Joint Virtual Reality Conference of EuroVR – EGVE – VEC (2010)
T. Kuhlen , S. Coquillart and V. Interrante (Editors)

A Further Assessment of Factors Correlating with Presence in Immersive Virtual Environments

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Abstract

In previous work, we have found significant differences in participants' distance perception accuracy in different types of immersive virtual environments (IVEs). Could these differences be an indication of, or consequence of, differences in participants' sense of presence under these different virtual environment conditions? In this paper, we report the results of an experiment that seeks further insight into this question.

In our experiment, users were fully tracked and immersed in one of three different IVEs: a photorealistically rendered replica of our lab, a non-photorealistically rendered replica of our lab, or a photorealistically rendered room that had similar dimensions as our lab, but was texture mapped with photographs from a different real place. Participants in each group were asked to perform a series of tasks, first in a normal (control) version of the IVE and then in a stress-enhanced version in which the floor surrounding the marked path was cut away to reveal a two-story drop. We assessed participants' depth of presence in each of these IVEs using a questionnaire, recordings of heart rate and galvanic skin response, and gait metrics derived from tracking data, and then compared the differences between the stressful and non-stressful versions of each environment. Pooling the data over all participants in each group, we found significant physiological indications of stress after the appearance of the pit in all three environments, but did not find significant differences in the magnitude of the physiological stress response between the different environment conditions. However, we did find significant differences in the change in gait: participants in the photorealistic replica room group walked significantly slower, and with shorter strides, after exposure to the stressful version of the environment, than did participants in either the photorealistically rendered unfamiliar room or the NPR replica room conditions.

CR Categories: I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism – *virtual reality*.

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1. Introduction

Virtual environments technology has tremendous potential to facilitate the process of architectural design by enabling architects and their clients to experience a designed space before it is built. The usefulness of this preview capability critically depends, however, on the ability of viewers to make judgments about what they see in the virtual environment that are equivalent to the judgments they would have made in the corresponding real environment.

Unfortunately, repeated studies of spatial perception in immersive virtual environments (IVEs) have shown that, under most common conditions, people act as if they do not perceive space in the same way in an IVE as they do in the real world. For the past several years, we have been working to understand the factors responsible for these differences, in order to gain insight into the most promising strategies for overcoming them.

In this paper, we report the results of a study that seeks insight into the potential of a relationship between distance perception accuracy and presence in an immersive virtual environment. Specifically, we use a variety of measures to qualitatively and quantitatively assess the extent to which participants might be experiencing different depths of presence in three different virtual environments in which different amounts of distance perception accuracy had been previously observed. Ultimately, we aim to explore the possibility that people's propensity to make accurate action-based judgments of spatial perception in an IVE might be affected by their depth of presence in that IVE. However, further studies that examine presence and distance estimation accuracy in a more tightly integrated fashion will be required before any definitive conclusions on that point can be drawn.

2. Previous and Related Work

Numerous studies over the years have found that people tend to significantly underestimate egocentric distances in immersive virtual environments, and the factors that underlie this phenomenon remain poorly understood. Investigations of the physical limitations of the virtual reality equipment have not indicated any single factor as having a large significant effect on distance estimation accuracy [LK03]. Recently, it has been discovered that people tend *not* to severely underestimate distances when they are immersed in a highly photorealistic virtual environment that is an exact replica of the same real environment that they know themselves to be concurrently occupying [IRA06], but that they *will* underestimate distances when this virtual replica environment is portrayed in a non-photorealistic (NPR) line drawing style [PRI*09].

NPR renderings can be useful for conveying the preliminary nature of a design and inviting modification. The question of distance perception in NPR virtual environments was first investigated by [GW02] and [TWG*04], who found no effect of graphics quality on user's accuracy, although Kunz *et al*. [KWS*09] find different results when verbal report rather than an action based measure of distance perception is used. [SKM*09] found that adding more quality to the computer graphics, using real-time ray tracing to create realistic light and shadows, increased users' subjective presence and their stress response when faced with a virtual precipice.

