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Elucidating Factors that Can Facilitate Veridical Spatial Perception in Immersive Virtual Environments

Abstract

Ensuring veridical spatial perception in immersive virtual environments (IVEs) is an important yet elusive goal. In this paper, we present the results of two experiments that seek further insight into this problem. In the first of these experiments, initially reported in Interrante, Ries, Lindquist, and Anderson (2007), we seek to disambiguate two alternative hypotheses that could explain our recent finding (Interrante, Anderson, and Ries, 2006a) that participants appear *not* to significantly underestimate egocentric distances in HMD-based IVEs, relative to in the real world, in the special case that they unambiguously know, through first-hand observation, that the presented virtual environment is a high-fidelity 3D model of their concurrently occupied real environment. Specifically, we seek to determine whether people are able to make similarly veridical judgments of egocentric distances in these matched real and virtual environments because (1) they are able to use metric information gleaned from their exposure to the real environment to *calibrate* their judgments of sizes and distances in the matched virtual environment, or because (2) their prior exposure to the real environment enabled them to achieve a heightened sense of *presence* in the matched virtual environment, which leads them to act on the visual stimulus provided through the HMD as if they were interpreting it as a computer-mediated view of an actual real environment, rather than just as a computer-generated picture, with all of the uncertainties that that would imply. In our second experiment, we seek to investigate the extent to which augmenting a virtual environment model with faithfully-modeled replicas of familiar objects might enhance people's ability to make accurate judgments of egocentric distances in that environment.

1 Introduction and Previous Work

Virtual environment technology enables information to be presented in the context of a user's natural, egocentric frame of reference. It therefore has great promise as an enabling technology in fields such as architecture and engineering where designers and others can benefit from experiencing virtual models first-hand at true scale. However, when considering the practical use of this

Presence, *Vol. 17, No. 2, April 2008,* 176–198

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technology, it is important to have a reliable understanding of the conditions under which, and the extent to which, a user is likely be able to actually achieve an accurate understanding of spatial relationships (i.e., size and distance) within a given virtual environment.

Numerous previous studies (e.g., Henry & Furness, 1993; Witmer & Kline, 1998; Gooch & Willemsen, 2002; Messing & Durgin, 2005; Bodenheimer et al., 2007) have assessed the accuracy of spatial perception in immersive virtual environments presented via head mounted display (HMD) systems, and nearly all have found that people appear to systematically underestimate egocentric distances in these environments. However, the complete set of factors influencing the accuracy of people's distance estimates in immersive virtual environments has yet to be clearly identified. Various studies have specifically investigated, and ruled out as the root cause of the distance underestimation phenomenon, numerous characteristics that differentiate virtual from real environments, including: limited field of view (Knapp & Loomis, 2004; Creem-Regehr, Willemsen, Gooch, & Thompson, 2005), not being able to see one's body (Creem-Regehr et al.), potential minor inaccuracies in the calibration of the stereo display (Willemsen, Gooch, Thompson, & Creem-Regehr, 2008), the quality of the computer graphics representation of the environment (Willemsen & Gooch, 2002; Thompson et al., 2004), and the blind walking methodology typically used to assess participants' judgments of target location (Sahm, Creem-Regehr, Thompson, & Willemsen, 2005). Loomis and Knapp (2003) provide an excellent early review of the extensive literature on this topic. More recently, Willemsen, Colton, Creem-Regehr, and Thompson (2004) have found a small effect of the ergonomics of wearing the HMD, but they conclude that this only explains a part of the underestimation observed. Also, Mohler, Creem-Regehr, and Thompson (2006) and Richardson and Waller (2005, 2007) have found that participants can readily achieve accurate performance when provided with various types of feedback, and some of this work supports the idea that it is *cognitive* rather than *perceptual* factors that are at the root of the problem.

Over the past several years, we have undertaken a series of experiments intended to elucidate the factors influencing people's judgment of egocentric distances in immersive virtual environments with the aim of gaining insight into potential methods for facilitating more accurate distance perception in these environments. Initially, we discovered that people seem to be able to make surprisingly accurate judgments about egocentric distances in an immersive virtual environment when the IVE represents a high-fidelity model of the same physical space that the user is actually occupying, and the user has been able to unambiguously verify this by viewing the real space prior to donning the display upon which the corresponding virtual environment is presented (Interrante, Anderson, & Ries, 2006a). However we have replicated these findings in situations where the IVE represents a high-fidelity model of a real space that the user is not currently occupying but has recently spent time in (Interrante, Anderson, & Ries, 2006b).

One possible interpretation of these intriguing results is that observers are better able to make accurate judgments of egocentric distance in an immersive virtual environment when they are able to become cognitively immersed, or *present*, in the IVE—that is, when they are able to accept the virtual environment as being equivalent to the real world and therefore to act on their visual input in the virtual world in the same way that they would in the real world. However, other interpretations are also possible: for example, it could be that when people are exposed to a virtual environment that exactly corresponds to a real environment that they have just seen, they are able to make accurate judgments of egocentric distances in that IVE because they were able to form a metrically accurate mental model of the spatial structure of the real environment upon their brief exposure to it, and when they are subsequently presented with the corresponding virtual environment they are able to calibrate their interpretation of sizes and distances in the visually presented IVE to be consistent with their remembered model of the real environment.

It is useful to be able to differentiate between these two hypotheses because each suggests a different strategy for attempting to facilitate accurate distance perception in an immersive virtual environment that is *not* a faithful replica of an actual existing environment,

which is our ultimate practical objective. For example, to the extent that it is a question of enhancing presence, we might want to consider providing users with a behaviorally-faithful representation of their body in the virtual environment (Slater, Usoh, & Steed, 1994), or augmenting the virtual environment with passive haptics, enabling users to physically interact with real objects that are also tracked and represented in the virtual environment (Lok, Naik, Whitton, & Brooks, 2003). To the extent that it is a question of providing reliable indicators of familiar size, we might work on enhancing the virtual environment with *entourage elements,* such as models of people, as architects often do to provide a sense of scale in their drawings. The immersive modeling software that we have developed for use in our design studio classes (Anderson, Esser, & Interrante, 2003) already includes this feature.

2 Our First Experiment

In order to disambiguate the presence hypothesis and the visual calibration hypothesis, we designed the following study. Using a mixed within- and between-subjects design, we asked observers to make judgments of egocentric distance in a real room and in one of three different virtual environment models, each of which was described, via written instructions, as representing a "high-fidelity virtual model of that same room." However, only one of the virtual models was actually an identical match in size to the real room. One third of the participants viewed a virtual model in which each of the walls had been surreptitiously moved 10% inward toward the center of the room (and the textures touched up in Photoshop to hide this change, without scaling anything), and another third viewed a virtual model in which each of the walls had been surreptitiously moved 10% outward from the center of the room (and the textures appropriately filled in to hide this change, without scaling anything). The explanation for this choice of experimental design is as follows. In our previous studies, we had anticipated, and noted, some subtle systematic individual differences in participants' distance estimations made using the blind walking metric, with some people walking a bit longer than average, and some walking a bit shorter than average, consistently across conditions—an observation that was also made, in the case of real-world blind walking, in a large retrospective study by Kuhl, Creem-Regehr, and Thompson (2006). Therefore we felt it important to design our current study so that each person could serve as his or her own control to the greatest extent possible. However, because we did not want to overtly inform participants about the room size manipulation, we could have each participant experience only one of the three virtual room models. In addition, we felt that it would be important to have participants always perform the trials in the virtual environment first, out of concern that extensive prior physical experience in the real room might increase the likelihood of their consciously noticing any size mismatch between the real and virtual rooms. In a previous study in which we specifically investigated the effects of presentation order in matched real and virtual room conditions, we had found no significant differences between the conditions in which participants made distance judgments in the real world first versus in the virtual world first (Interrante et al., 2006a). However, this does not preclude the possibility that order effects could occur in unmatched real and virtual room size conditions.

In sum, through this experiment we aim to see how participants' real-world and virtual-world distance judgments might be differently affected by subtle, covert manipulations in the size correspondence (smaller/same/larger) between real and virtual room models that they are led to believe correspond exactly. In light of our previous finding that participants appear to estimate distances with near-accuracy in our matched real and virtual room environments, if the visual calibration hypothesis holds, then we should expect to find that participants who see the *smaller* room will *overestimate* distances in the virtual environment relative to in the real room, and that participants who see the *larger* room will *underestimate* distances in the virtual environment relative to the real room. For example, if the real room is 30′ long, and the virtual room model is only 24′ long but participants interpret it as being 30′ long, then when they are asked to close their eyes and walk toward

a marker that is placed at a distance halfway down the virtual room model, we would expect them to walk 15′ in the direction of the marker, rather than 12′. Likewise, if the virtual room is 37.5′ long, but participants interpret it as being 30′ long (matching the size of the real room), then when they are asked to blind walk toward a marker that is placed halfway down the length of the virtual room model, we would expect them to walk only 15′ in the direction of the marker rather than the full extent of the marker's true distance, 18.75′. On the other hand, if the presence hypothesis holds, then we should expect that participants will judge distances with equivalent accuracy under all three virtual room conditions if the size manipulation is completely unperceived, or, that they will make similar errors in each of the manipulated conditions, to the extent that they might subjectively perceive the modified virtual room environments as being in some way unreliable representations of the real room.

