance moderated by directionality indicates as distances increased, participants had larger errors when they were underestimating than when they were overestimating.

Condition had a significant main effect as well (Figure 7). As predicted, participants' reach estimates were significantly different from real-world condition. Participants in the real-world condition had the smallest error while reaching towards targets ($M = 2.78$, $SE = 0.37$) and the highest error was measured in the end-effector condition ($M = 3.96$, $SE = 0.34$), in which participants had the minimum amount of visual information. In the immersive self-avatar condition ($M = 3.39$, $SE = 0.34$) participants performed slightly worse than the real-world condition but better than the low-fidelity self-avatar ($M = 3.62$, $SE = 0.35$). Although, a two-way interaction of phase moderated by condition was not statistically significant, there was a significant three-way interaction of quadratic presented distance moderated by phase and condition. A further investigation on the significant three-way interaction of quadratic presented distance, phase and condition was conducted and found that only changes form pre- to post-test in the immersive self-avatar was significantly different from real-world condition (Figure 8). As evidence in Figure 8, in pre-test phase, participants in self-avatar condition showed a similar behavior regarding the absolute error with real-world condition that could be due to the induction stage, which was experience by the participants in all the VR conditions. The induction stage tried to evoke the self-embodiment without letting participants to calibrate to any of the target distances which could potentially cause participant to perform similarly to real-world condition in pre-test. However, after calibration phase in which participants received feedback, their performance in the self-avatar condition differed from the real-world condition. Participants' distance estimation became more accurate for closer and far distances but the error increased for middle target distances which requires further investigation. Additionally, in the post-test phase, the two self-avatar viewing conditions' absolute error pattern became more similar to each other and parted from real-world condition.

5.5 Discussion

In summation, all three hypotheses were supported by the results from the absolute error. First, we expected that calibration would decrease the absolute error from pre- to post-test regardless of the visual fidelity of the self-avatar (H1). We found after calibration participants' reaches became more consistence and absolute error also reduced and reached a statistical significance which supports the first hypotheses. Secondly, we expected that the rate of improvement in the accuracy would be different from pre- to post-test between different experimental conditions (H2). The second hypothesis was supported via a three-way interaction between quadratic presented distance moderated by phase and condition revealing that interaction between phase and condition was also dependent on the quadratic presented distance. However, further investigation revealed that only the self-avatar condition was different from the real-world condition which was unexpected. The low-fidelity self-avatar and end-effector conditions had the least similarity to the real-world and were expected to be different from it, although, the results did not support it. Thirdly, we predicted that the four viewing conditions would have different absolute errors with the end-effector and real-world conditions being the highest and lowest, respectively (H3). The results revealed the expected trend, the error increased as the visual fidelity of the self-avatar decreased, therefore the absolute error was the highest in the end-effector conditions was lower in the low-fidelity self-avatar condition, and lowest in self-avatar condition which supports the third hypotheses. The smallest absolute error was for the real-world condition. Additionally, the pattern of the absolute error from pre- to post-test stayed same in real-world and end-effector conditions however it differed from real-world in the two self-avatar viewing conditions. Further analysis is required to explore why such a pattern was observed.

6 Conclusion and Future Work

Previous work showed that the presence of a self-avatar affects users' behavior, their perception of the environment, and more specifically, their space perception in medium field IVEs [13, 25, 33, 38]. It is argued that a minimum level of self-avatar fidelity is required to change a users' perceptual judgments [25, 28] as well as a proper interaction with the virtual environment [9, 24]. However, it is not clear how much self-avatar's visual information is required for participants to improve their spatial perception in near-field.

Based on real-world studies, three different theories are suggested when estimating distance in order to properly scale ones' reach; First, the main visual contributor is the position of the end-effector/hand [31]. Our results showed that when calibrated to the end-effector only, participants perceived reachability to the presented target distance became similar to real-world condition although the error was higher than in the real-world. Additionally, distance estimation in end-effector condition had the highest dissimilarity and inaccuracy as compared to real-world. Therefore, depending on the application of the VR system, the existence of the end-effector could suffice where only the perceived reachability is critical. Second, it is discussed that the joint positions are crucial to create an accurate body map and consequently a better distance estimate [17, 30]. Therefore, the low-fidelity self-avatar condition tried to replicate the same condition in which only the joint positions are presented to the users in VR when estimating distance. We found that distance estimation improved as compared to end-effector condition but still was statistically worse than real-world. Third, it is shown that the presence of self-avatars improved distance estimation in virtual environment [25, 38]. Thus, we created a realistic, accurately scaled self-avatar to investigate this possibility in the near-field. We found that visuo-motor calibration to a realistic self-avatar improved near-field distance estimation as compared to the other two VR self-representations, but it still failed to reach to the same accuracy as the real-world. Therefore, depending on the near-field depth information needs of a VR application, VR developers could decide the level of the self-representation that could be utilized by users to recalibrate their near-field distance estimation and effectively perform fine motor tasks.

Future work will be directed on how anthropometric fidelity of self-avatars affects properties of physical reach motion, perceived reachability and action taken in near-field VR experiences.

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