These and other related findings, e.g. [IRL*08], have led us to wonder if the problem of distance underestimation in head-mounted display (HMD)-based IVEs may be rooted less principally in the low level visual cues provided (or not) by the visual stimulus as in higher level factors related to how people *interpret* what they see. In particular, we hypothesize that if users lack a sense of presence in an IVE, they may be hesitant to act on what they see through the HMD in the same way as they would act on the equivalent visual stimulus obtained in the real world, resulting in underperformance on distance estimation tasks that require them to move through the environment.

To explore this possibility, we seek to 1) determine reliable methods for assessing the depth of a participant's sense of presence in an immersive virtual environment, and 2) compare these measure of presence across the variety of environmental conditions in which we have previously found systematic differences in peoples' distance estimation accuracy.

Previous researchers have investigated many different measures of presence in virtual environments. The Slater-Usoh-Steed [SUS94] and Witmer-Singer [WS98] questionnaires were popular early methods for assessing users' subjective sense of presence; however more recent research has raised concerns about the general applicability and robustness of such measures [SG07]. Meehan *et al*. [MRI*05] looked at physiological as well as qualitative measures and found a correlation between users' subjective sense of presence and the change in their skin conductance (galvanic skin response) and heart rate after looking down from a virtual precipice. Brogni *et al*. [BVS*06] and Wiederhold *et al*. [WJK*02] also explored the use of physiological monitoring in virtual environments. Insko [Ins03] gives a comprehensive survey of the many ways in which presence has been measured.

Gait analysis has also been used in studying virtual environments. Mohler *et al*. [MCW*07] found that users walk with shorter strides during free walking in an HMD virtual environment than they do in the real world. Phillips *et al*. [PRK*10] introduced the use of gait analysis as an indicator of how frightening a participant finds a virtual environment.

3. Our Experiment

We designed a between-subjects experiment to assess the potential differences in presence evoked by the three different immersive virtual environment conditions in which we had previously noted differences in distance perception accuracy.

3.1 Apparatus

The experiment was conducted in our laboratory, which is approximately 30′ long and 16-25′ wide.

Participants viewed the virtual environment using an nVisor SX head mounted display, which has two screens offering a 1280 x 1024 resolution image over a manufacturer-specified 60° diagonal field of view with 100% stereo overlap.

Tracking was provided by a Vicon motion capture system consisting of 12 MX 40+ cameras and the Vicon IQ software. Since we did not intend to provide participants with a full-body avatar in this study, we did not ask them to wear a motion capture bodysuit. Instead we used retro-reflective markers attached to a pair of shin guards and a glove to track the movements of the participants' lower legs and right hand only. Figure 1 shows these implements. Additional tracking markers attached to the head mounted display allowed interactive control of the viewpoint.

Figure 1: *Shinguards and glove used for tracking.*

Three different virtual environment models were used: a photorealistic replica of our lab (PR room); a non-photorealistic replica of our lab (NPR room); and a photorealistic model of an unfamiliar place that was similar in dimensions to the lab space (PR hall). The PR room and PR hall models were created by texture mapping photographs of the real environment onto the surfaces of the models. The NPR room model was created from the PR model by replacing the photographic textures with line drawings obtained by hand tracing thick black lines at the locations of the most salient edges in the photographs, and in a wide grid pattern on the floor. The virtual environments were modeled in Google SketchUp or Autodesk Maya and rendered on a custom built PC with an nVidia Quadro FX 5800 card, using our virtual environment software built on the OGRE gaming engine.

Each virtual environment contained a path, marked in masking tape on the floor, traversing the long dimension of the space. A chair stood at the far end of the path, and a pair of wooden blocks lay alongside the path, extending towards the open space in the room. These elements were present in the real environment as well, to provide passive haptic cues and enhance presence. In the virtual environment, a red cube sat on the chair, and a virtual target marked with a number sat out in the open space of the floor. A stressful version of each virtual environment was created by removing the floor in the area unbounded by the path and replicating the environment two more times below to reveal a two story drop, leaving the marked path as a bridge to be traversed. The dimensions and location of the bridge, and the depth of the drop, were identical in all three environments, and the sizes of the gaps in the floor were as closely matched between the environments as possible. Additional furniture, consisting of tables and chairs modeled after the tables and chairs in the real lab space, was placed on the lowest level along with the numbered target, to provide cues to the height of the path over the floor below. Figure 2 shows a photograph of the real lab, and figures 3 and 4 show images of the virtual models, taken from a similar vantage point.