Figure 1. *A photograph of the real room environment, illustrating a typical position of a participant at the start of a trial, and showing the arrangement by which the experimenter assisted with the management of the cables.*

2.1 Method

As in our previous experiments, we used blind walking (Rieser, Ashmead, Taylor, & Youngquist, 1990) to assess distance perception. Although some questions have been raised about potential problems with this metric (e.g., Philbeck, 2005), due to a lack of good alternatives it remains the most commonly-used metric for judgments of egocentric distances in virtual environments over intervals of less than 20 m. We used written instructions to enforce consistency in the presentation of information and instructions to participants across groups. All participants were informed that they would be taking part in one of a number of experiments being undertaken as part of a larger study whose purpose was to "compare space and distance perception in virtual environments with space and distance perception in the real world under various different display and interaction conditions." They were further informed that that they would be participating in the condition "virtual room, real room." Participants were *not* informed about the existence of different room models; on the contrary, each participant was *explicitly* told that the virtual room model that he or she would be seeing was an *exact replica* of the real room. Participants did not go through any training prior to testing and no feedback was made available to any participant about his or her performance at any time.

2.1.1 Apparatus. Testing took place in the Digital Design Lab located on the first floor of Walter Library on the University of Minnesota campus. This lab includes a fully tracked open space and a large, rear projected, curved screen display. The dimensions of the open space of the lab are 30′ long × 25′ wide in the center, tapering down to 16.5′ wide at the edges due to the curvature of the screen. Figure 1 shows a photograph of the real-world lab environment.

The virtual environment was presented using an nVisor SX head mounted display manufactured by nVis. This visor provides 1,280 × 1,024 resolution images to each eye with an ~60° diagonal monocular field of view (for an effective resolution of about 2.2 arc minutes of visual angle per pixel) and 100% stereo overlap. The head mounted display is connected via a 15′ cable to a video controller box stationed on a wheeled cart. This allows ample cord length to reach any point in the open space of the lab. We use a HiBall 3000 optical ceiling

tracker, manufactured by 3rd Tech, to obtain information about the position and orientation of the user at a rate of about 500 Hz. With this tracker, and our real-time rendering software, which was run on a PC with a 2.83 GHz Intel Xeon processor with 2.0 Gb of RAM and a Quadro 4900 XGL graphics card, we were able to present our simple virtual room model to our participants with minimal latency.

The original high-fidelity virtual model of our real room environment was geometrically defined to be an exact match, in which each of the surfaces (floor, ceiling, and walls) was texture mapped with a mosaic of high resolution photographs obtained from the real room. There was a small amount of furniture in the real lab, such as chairs, computers, and computer desks, but these were not included in the virtual model. For this experiment, we constructed smaller and larger versions of the original virtual room model by applying an $\sim\pm 20\%$ nonuniform scaling to the original model in the horizontal plane about the center of the room. Specifically, the scaling factors for the smaller and larger rooms were defined so that the ratio of the length of the longest wall in the smaller room to the length of the longest wall in the default room would be the same as the ratio of the length of the longest wall in the default room to the length of the longest wall in the larger room. This had the effect of moving each of the walls in by exactly 2.4′ toward the center in the case of the smaller room model, and out by exactly 3.0′ from the center in the case of the larger room model, without changing the height of the room. We felt that it was important to leave the vertical extent of the rooms unchanged between conditions because of the potential complications that could be introduced if participants adopted a different understanding of their eye height in the different conditions as a result of the ceiling seeming closer or farther away from them in the virtual model than in the real space.

To accommodate the smaller or larger extents of visible floor, wall, and ceiling surfaces in the modified room models, we had to define new textures for these surfaces, based on the textures used in the original. To create these new textures, we did not use any rescaling. Instead, for the wall surfaces, we took the prominent features, such as the doors and panels, reflected highlights, and so on, and uniformly repositioned them, adding or subtracting white space using Photoshop's clone tool and touching up the result to hide any seams. For the ceiling surface we added or subtracted panels, taking care to maintain consistency between the locations of the light fixtures and the locations of the reflected highlights on the walls, and for the floor surface we simply extended or truncated the default repeating texture pattern. Figures 2–4 show screenshots of each of the three different virtual room models taken from approximately the same position, representing a typical starting location at the beginning of a trial. From these images, it is clear that only the spacing of the prominent features was adjusted, while their size and general relative layout remained fixed.

Figure 2. *An image of the smaller virtual lab model, in which each of the walls was moved 10% inward toward the center of the room.*

The black electrical outlet floor plates that can be seen in Figure 1 were omitted from all three of the virtual models in this experiment. This is a change from the situation in our previous experiments, in which the matching virtual room model included the floor plates. We felt that in this experiment the floor plates needed to be removed because there was simply no good way to incorporate them into the resized virtual models. Because the floor plates are occasionally stepped on during

Figure 3. *An image of the original (same sized) virtual lab model.*

Figure 4. *An image of the larger virtual lab model, in which each of the walls was moved 10% outward from the center of the room.*

the trials (though we try to set things up to minimize this occurrence), we felt that it could be misleading to explicitly display them at positions in the virtual models that were offset from their actual positions in the real world. However, since the participants focus intently on the floor when making their distance judgments, we felt that if we were to leave the floor plates in their original positions relative to the center of the room in the resized room models, we would risk introducing an obvious indication of a change in the wall positions between the real and virtual scenes, as the walls would begin to overlap the plates in the case of the smaller room model.

2.1.2 Participants. We recruited 23 participants for this study. None of these people had participated in any of our earlier experiments and all were naïve to the hypotheses underlying the current study. Nine of our participants were undergraduate students from various departments at the University who were recruited through a filmmaking/special effects interest group on campus; the remaining fourteen were undergraduate students and teaching assistants from the Department of Architecture, recruited from a large design studio class. Participants' ages ranged from about 20 to 30, and they included 16 males and 7 females. Nine of the students experienced the smaller lab model, nine experienced the larger lab model, and five experienced the accurate (same sized) lab model, as a control and to verify consistency with our previous findings. Although we had initially planned to recruit participants only for the different-sized room conditions, and to rely on the results from our previous findings with the same-sized room model for comparison, we ultimately decided that it would be prudent to run additional, new participants in the same-sized room condition, in order to explicitly control for any possibility of effects due to any subtle differences in methodology between our current and prior experiments, such as the elimination of the floor plates or the recalibration of our tracking system subsequent to its reinstallation in the room after having been moved to a different location for an intervening experiment. Each participant was given a $10 gift certificate in compensation for his or her efforts.

2.1.3 Procedure. All participants began by entering the lab and sitting down at a desk to read the written instructions and sign the consent form. After this, they were given verbal instructions about how to put on and adjust the head mounted display for optimal viewing. They were then guided to the edge of the room, where they put on the head mounted display and

a small portable radio with headphones, which played static noise intended to drown out any subtle auditory cues that participants might acquire from the physical lab environment. Participants viewed the virtual model from a stationary position with an example target location displayed while the procedure for the blind walking task was described to them again, verbally. After this, they began the experiment.

We had each person perform 20 trials of blind walking in the virtual environment, followed by 10 trials of blind walking in the real world. The number of trials was chosen so that the amount of time participants spent in each condition would be approximately equal. Participants were allowed to reacclimate to the real world before testing by taking a short break between the virtual- and real-world trials. Each trial consisted of a direct blind walk from the participant's current location to a target "tape" mark positioned at a randomly determined distance 8–25 feet away from the participant along his or her direction of view. We used a boundary condition to ensure that all of the target locations generated by the random process were displaced by at least 2 m from both the virtual and real walls in all conditions. All procedures were conducted identically, regardless of which room model the participant experienced.

Two people were involved in running the experiment. During the virtual-world trials, one person (the operator) ran the keyboard controls at the computer, while the other person (the assistant) managed the cables for the participant, both keeping them out of his or her way and relieving any backwards tugging on the headset due to their weight. To simulate a blindfold in the virtual environment, the images to the head mounted display were cleared to black while the participant was walking. For timing purposes the participants announced when they were ready to close their eyes and begin walking and at that signal the display was blacked out by the operator. When the participant felt he or she had reached the target tape's location, he or she stopped walking and announced that he or she was done, and the operator used this as the signal to record the ending position. To prevent the participant from gaining any insight into the accuracy of his or her performance, the assistant then gave verbal commands to walk in a circuitous route to a different location while the subject kept his or her eyes shut and the display remained turned off. Because the tape marks were placed virtually, the assistant managing the cables was generally unaware of their corresponding location in the real room, and it is highly unlikely that the assistant would be able to subconsciously influence the participant to walk shorter or longer on any trial.

Distance interval endpoints in the real-world trials were indicated by two thin strips of cloth, sewn to pieces of Velcro, which were applied to the floor at random locations by one of the experimenters just before the beginning of each trial, and out of sight of the participant. Participants began each trial by lining up with one of these "tape" marks, taking visual aim at the other, then putting on a blindfold, closing their eyes, and walking. When the participant reached the estimated target location, the two experimenters used a tape measure to record the distance of the walk and the distance between the cloth markers. The participant was then verbally instructed to move to a different starting location while remaining blindfolded, and the strips were repositioned for the next trial.

Upon completion of all walking trials, the participants were seated once more and asked to fill out a two-page questionnaire regarding their experience. Although it has been shown that questionnaires are generally not a reliable tool for determining the extent to which a person feels "present" in a virtual environment (Slater, 2004), our primary intent was to use the questionnaire not so much to assess presence as to provide a device for encouraging participants to let us know if they noticed anything not right about the virtual environment. On the first page, participants were asked to provide ratings, on a scale from 1 to 7, about various aspects of their experience in the virtual environment. On the second page they were asked to provide an open-ended response to the following question: "Please describe in detail each of the characteristics of the presented virtual environment, or your experience in it, that felt unnatural or that you think might have detracted from your ability to function in the virtual environment in the same way that you would have functioned in the real

world. We appreciate all of the insights that you can offer."

2.2 Results

Because of an error in the data recording, which we discovered only upon subsequent detailed analysis of the individual starting and stopping points for each trial, a small, randomly affected portion of the data under each of the three room conditions had to be discarded as unreliable.[1] The next figures in this section illustrate the remaining, corrected data from this experiment. Figures 5–7 show scatter plots of each of the individual distance judgments made by each of the participants in each of the three room size conditions.

Figures 8–10 show individual point plots of the average relative errors in distance judgments made by each participant in the real versus virtual environments under the three different room size conditions. For comparison purposes, Figure 8 also shows data from the five participants in our previous experiment (Interrante et al., 2006a) who performed the identical task under the matched size condition.[2] Points are rendered as solid when the difference between a participant's performance in the real and virtual worlds was found to be strongly statistically significant ($p < .01$) and rendered with a small white dot in the center when the difference was significant with $p < .05$. Points are rendered as hollow (with a large white dot in the center) when the difference between a participant's performance in the real and virtual environments was *not* significant ($p \geq .1$). There were no points in the range $.05 < p < .1$.

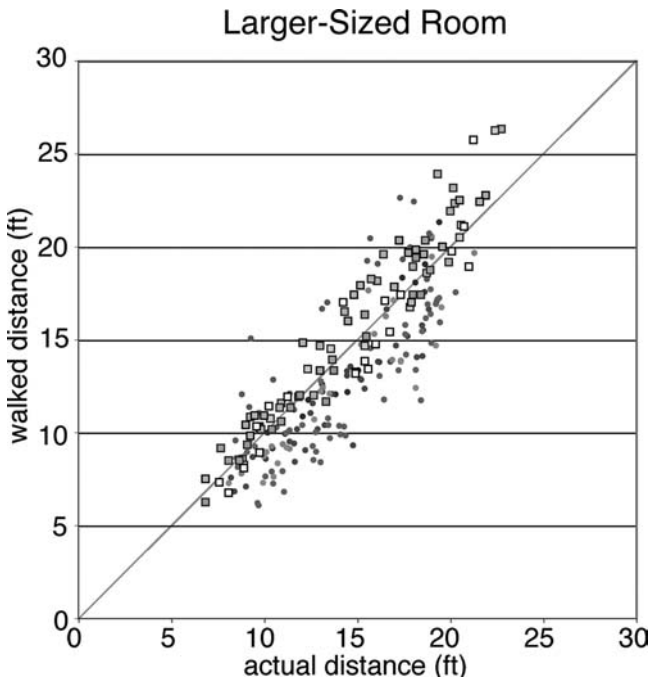

Figure 5. *A scatter plot showing all distance judgments made by the nine participants who viewed the larger virtual room, color coded by participant ID. Squares indicate judgments made in the real world; circles represent judgments made in the virtual world.*

We can see that, as in our previous experiments, most participants who experienced the same-sized virtual room model judged distances with nearly similar accuracy in both the real and virtual environments. However, in Figures 9 and 10, we can see that most of the participants who experienced the smaller and larger room models *underestimated* distances, on average, to a greater extent in the virtual world than in the real world. To quantify and verify these observations, we performed a statistical analysis on the effect of technology (trials done in the real world vs. trials done in the virtual world) on the magnitude of the average relative errors observed in each of the differently sized room conditions. In the case of the same-sized room data, pooling the data from the ten total participants who experienced this condition in our current and previous experiments, we found no significant main effect of

[1] In order to avoid asking participants to walk to a target that was too close to any wall in any of the virtual room models, we automatically clamped the 8–25′ distance of the randomly determined displayed target location to a shorter length if it was within 2m of the closest edge of the largest rectangle that could be inscribed within the boundaries of the smallest virtual room model. However, the target distance used in the data analysis was inadvertently recorded as the original (unclamped) value. Approximately one third of the trials were clamped. In ~30% of these cases, or slightly less than one ninth of the total, we were not able to unambiguously reconstruct the correct value of the difference between the target distance and the participant's walked distance; those trials were the ones discarded.

[2] Our previous experiments didn't use clamping and therefore didn't suffer from the clamping error; in those experiments we manually rejected the target tape marks that fell too close to any wall.

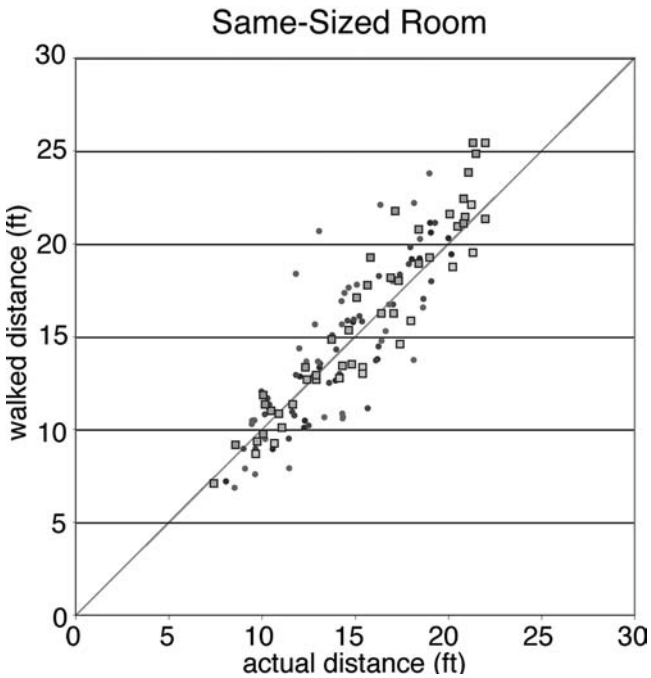

Figure 6. *A scatter plot showing all distance judgments made by the five participants in our current experiment who viewed the same-size virtual room. Squares indicate judgments made in the real world; circles represent judgments made in the virtual world.*

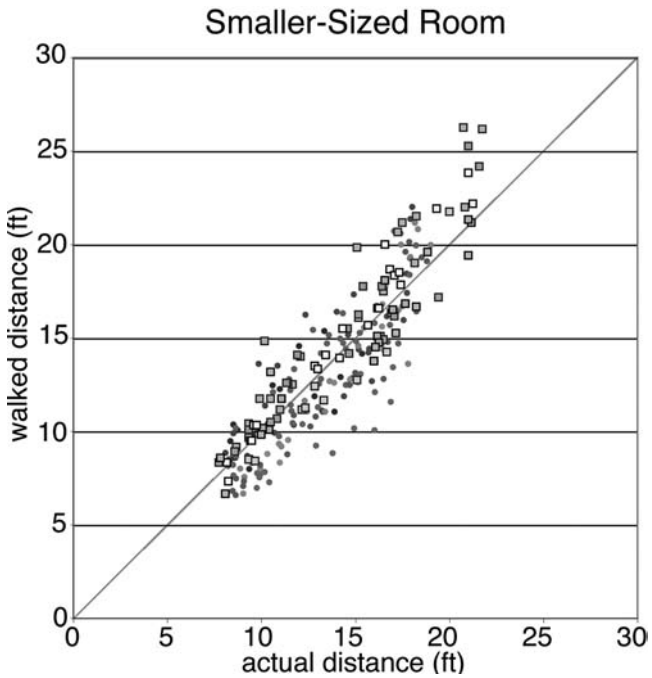

Figure 7. *A scatter plot showing all distance judgments made by the nine participants who viewed the smaller virtual room, color coded by participant ID. Squares indicate judgments made in the real world; circles represent judgments made in the virtual world.*

technology (real world vs. virtual world) on errors in distance judgments {$F(1,18) = 0.6137$, $p = .444$}. Looking only at the data from the five participants in our present study, the result is basically the same {$F(1,6) = 0.2285$, $p = .646$}. However, in the case of the larger-sized room, we did find a significant main effect of technology {$F(1,16) = 7.33$, $p = .0155$}. We likewise found a marginally significant main effect of technology in the case of the smaller sized room {$F(1,16) = 4.001$, $p = .0627$}.