Figure 2: *A photograph of the physical environment.*

Electrocardiograms (ECG) were sampled at 256 Hz, and skin conductance at 32 Hz, using EKG-Flex/Pro and SC-Flex/Pro sensors from Thought Technology and Biograph Infiniti software. The positions of tracked objects were recorded at 60 Hz from the VE software. Time synchronization between these disparate data sources was achieved by installing a Windows event hook in Infiniti so that when a key combination was typed in Infiniti it was also received and interpreted by the virtual environment software. These key events were time-stamped and recorded in the data stored by both programs.

3.2 Procedure

Participants were first tested for stereo vision capability, and then arbitrarily assigned to experience one of the three different virtual environments. For the stereo test, we presented three different random dot stereograms on the HMD and asked participants to identify the shapes shown. A total of three prospective participants failed the stereo test, and were excused from further participation in the study. Participants were next asked to sign a consent form, and to read written instructions describing the experimental protocol. They were then provided with instructions about how to attach the ECG electrodes, and directed to a small office within the lab where, for reasons of privacy, they were allowed to prepare their skin and attach the electrodes by themselves. When ready, they re-entered the main lab space, took off their shoes, and put on the shin guards and glove. At that point, the experimenter attached the skin conductance sensor and checked for signals from the Infiniti software, then assisted the participant to put on the HMD and adjust it for the correct view. One experimenter sat at the keyboard to control the virtual environment while another managed the HMD cables as the participant walked through the task.

The experiment consisted of three trials. On each trial, the participant's task was to: walk along the marked path from the pre-defined home base to the chair; pick up the virtual red cube by reaching their hand out towards it; turn and walk back to the wooden platform; step out to the edge of the platform, feeling the end with their toes; report the number on the target and drop the cube onto it by shaking their hand; then return to the path, go back to the home base, and stop facing the wall. After two trials in the control condition, the floor was virtually dropped out while the participant's back was turned, and a third trial was performed with the identical protocol. The first trial was treated as practice, and used to collect baseline heart rate and GSR data. We also used that opportunity to verify that the participant understood the task, and to correct any errors. The differences in participants' physiological measures and gait metrics between the second and third trials were our primary measures of interest.

After completing the third trial, participants removed the HMD and the tracking and sensing equipment, and sat down at a desk to fill out a 12-question presence questionnaire based on the SUS survey [SUS94].

3.3 Participants

We recruited a total of 40 participants (35 male, 5 female), ranging in age from 18 to 38 (average age = 21.58 ± 4.09) from our university community, through announcements in classes and via a sign placed on the door of our laboratory. Each participant was compensated with a $10 gift card. Data from nine participants had to be excluded from all analysis for varying reasons, including: critical loss of tracking (1), failure to follow the protocol (1), and breaks in presence that occurred due to experimenter error (2), or to the participant becoming snagged in the cables (4), or stopping and talking to the experimenters midway through a trial (1). Data from two additional participants had to be excluded from the gait analysis (only) because of a partial loss of tracking information, or because they stopped to look down at the pit midway along the path, and data from nine other participants had to be excluded from the physiological portion of the data analysis due to technical problems with getting a clean and uninterrupted signal from the ECG and/or skin conductance sensors. Table 1 lists the total number of participants with usable data in each condition.