Of course, the fact of our finding no significant effect of technology in the case of the same-sized real and virtual rooms is *not equivalent* to finding that distance estimation accuracy is the *same* in these two cases, since one cannot use this type of analysis to prove the null hypothesis. Nevertheless, the fact that we see that distances tend to be underestimated in the virtual environment relative to in the real environment when the virtual and real rooms are *differently sized* and *not* when they are the *same* size suggests a significant effect of the room size manipulation. To verify this, we ran an additional statistical test to directly determine whether there was a significant effect of the room size manipulation condition on the magnitude of the difference between the average relative errors that participants make in the virtual room relative to the real room. In that analysis, we found a significant main effect of the room size condition {$F(2,25) = 3.85$, $p = .0349$}. Running a Tukey HSD test on the pairwise differences between errors in the three room conditions, we found that the underestimation of distances in the virtual world relative to the real world was significantly greater ($p < .05$) in the larger virtual room condition than in the same-sized virtual room condition, and marginally significantly greater ($p < .1$) in the smaller virtual room condition than in the same-sized virtual room condition. Figure 11 shows the average overall relative errors in distance underestimation found in the three virtual world condi-

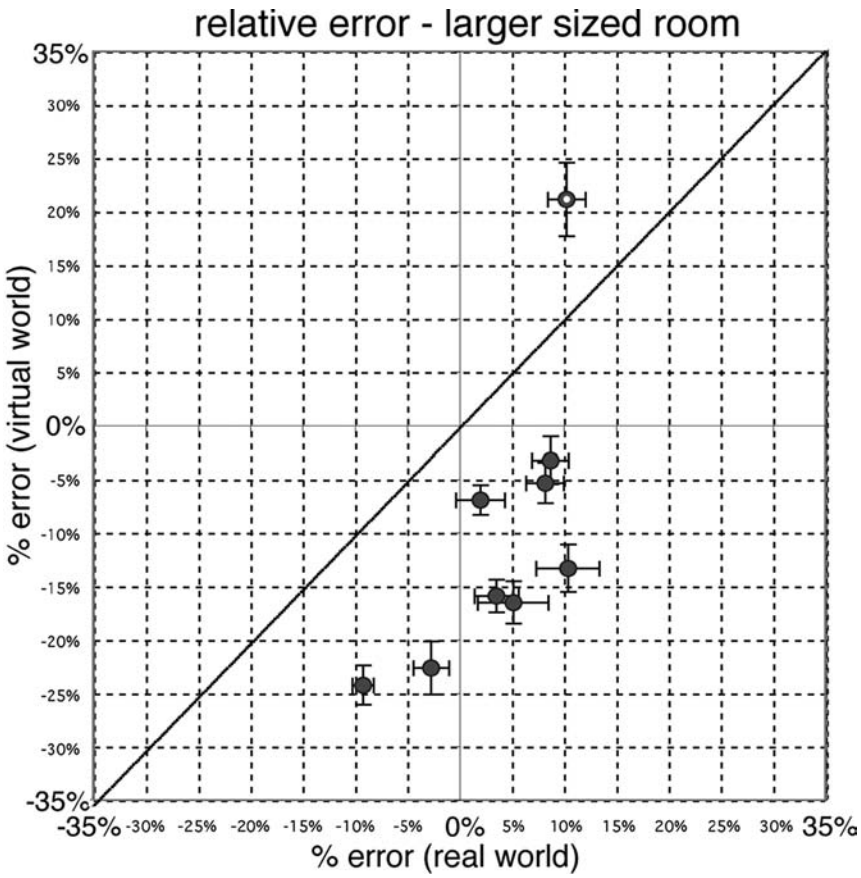

Figure 8. *A point plot showing the average relative error in distance judgments made in the real and virtual environments by participants experiencing the larger-size virtual room condition. Points with small white centers represent differences significant at $p < .05$; solid points represent differences significant at $p < .01$.*

tions, and in the real world trials subsequent to each virtual world experience.

In further analysis of the data, we found that participants systematically tended to walk longer (becoming more accurate) in successive trials in each of the virtual room conditions, a finding that is consistent with the concerns about recalibration during blind walking raised by Philbeck (2005). This trend reached statistical significance ($p = .0040738$) in the smaller virtual room environment and approached significance ($p = .05519$) in the larger virtual room environment, but was not significant ($p = .13924$) in the same-sized virtual room. We also found that participants who experienced the larger virtual room environment (only), when subsequently asked to estimate distances in the real room environment, tended to systematically walk shorter (also becoming more accurate) in successive trials in the real room ($p = .0066177$). Figures 12 and 13 show the relative errors, (target_dist – walked_dist) / (target_dist), in participants' distance judgments separately averaged by trial number over all of the participants in each condition; trend lines showing the best linear fit to the average data are superimposed where the trend was significant at $p < .05$.

Unfortunately, we were not able to gain much useful information from participants' responses to the questions on our presence questionnaire, as the (between-subject) responses were generally similar across all three

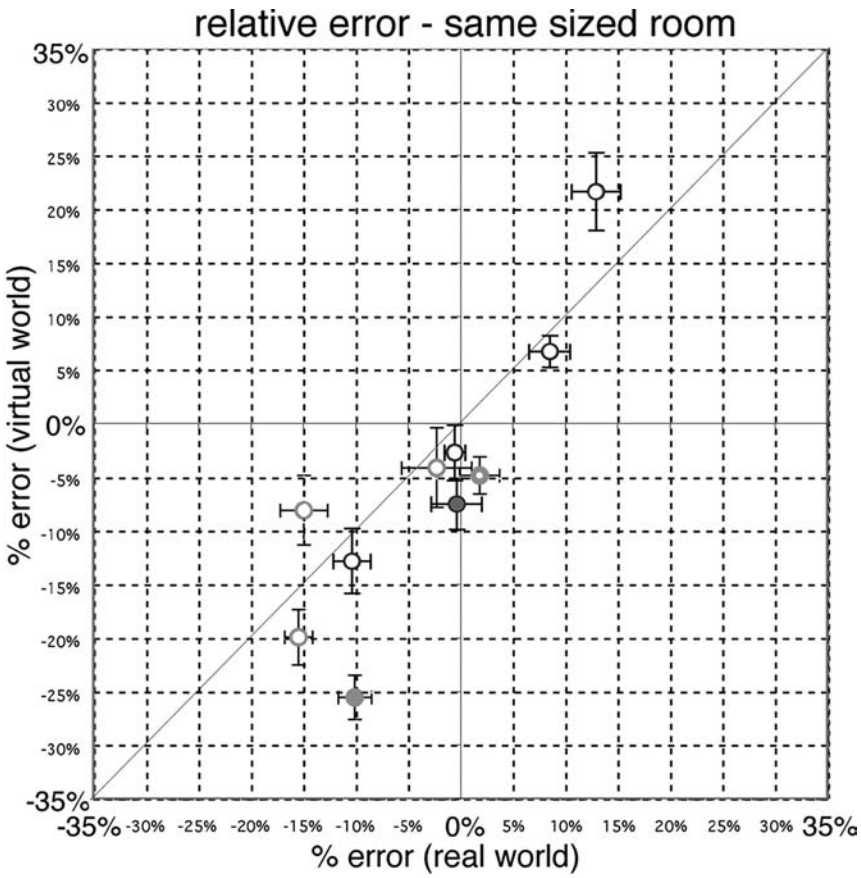

Figure 9. *A point plot showing the average relative error in distance judgments made in the real vs. virtual environments by participants experiencing the same-size virtual room condition. Data from the current participant cohort is shown in dark gray; data from our previous participant cohort is shown in light gray. When the point has a large white center, the difference in error between conditions is not significant; points with small white centers represent differences significant at $p < .05$; solid points represent differences significant at $p < .01$.*

virtual room conditions. The only significant differences we found were in the responses to questions 1 and 2 in the cases of the smaller versus same-sized environments. Question 1 asked "How 'real' did the depicted virtual environment *look* to you, while you were in it, on average?" and question 2 asked "How 'real' did the depicted virtual environment *feel* to you, while you were in it, on average?" The mean response to these questions from the 9 participants who experienced the smaller room was slightly lower than the mean response from the five participants who experienced the same-sized room in this experiment. The other questions asked were:

3. "How comfortable did you feel in the presented virtual environment?"
4. "To what extent did you feel that your ability to perform actions in the presented virtual room resembled your ability to perform these same actions in the corresponding real room?"
5. "To what extent, on average, did you feel as if you were actually physically present in the environment

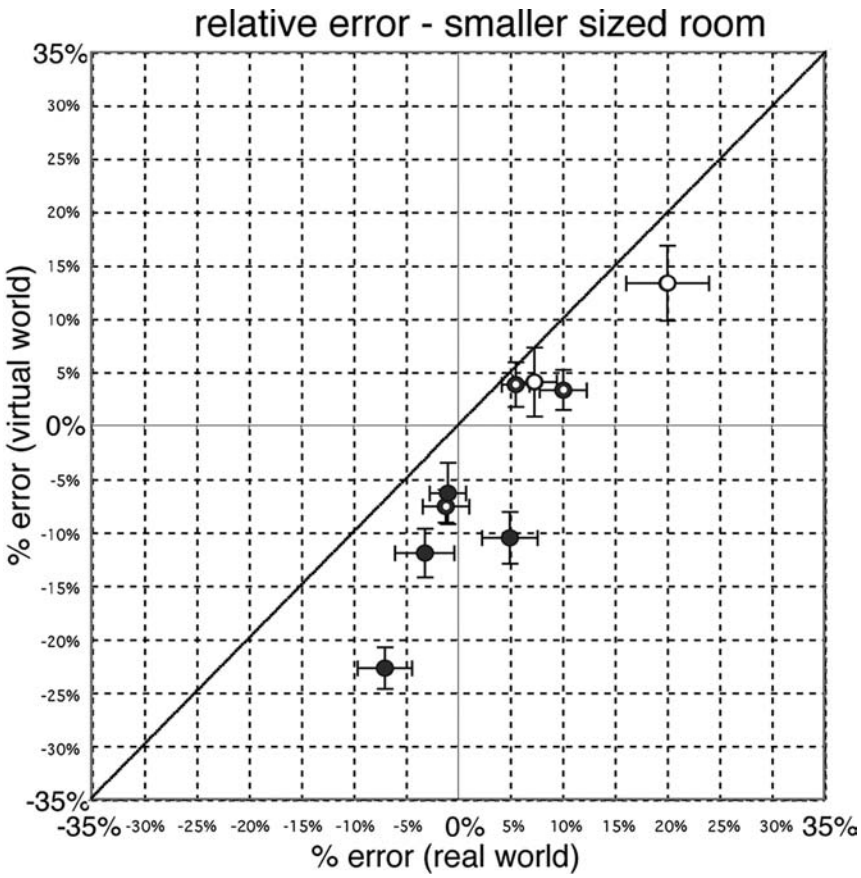

Figure 10. *A point plot showing the average relative error in distance judgments made in the real and virtual environments by participants experiencing the smaller-size virtual room condition. When the point has a large white center, the difference in error between conditions is not significant; points with small white centers represent differences significant at $p < .05$; solid points represent differences significant at $p < .01$.*

depicted by the head mounted display, over the course of the experiment?"

6. "To what extent/how often did you think about the fact that the room presented via the head mounted display represented the same physical space as the room you were actually in?"
7. "To what extent/how often did you feel as if the room presented via the head mounted display didn't 'feel the same' as the room you were actually in?"

Figure 14 shows a bar graph of the questionnaire results.

In their responses to the final, open-ended question, only 2 of the 23 participants mentioned anything about the size of the room seeming "off." One participant in the larger room condition remarked that "the virtual room was empty which makes it feel somewhat bigger"; however, another participant in this same condition wrote that "the room looked smaller, and it looked like the ground was closer than normal." In addition, one person in the smaller room condition remarked that she "somehow felt taller with the virtual reality," which is consistent with an underestimation of distances. However, to the major-

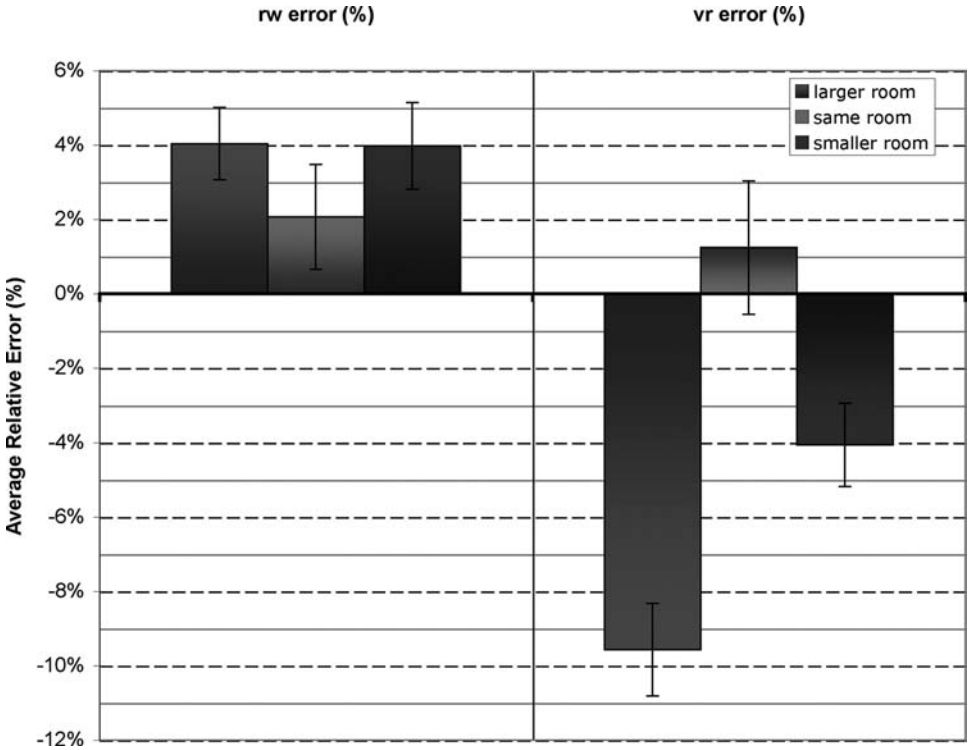

Figure 11. *A chart showing the average relative errors in distance judgments made by participants in each of the virtual room conditions, and in the real world. The error bars represent the 95% confidence intervals about the mean in each case, computed over all trials for all participants.*

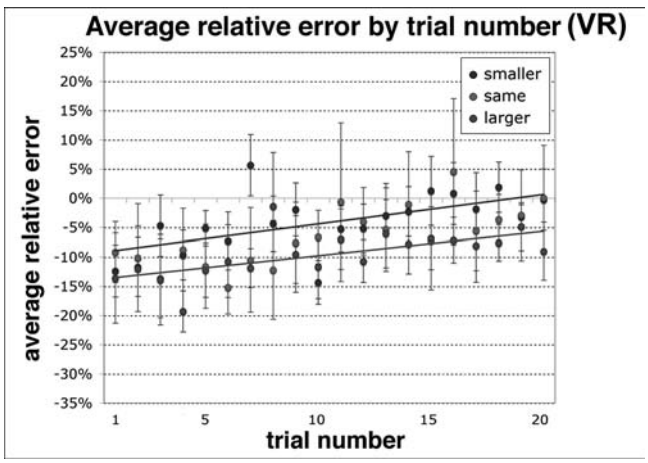

Figure 12. *The average relative errors in participants' distance estimates by trial number in each of the three different virtual room conditions. Only two trendlines are shown because the pattern of increasing accuracy over time is only significant for the smaller and larger virtual room environments.*

ity of participants, it seemed to appear as if the virtual and real rooms were perceived to be good matches, in terms of size. One participant in the larger room condition wrote that he was "amazed by the head mounted display and how realistic in proportion and scale it was." Similarly, a participant in the smaller room condition wrote that "the dimensions felt very similar to the actual room, which helped me in the virtual simulation because I had already seen the real room." Nearly all of the participants commented on various other factors related to the difference between the virtual- and real-world experience but unrelated to the perception of size differences. These factors included, in rough order of frequency: the more limited field of view in the head mounted display; noticing a latency in the display, especially when they swung their head around; being disturbed by the inability to see their feet; not being able to see the fur-

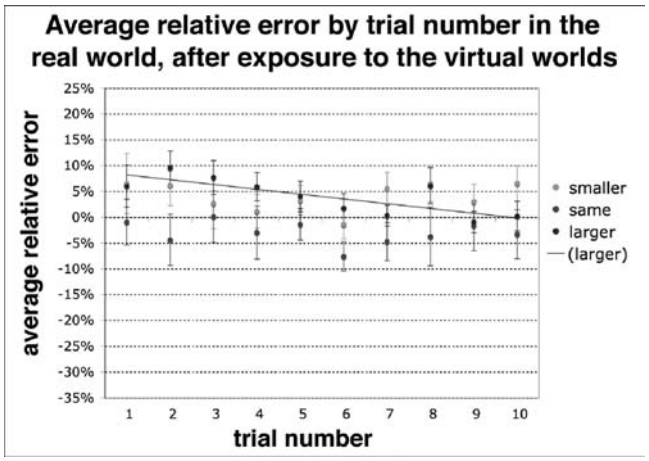

Figure 13. *The average relative errors in participants' distance estimates by trial number in the real world, after exposure to one of the three virtual environment room conditions. Only one trendline is shown because a significant relationship between walk number and relative error exists only in the case that participants experienced the larger virtual room environment before performing the subsequent real-world trials.*

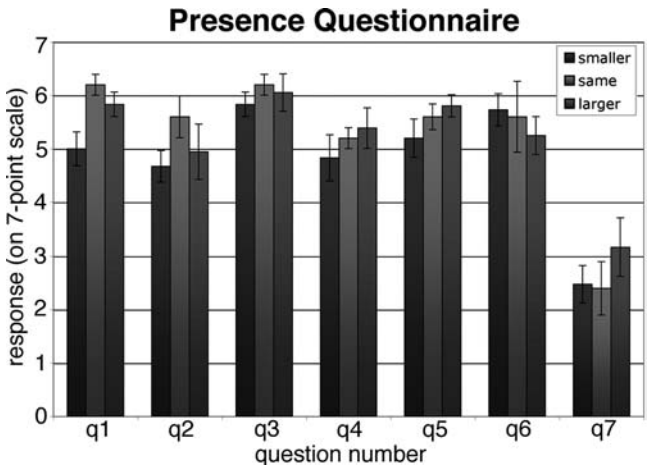

Figure 14. *Presence questionnaire responses, averaged over all participants in each of the different room conditions. The error bars show the 95% confidence intervals of the means in each case.*

niture in the virtual environment, which for one person induced a concern about walking into unseen objects; being able to feel the floor sockets in the real room but not to see them in the virtual room; perceiving a "fuzziness" in the image presented by the HMD; being "distracted by the weight of the head mounted display and the way the screen moved (a little shakey/wobbley)"; the virtual environment seeming brighter; everything looking "too perfectly crisp" in the HMD; and noticing that the moldings around the door were not being modeled in 3D. Of note, one person in the larger room condition wrote: "I feel that the environment of virtual reality has very much difference from reality, and this makes me feel unsecured to walk freely." Clearly, different participants are apt to respond somewhat differently to the experience of being in a virtual environment. That's one of the reasons we take care to individually visualize each participant's data, as well as to visualize the pooled data, so that we can be clearly aware of any effect that outliers may be having on our results.