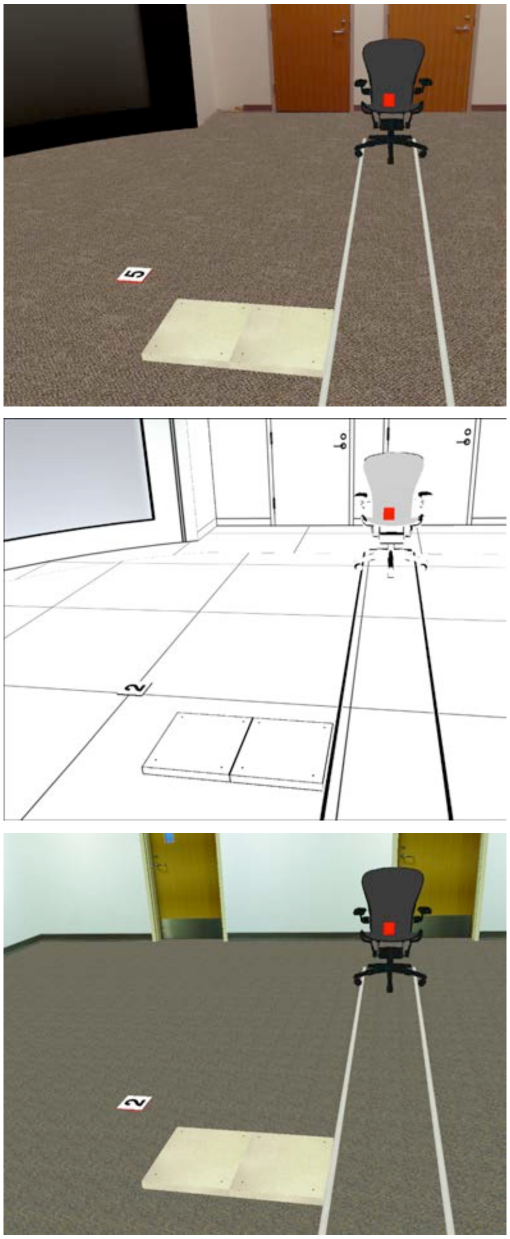


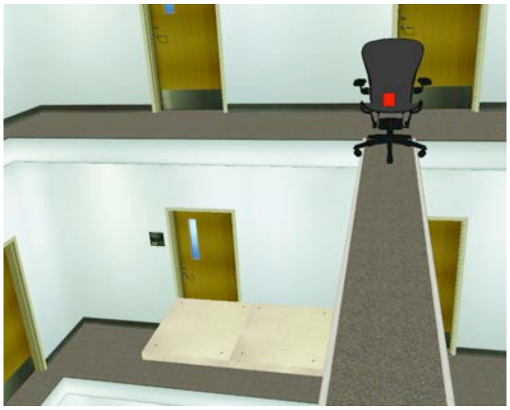
Figure 3: *The three different control environments. From top to bottom: PR room, NPR room, PR hall.*

	Gait	GSR	ECG	Survey
PR room	11	12	9	12
NPR room	10	9	7	10
PR hall	10	10	8	11

Table 1: *Total participants with usable data in each group.*

4. Results and Discussion

In an ANOVA analysis of the physiological data over the course of each trial between the time a participant's leg first came within 1m of the wooden blocks while walking towards the chair, and the time their second leg passed this same point on the way back from the chair, we found a



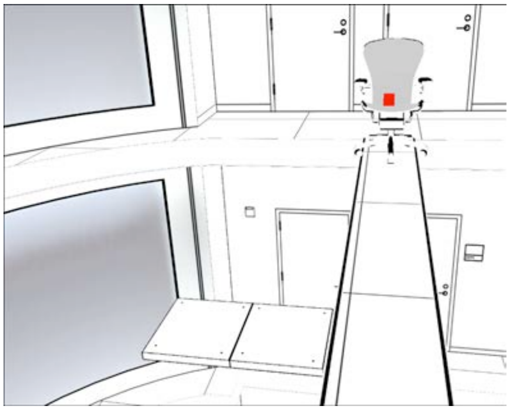


Figure 4: *The three different corresponding pit environments.*

significantly greater rate of increase in galvanic skin response (GSR) over the course of the trials in the pit environment than in the control environment, for participants in each of the three virtual environment conditions {PR room: F(1,22) = 6.90, p = 0.015; NPR room: F(1,16) = 6.91, p = 0.018; PR hall: F(1,18) = 7.41, p = 0.014}. An average GSR was recorded once per second, and the rate of increase was computed as the difference between the average GSR measured at the start and at the end of each trial, divided by the amount of time elapsed. We chose this measure in order to control for the fact that GSR tends to rise over time, by default. Our results suggest that each of the virtual environments was capable

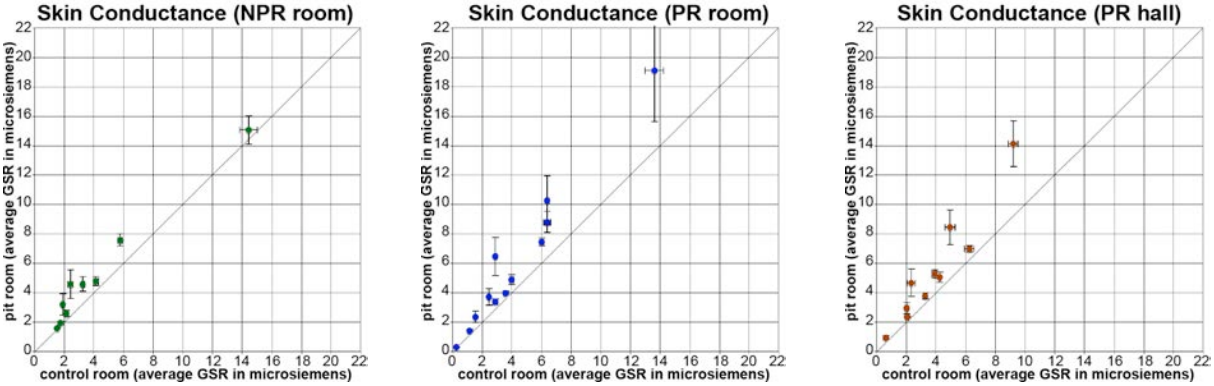


Figure 5: *Average galvanic skin response in the control and pit conditions for each participant in each virtual environment.*

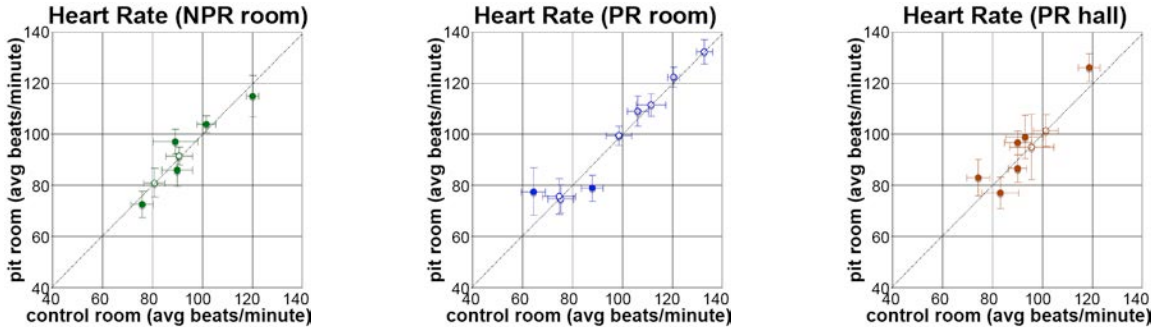


Figure 6: *Average heart rate in the control and pit conditions for each participant in each virtual environment.*

of inducing a significant stress response in most participants. However, we did not find any significant differences in the relative amount of the increase in GSR, after exposure to the pit, between the different environments. Figure 5 plots the average GSR for each participant in each environment, showing the magnitude of the individual differences observed; the error bars in these charts indicate the standard deviations about the means.

We computed the average heart rate at one second intervals over the course of each trial, within the period described above, based on heart beat counts derived from the ECG data using the QRS detection algorithm described by [KHO03]. Any mislabeling of a heart beat was corrected by hand. Figure 6 plots the average heart rate for each participant in each environment; the error bars indicate the standard deviations about the means. No significant differences in the average heart rate between the control and pit environments were observed in the pooled data from any of the three different virtual environment conditions. This finding was disappointing, and is inconsistent with the results of the earlier study by Meehan *et al*. [MRI*05]. We are at a loss to explain this shortcoming, but plan in the future to consider measuring heart rate variability [RSI98], which may be more sensitive and appropriate for our purposes.

For the gait analysis, we identified participants' foot steps by recording the position of the shin guards at the points where the speed reached a local minimum. These minima were computed by smoothing the position data with a linear low pass filter and then computing the speed.