2.3 Discussion

Overall, the "visual calibration" hypothesis does not seem to be very well supported by the results of this experiment. If participants had been using metric information gleaned from their exposure to the real room to calibrate their interpretation of sizes and distances in the virtual room, we would have expected to see *opposite* effects on distance judgment errors as a result of presenting them with a surreptitiously larger versus smaller virtual room model. Instead, we found that distance perception accuracy was diminished in the *same way* (towards an underestimation of distances) in each of these size-mismatched cases. However, our results can only be generously interpreted as being partially consistent with the presence hypothesis. If participants who experienced the smaller and larger virtual room environments did not notice the difference in size between the virtual and real environments, the presence hypothesis would have predicted that their distance judgments would have been equivalently accurate in all three (smaller, same, and larger) virtual environments. It is only if they *were* to some extent aware that something about the sizes of the presented environments was off that we would expect their default level of presence to decrease in the size-mismatched virtual environments

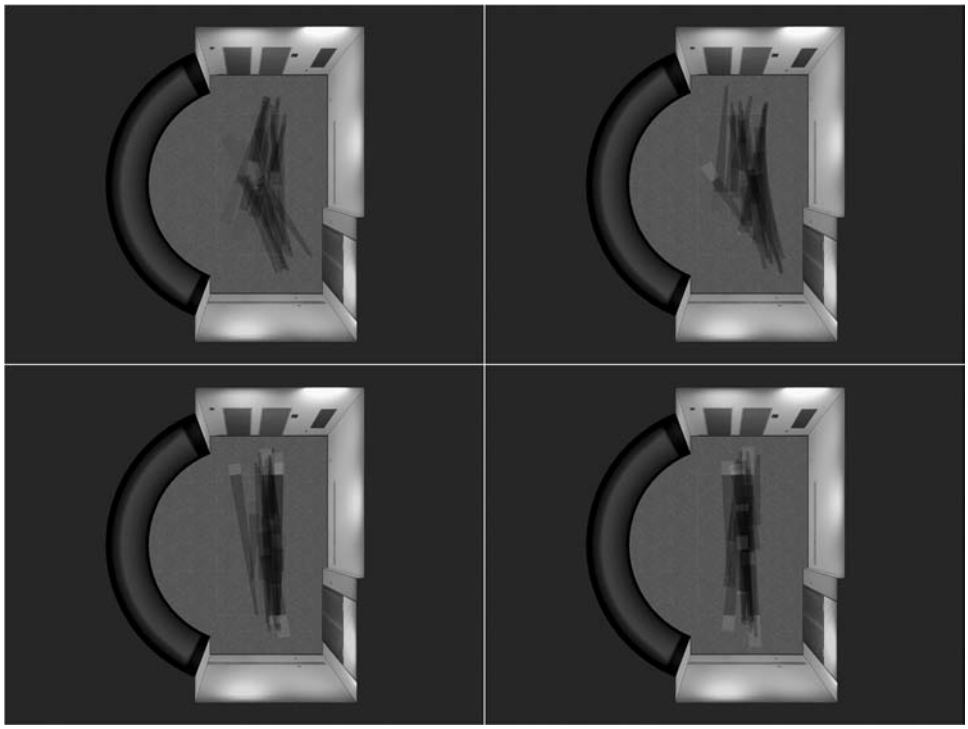

Figure 15. *An illustration of the paths walked by three representative participants for each trial in the smaller virtual room condition, color coded according to the accuracy of their distance estimate. Paths ending in red (dark gray) show the amount of shortfall as the red portion; paths ending in green (light gray) show the amount of overestimation as the green portion. The direction of the path is shown by increasing width. Where distance underestimation errors occurred, they did not appear to be caused by a fear of walking into a wall; on the contrary, errors of overestimation seemed to appear more often when targets were close to a wall than when they were not.*

relative to the size-matched virtual environment, causing the errors in those cases to be greater, which would be consistent with the results found. In that case, the greater errors found in the case of the larger room would be explained by its greater absolute size difference from the size of the actual room. However, this is not the only possible explanation.

To gain further insight into the nature of the errors made by each participant in each environment, we developed an application that enabled us to visualize the participant's starting position on each trial and the location of the target to which he or she was asked to walk, as well as the distance actually walked. Figures 15–17 show the results of this visualization. The red (dark gray) and black arrows correspond to trials in which the participant walked short of the target; the total length of the arrow corresponds to the length of the presented interval and the amount of red indicates the amount of underestimation. The green (light gray) and black arrows correspond to trials in which the participant walked beyond the target; the black portion of the arrow shows the length of the presented interval and the additional green portion indicates the amount of overestimation. The first thing we notice is that because we held the range of requested path lengths consistent across all three room size conditions, the traversed intervals tended to span more of the available floor space in the smaller virtual room model than in the larger virtual room model. This means that targets presented in the smaller room environment were more likely to be

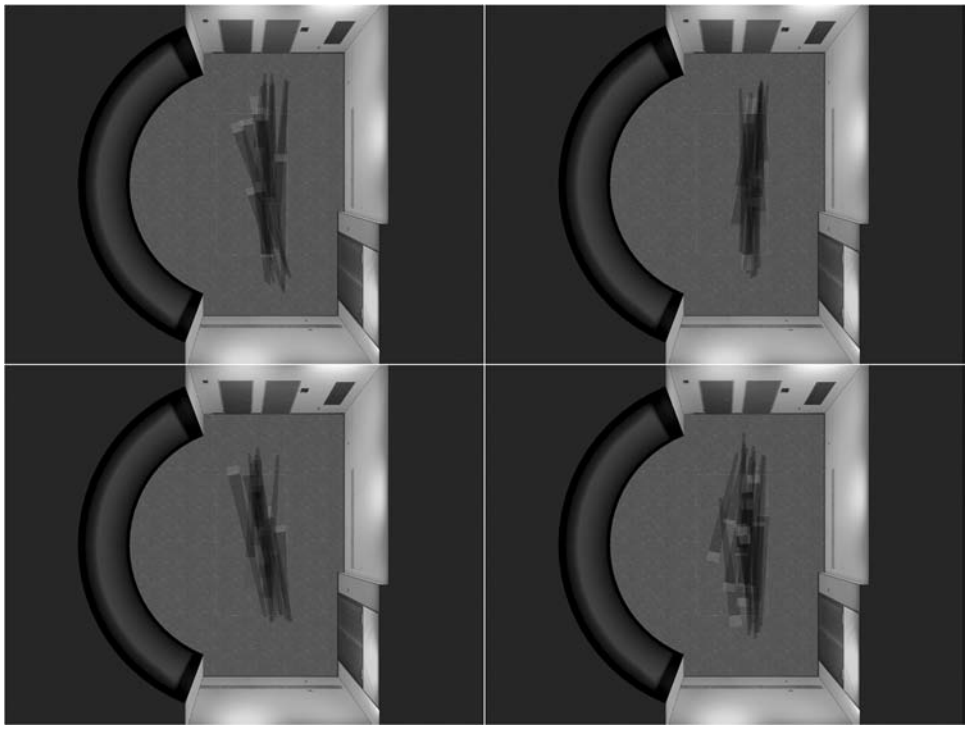

Figure 16. *An illustration of the paths walked by three representative participants for each trial in the same sized virtual room condition, color coded according to the accuracy of their distance estimate. Paths ending in red (dark gray) show the amount of shortfall as the red portion; paths ending in green (light gray) show the amount of overestimation as the green portion. The direction of the path is shown by increasing width. Most participants estimated distances with equivalent accuracy, overall, in the virtual environment, relative to in the real world, in this condition. When they occurred, errors of underestimation appeared to be more common for targets located closer to the center of the room than for targets located near a wall.*

near a wall than were targets in the larger room. If a participant's estimate of the location of the target marking the endpoint of the path to be traversed is not only based on an egocentric estimate of the distance to the target but is also affected by the relative distance between the target and the opposing wall of the room, as suggested by Witt, Stefanucci, Riener, and Proffitt (2007), this could lead to systematic differences in the errors observed between the room conditions. In addition, it has sometimes been suggested that participants' tendency to walk short in an unfamiliar virtual environment might be provoked by fear of walking into a wall. However, informal observation of the current data does not support this interpretation. If anything, the visualization suggests that underestimation errors may be more likely to occur on paths that end closer to the middle of the room. This insight led to the design of our follow-on experiment.