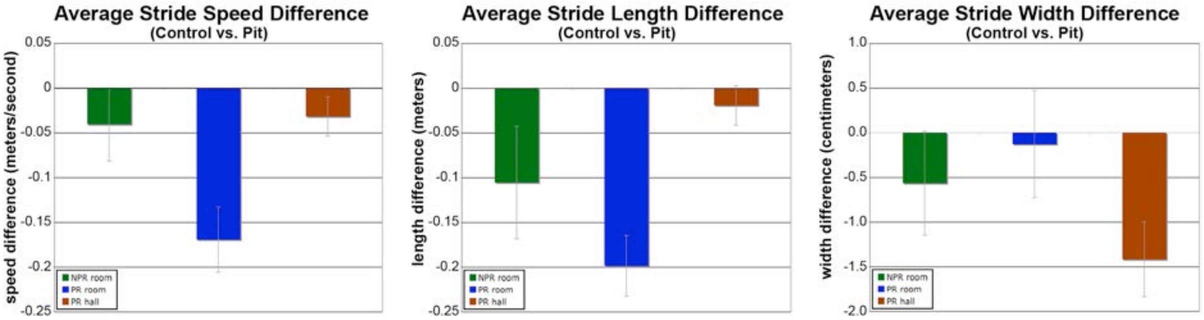


Figure 7: *Relative differences in the average stride speed, stride length, and stride width, computed over all participants, between the control and pit conditions in each virtual environment.*

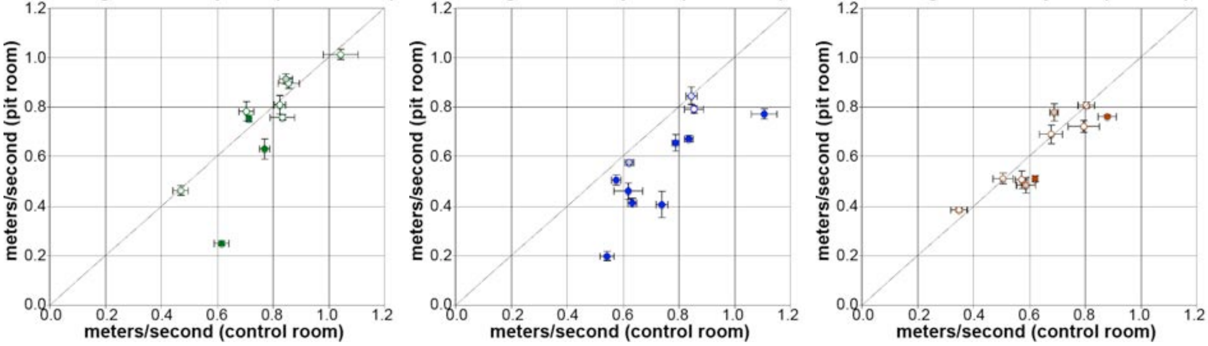


Figure 8: *Average stride speed in the control and pit conditions for each participant in each virtual environment.*

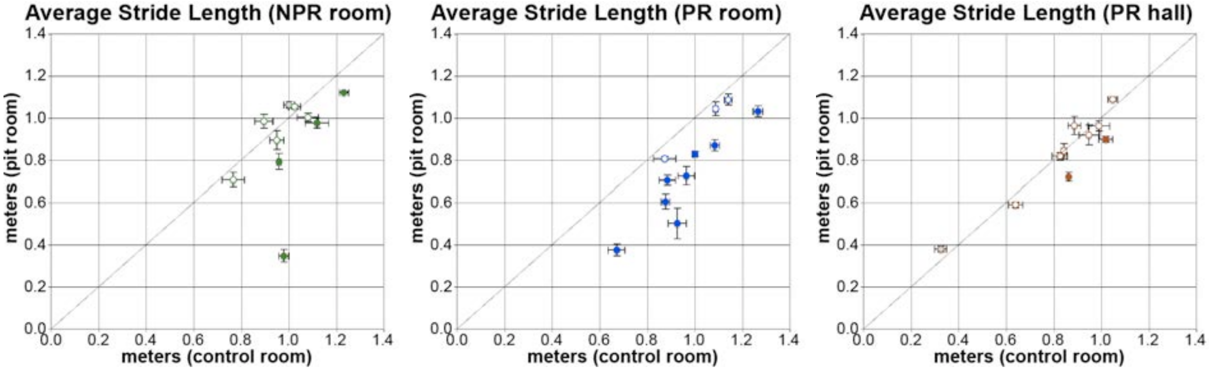


Figure 9: *Average stride length in the control and pit conditions for each participant in each virtual environment.*