3 Our Second Experiment

Our second experiment aimed to directly test the hypothesis that by populating a virtual environment with landmark objects that have the potential to provide reliable cues to familiar size, we might enhance participants' ability to make accurate judgments of egocentric distances in the virtual world. The use of these entou-

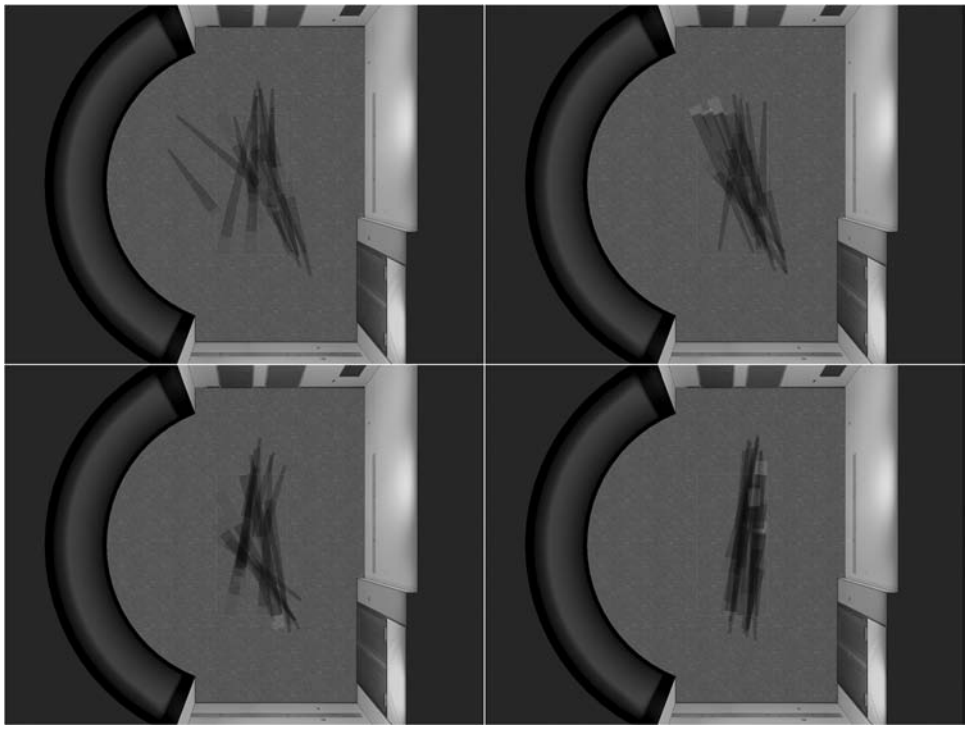

Figure 17. *An illustration of the paths walked by four representative participants for each trial in the larger virtual room condition, color coded according to the accuracy of their distance estimate. Paths ending in red (dark gray) show the amount of shortfall as the red portion; paths ending in green (light gray) show the amount of overestimation as the green portion. The direction of the path is shown by increasing width. Most participants consistently underestimated distances on all trials, but there were some trials in which distance was overestimated. To the extent that they occurred, overestimation errors appeared to be more common on the longer than on the shorter paths.*

rage elements is a standard technique employed in architectural practice to help viewers to assume an appropriate interpretation of scale in drawings. In particular, we chose to examine the effect of augmenting our larger virtual room environment with faithfully-sized models of tables, chairs, and computer monitors. If participants' tendency to walk short in this larger room environment was affected by the relative preponderance of trials in which there was a relative lack of good landmark cues from familiar-sized objects near the target, we would expect to see a lower incidence of distance underestimation errors in the furniture-augmented larger virtual room environment, relative to in the real environment, than in the corresponding furniture-less condition.

3.1 Method

We used the same basic methodology in our second experiment as in our first. Participants were informed that the goal of the experiment was to "compare space and distance perception in virtual environments with space and distance perception in the real world under various different display and interaction conditions." They were explicitly *not* informed about there being any size differences between the real and virtual rooms. On the contrary, they were led to believe that the virtual reality representation of our lab was as close to an exact replica as we could achieve. Participants did not go through any training and care was taken to pre-

Figure 18. *Left: the larger virtual room environment augmented with faithfully-sized models of familiar objects; right: photographs of the corresponding real room environment.*

vent any participant from getting any feedback about his or her performance at any time during the experiment.

3.1.1 Apparatus. We used the same location and equipment for our second experiment as our first. However, in this experiment we augmented our larger virtual room environment with faithfully-sized replicas of the chairs, tables, and computer equipment that were found in the actual room. We obtained the computer and Aeron chair models from Google SketchUp's 3D Warehouse and modeled the tables using measurements from the tables in our lab. The chairs were diffusely rendered using a dark gray color and lit from above, the computer monitors were texture-mapped with a screen shot of the desktop of a machine in our lab, and the tabletops were texture mapped using photographs of the actual tables in our room. Soft shadows from the tables and chairs were baked into the texture map used for the floor. Figure 18 shows images derived from screen shots of our furniture-enhanced larger virtual room environment alongside photographs of the corresponding areas of our actual room. Note that the camera parameters are not matched between the photograph and the rendering. Nevertheless it is possible to get a general sense of what participants saw in each of the two environments. Not pictured are a second chair, located to the left side of the large curved screen display, and a third table, chair, and computer located along the wall adjacent to the screen at its leftmost end.

3.1.2 Participants. We recruited 10 new participants (3 female, 7 male) for this second study from passersby in front of the building housing our lab. All were undergraduate students at the University of Minnesota and each was compensated with a $10 gift certificate for his or her time.

3.1.3 Procedure. The procedures followed for the second study were identical to those of the first. After entering our lab and signing the consent form, participants were asked to put on a radio playing noise to block out audio cues and to perform 20 trials of blind walking to targets randomly placed in the furniture-enhanced larger virtual room environment, followed by 10 trials of blind walking to targets arbitrarily placed in the actual room. Each trial in the virtual room consisted of a direct blind walk from the participant's current location to a virtual tape mark placed at a randomly determined location 8–25′ away from them along their direction of view. Although the major pieces of furniture in the real room were also represented in the virtual room, because of the size mismatch between the two environments, the locations of these objects were not precisely aligned. Therefore participants were not allowed to touch any of the furniture and care also had to be taken to avoid placing a target too close to any furniture object. As in our first experiment, the head mounted display was cleared to black while the participant was walking with his or her eyes closed and was not turned on again until the trial had ended and the participant had been led in a circuitous path to a new starting location. Target locations in the virtual environment were clamped away from the walls of the room using the same rules applied in Experiment 1. The participant did not wear the HMD in the real-world trials; distance intervals were indicated with physical markers, and presented and walked distances in those trials were recorded using a measuring tape. Unlike in our first study, however, participants in our second study were not asked to complete a questionnaire about their experience.

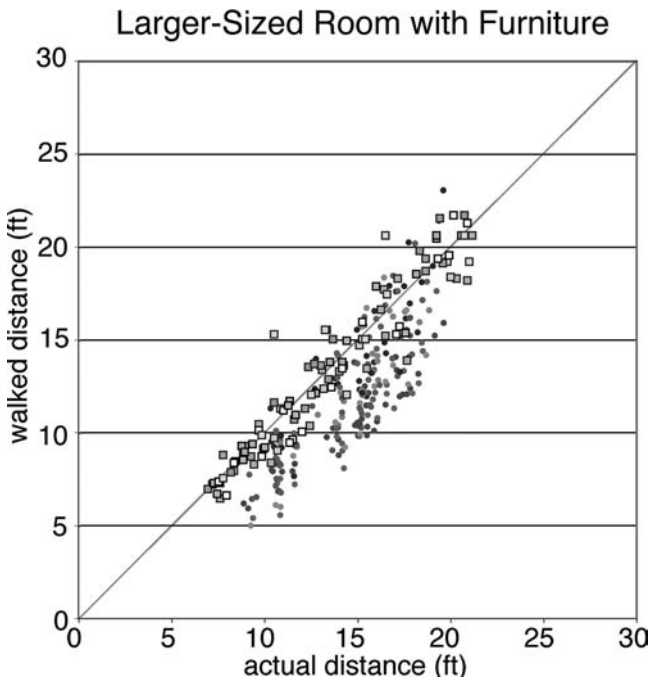

Figure 19. *A scatter plot showing all distance judgments made by the ten participants who viewed the furniture-enhanced larger virtual room, color coded by participant ID. Squares indicate judgments made in the real world; circles represent judgments made in the virtual world.*

3.2 Results

Figure 19 shows a scatter plot of the raw data from our second experiment, color coded by participant. Each distance judgment made by each participant is individually displayed, using a circle for judgments made in the virtual environment and a square for judgments made in the real environment.

Figure 20 shows a point plot of the average relative error in the distance judgments made by each participant over all trials in the virtual and real environments. A participant's average relative real-world error is plotted along the horizontal axis while virtual-world error is plotted along the vertical axis. Points landing close to the diagonal represent cases in which participants' real and virtual world errors are on average very similar; points falling well below the diagonal represent cases in which participants underestimated distances in the virtual world to a greater extent on average than in the real world. Points are rendered as solid when the difference between a participant's performance in the real and virtual worlds was found to be strongly statistically significant ($p < .01$). Points are rendered as hollow (with a large white dot in the center) when the difference between a participant's performance in the real and virtual environments was *not* significant ($p \geq .1$).