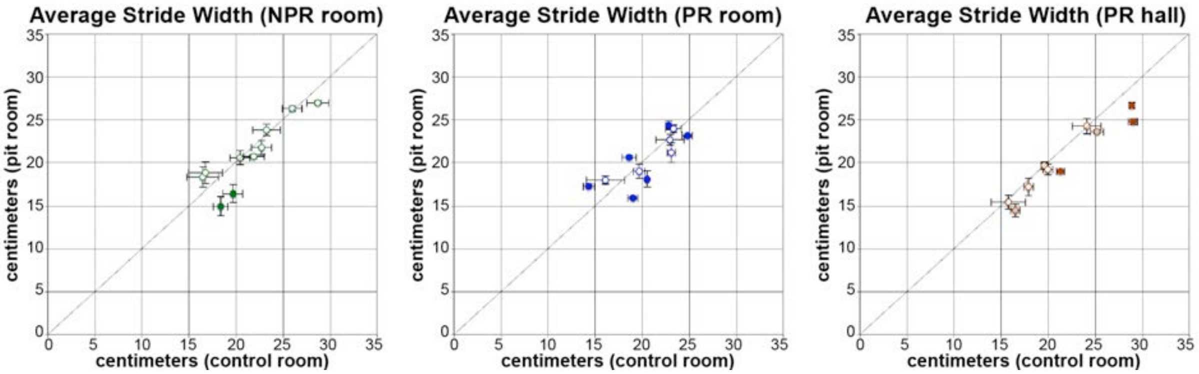


Figure 10: Average stride width in the control and pit conditions for each participant in each virtual environment.

Due to intermittent occlusion, the tracking system would occasionally lose track of one of the shin guards, but fortunately this mostly happened on the swinging foot, so we could still identify the position of the standing foot. We computed stride length, stride width and stride speed for the first four strides at the start of each trial, after the participant stepped out of the home base. We chose to consider this portion of the data only, because we felt that this allowed the best consistent measure of active gait over all trials, uncorrupted by startup and slowdown effects due to stopping at the chair or at the wooden blocks. Stride length is defined as the distance between successive steps with the same foot, and stride width is defined as the perpendicular distance between adjacent strides. Figures 7-9 plot the average stride length, stride width and stride speed for each participant in each environment, and the error bars indicate the standard deviations about the means. Again using ANOVA, we found significant differences in the amount of change in both stride speed {F(2,28) = 4.98, p = 0.014} and stride length {F(2,28) = 4.30, p = 0.024} between the control and pit conditions between the different virtual environments, but no significant differences in stride width, possibly due to the implicit constraints on foot position imposed by the path.

Overall, we found that participants walked significantly more slowly after exposure to the pit in the photorealistic room than in the photorealistic hall {F(1,19) = 9.52, p = 0.006} or in the non-photorealistic room {F(1,19) = 5.33, p = 0.032}. Figure 8 shows the average stride speed for each participant in each environment, and figure 7a shows the average relative change in stride speed between the control and pit conditions in each environment.

Similarly, we found that participants took significantly shorter steps after exposure to the pit in the PR room than in the PR hall {F(1,19) = 17.93, $p < 0.001$}. However, the variance in stride length between participants in the NPR room environment was relatively high, and the differences between the PR room and NPR room were not significant {F(1,19) = 1.71, p = 0.206}. Figure 9 shows the average stride lengths for each participant in each environment, revealing the nature of the variance in each condition, and figure 7b shows the average relative change in stride length between the control and pit conditions in each environment.

Figure 10 shows the average stride widths for each participant in each environment, and figure 7c shows the average relative change in stride width between the control and pit conditions in each environment. One can observe in figure 9 that the variance in width, where it occurs, tends to be higher in the control than in the pit environments, indicating that participants were likely motivated to take particular care to keep their feet safely within the confines of the path when the area outside of the path was portrayed to be vacant. As this incentive to decrease stride width to stay on the path works at odds with the expected tendency for participants to increase their stride width to better maintain their balance under vertigo-inducing conditions, the narrowness of the path we defined in the environments may therefore, in hindsight, have been a shortcoming in our experimental design.

Figure 11 shows the average responses to each of the survey questions, by question number. Significant differences were found, between participants in the PR condition and participants in one or more of the other conditions, in the responses to two of these questions, Q5 and Q9, and marginally significant differences were found in the response to a third (Q8).

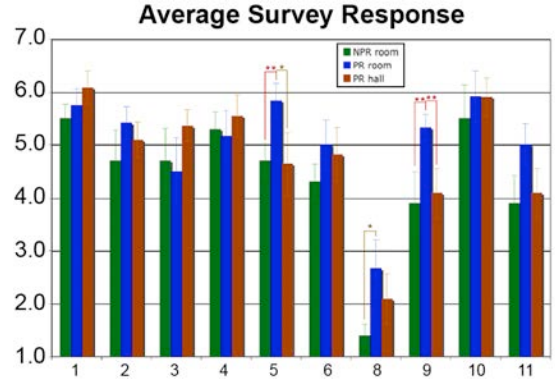


Figure 11: Average responses to survey questions.

Question 5 probed the depth of participants' place illusion, reading: "*Consider your memory of being in the virtual* *room. How similar in terms of the structure of this memory is this to the structure of the memory of other places you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the virtual world, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other structural elements*." Participants were asked to indicate their response on a 7 point scale, under the heading "*I think of the virtual world as a place in a way similar to other places that I've been today. 1 = not at all, 7 = very much so*." Unfortunately, question 5 contains the assumption that the virtual environment would represent a different place than any other the participant would have visited that day. Participants in our study could have misunderstood this question as asking them to compare the virtual environment to somewhere they had visited earlier. In that case, the PR room would be expected to score highly, since it was a faithful replica of the real environment that the participants were in while completing the survey. Although by similar logic the same effect might also have been expected to apply to the NPR replica room, it clearly did not.

Question 9 asked: "*How disturbed by the environment were you during the third task?*" Participants were asked to indicate their response on a seven point scale, under the heading "*During the third task, I was… 1 = not at all uncomfortable, 7 = very uncomfortable*". Participants in the realistic replica room rated the pit version of the environment as significantly more disturbing than did those who experienced either of the other two VEs.

Question 8 was meant to establish a baseline for question 9. It asked: "*How disturbed by the environment were you during the second task?*", and participants were asked to indicate their responses in the same way as above. These responses indicate that the participants immersed in the NPR replica room were very comfortable with that environment. It is interesting that the participants in the PR replica room rated it as marginally more disturbing. It is possible that those participants were implicitly comparing the virtual environment to the real environment. However it is also possible that some participants got confused by the phrasing of the question. One particular outlier in the PR room condition gave a 7 as his answer to question 8 but only a 4 as his answer to question 9. In hindsight it might have been wiser to use more explicit terms to differentiate the control and pit environments.

5. Conclusions

Some of the results of this experiment appear to offer marginal support for the hypothesis that the participants who were immersed in the photorealistic replica room experienced a greater depth of presence than both the participants who were immersed in the unfamiliar virtual hall environment, despite its similarly photorealistic quality, and those who experienced the non-photorealistic replica room, despite their having been explicitly told that the model they were seeing was intended to represent the same space that they were concurrently occupying. Specifically, the gait data and the survey data seem to support this interpretation fairly strongly. Yet others of the results, specifically the results of the physiological data analysis, which do not show significant differences between the environment conditions, do not support the hypothesis that significant differences in presence are occurring, and the overall picture remains far from clear. Because of the between-subjects design, the possibility of unbalanced individual differences in immersive tendencies also cannot be ruled out, and further complicates the interpretation. In future investigations, we hope to refine our investigations of presence by, among other things, better controlling for the potential effects of individual differences in immersability through the use of an immersive tendencies survey. Finally, as recently suggested by Slater [Sla09], it may be necessary to consider a more nuanced interpretation of what it means to be 'present' in an immersive virtual environment. Different types of presence may be evoked in different environments, and result in different response behaviour to presented situations or stimuli.

Acknowledgments

This research was supported by a grant from the National Science Foundation (IIS-0713587), and by the University of Minnesota through the Digital Technology Center and the Linda and Ted Johnson Digital Design Consortium Endowment and Lab Setup Funds. We are grateful to Seth Berrier for his assistance with running the experiments.

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