As in our first experiment, most participants tended

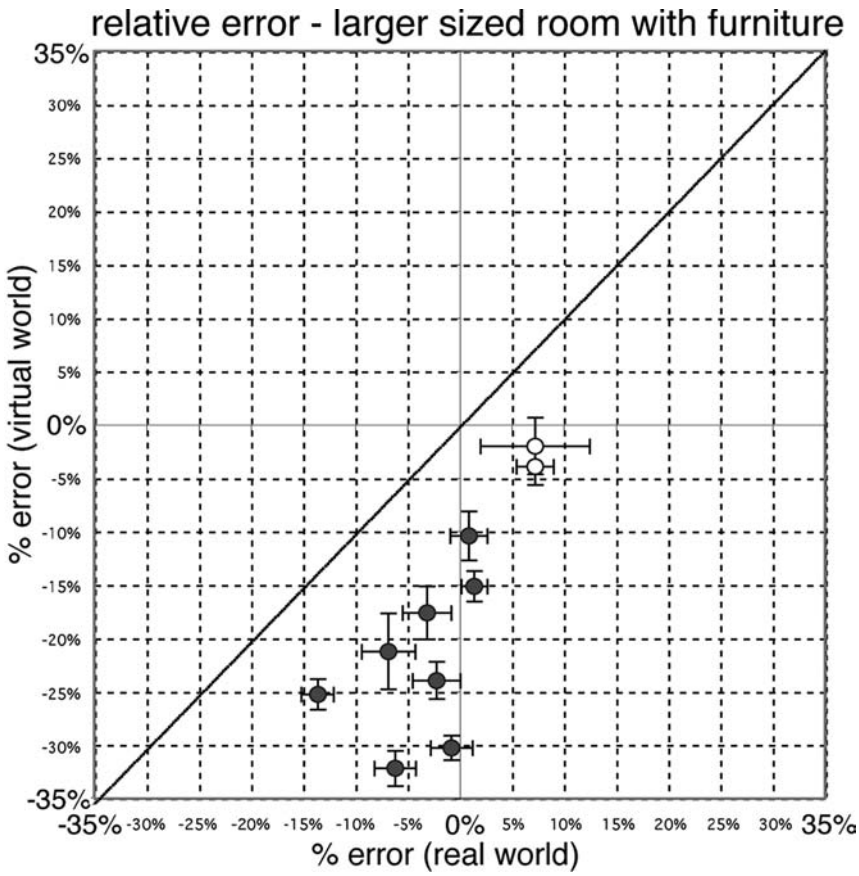

Figure 20. *A point plot showing the average relative error in distance judgments made in the real and virtual environments by participants experiencing the furniture-enhanced larger-size virtual room condition. When the point has a large white center, the difference in error between conditions is not significant; solid points represent differences significant at $p < .01$.*

to make greater errors of distance underestimation in the furniture-enhanced larger virtual room model than they did in the real world, despite the presence of multiple familiar-sized objects in the environment. Statistical analysis confirmed a significant main effect of technology (real world vs. virtual world) on the average relative error in the distance judgments made by each participant $\{F(1,18) = 18.54, p = .0004255\}$. We did not observe a significant trend for participants' distance estimates to become more accurate over time in the furniture-enhanced larger virtual room ($p = .42117$), as we had in our first experiment in the original virtual room condition, but we did observe a tendency for participants to overestimate distances in the real room immediately after experiencing the furniture-enhanced larger virtual room, and for these errors to decrease over subsequent trials ($p = .033481$). Figure 21 shows these average relative errors by trial number.

3.3 Discussion

Overall, the average errors in distance estimation made by participants in our furniture-enhanced larger virtual room model closely resembled the average errors in distance estimation made by participants in our original larger virtual room model. The results of our second

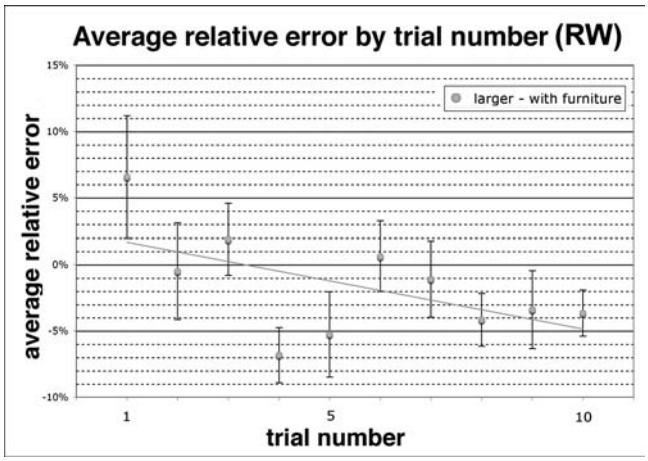

Figure 21. *Average relative error over all participants by trial number for real world trials performed subsequent to experiencing the furniture-enhanced larger virtual room environment.*

experiment therefore do not support the hypothesis that we can enable participants to make more accurate judgments of the distances of target markings in an arbitrary virtual environment simply by liberally incorporating faithfully-sized replicas of familiar objects into the virtual environment model. Our results also do not support the hypothesis that the underestimation errors in the larger virtual room condition found in our first experiment can be explained by the relatively greater lack of detail, or paucity of landmark cues, in that model near the typical target locations. Regarding the implications of these findings with respect to disambiguating *visual calibration* from *presence* as the more likely explanation for our consistent finding that participants are able to make accurate judgments of egocentric distance in a virtual environment that is an exact match to an existing real environment that participants have previously experienced: they seem to provide evidence against the visual calibration hypothesis, as one might expect that if this hypothesis held, participants would have been able to use the known sizes of the familiar objects—which they had previously seen in the real room—to calibrate their perception of sizes and distances in the larger virtual room environment. However, the implications of our findings with regard to the presence hypothesis are less clear. On the one hand, we might have expected that by augmenting the virtual room model with faithfully-modeled replicas of the main items of furniture in the physical room, we would have increased the faithfulness of the correspondence between the two spaces and thereby had the potential to evoke a stronger sense of presence. On the other hand, the unrealistic shading applied to the furniture, compounded by the inability of participants to interact with it (i.e., touch it), could have interfered with participants' ability to accept the entire computer-generated stimulus as an equivalent stand-in for an actual view of a real environment. We could explore these ideas further by investigating the effect of augmenting our same-sized virtual room environment with the same objects, or by improving the shading model used.

4 Conclusions and Future Work

The experiments reported in this paper contribute insight to our understanding of the commonly encountered problem of distance underestimation in immersive virtual environments by probing the characteristics of situations in which distance underestimation does and does not occur. Our first experiment replicates our earlier findings (Interrante et al., 2006a) that people appear to judge distances with equivalent accuracy as in the real world in a virtual environment that represents a highly faithful replica of an actual physical environment that they have recently experienced. Our first experiment also, along with a follow-on study, seeks to more precisely identify the specific factors that are responsible for enabling this accuracy in this situation. Our results from both experiments suggest that people are not able to extract metric information about sizes and distances from prior exposure to a real environment and directly use it to calibrate their judgments of sizes and distances in a corresponding virtual model of that same environment. However, these results leave open the possibility that presence, or the willingness to accept a computer-generated representation of a virtual environment as being equivalent to real, plays an important role in enabling people to interpret, and hence to act upon, the

visual stimulus provided by the HMD as they would an actual view of a real environment.

In future work, we would like to explore the development of robust, proactive strategies for facilitating more accurate distance perception in noncolocated virtual environments. Although we are aware of strategies that rely on manipulations of the visual stimulus to counter the effects of apparent spatial compression, we are concerned that such strategies could backfire if it turns out that what everyone is interpreting as spatial compression turns out to be merely an artifact of peoples' inherent biases under the conditions of uncertainty that arise when they are reluctant to assume the equivalence of the presented virtual environment to the real world. In that case, the amount of spatial compression experienced would be a moving target, and fixed compensatory manipulations that initially seem to help could eventually backfire over time. As an alternative to that sort of approach, we are interested in studying the effects of pursuing techniques that have been shown to enhance participants' subjective sense of presence in a virtual environment, such as providing them with a visually and/or behaviorally faithful representation of their body using an auxiliary tracking system, and enhancing the virtual environment with ambient spatialized sound sources. Finally, we plan to reexamine the effects of near-range, sighted, active experience in a realistic but unfamiliar virtual environment on a participant's subsequent ability to accurately judge spatial relationships over farther extents in that same environment.

Acknowledgments

This research was supported by grants from the National Science Foundation (IIS-0313226, IIS-0713587), by the University of Minnesota through a Digital Technology Center seed grant, and by the Linda and Ted Johnson Digital Design Consortium Endowment and Lab Setup Funds. We are grateful to the many people who have helped us to think through questions related to this work, particularly including Bernd Frölich, and we are indebted to an anonymous reviewer of one of our earlier papers for suggesting the possibility that the participants in our earlier studies might be acquiring metric information about the real environment when they see it for the first time upon entering the space, and using that information to calibrate the perceived size of the matching virtual environment. We are also grateful to Ed Swan for suggesting that we take a closer look at whether the magnitude of our participants' errors changes over time. Finally, we are grateful to everyone who helped recruit participants for the studies reported in this paper, and to all of our participants for their dedicated and conscientious efforts.

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