# Transitional Environments Enhance Distance Perception in Immersive Virtual Reality Systems

Frank Steinicke,[*] Gerd Bruder,[†] Klaus Hinrichs,[‡] Markus Lappe[§]
Visualization and Computer Graphics Research Group
Department of Computer Science, Psychology Department II
University of Münster

Brian Ries,[¶] Victoria Interrante[‖]
Department of Computer Science and Engineering
University of Minnesota

## Abstract

Several experiments have provided evidence that ego-centric distances are perceived as compressed in immersive virtual environments relative to the real world. The principal factors responsible for this phenomenon have remained largely unknown. However, recent experiments suggest that when the virtual environment (VE) is an exact replica of a user's real physical surroundings, the person's distance perception improves. Furthermore, it has been shown that when users start their virtual reality (VR) experience in such a virtual replica and then gradually transition to a different VE, their sense of presence in the actual virtual world increases significantly. In this case the virtual replica serves as a *transitional environment* between the real and virtual world.

In this paper we examine whether a person's distance estimation skills can be transferred from a transitional environment to a different VE. We have conducted blind walking experiments to analyze if starting the VR experience in a transitional environment can improve a person's ability to estimate distances in an immersive VR system. We found that users significantly improve their distance estimation skills when they enter the virtual world via a transitional environment.

**CR Categories:** H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

**Keywords:** Virtual reality, distance estimation, transitional environment

## 1 Introduction

Virtual reality environments provide some of the most sophisticated technologies for human-computer interfaces developed so far. Employing head-mounted displays (HMDs) and a tracking system for capturing position and orientation data [Burdea and Coiffet 2003], immersive virtual environments (IVEs) can present virtual worlds to users from an egocentric point of view. Using stereoscopic rendering techniques and tracking of user movements, a virtual world can be displayed with correct perspective using only the natural movements of the user's head. This provides an immersive experience to users, and enables them to view the virtual world at true scale. Hence, VR systems have great potential as advanced exploration tools for many application domains.

IVEs were initially restricted to visual displays and used hand held interaction devices such as a joystick or mouse to generate self-motion. In such setups, usually physical user movements were not reflected in the VE, hence the research of natural multimodal methods has been a focus of investigation of many research groups. In particular, many research groups analyze locomotion and perception in both the real world and virtual worlds. In this context, it has been shown that physical locomotion is the most natural and preferred method of traveling through IVEs.

### Background

While moving, visual flow provides cues about the travelled distance. Within a VE, these cues are consistent and hence provide veridical information to the user about her motion. Although human subjects can use these cues to discriminate travelled distances [Frenz et al. 2007], it has been shown that perception in the virtual world varies significantly from perception in the real world. For example, when travelled distances are compared to static distances, even within the VE, characteristic estimation errors occur, and distances can be severely under- [Frenz et al. 2007] or overestimated [Redlick et al. 2001], depending on the perceptual task given to the subject [Lappe et al. 2007]. Researchers have described that distances in virtual worlds are underestimated in comparison to the real world [Interrante et al. 2006; Interrante et al. 2007; Loomis and Knapp 2003], that visual speed during walking is underestimated in VEs [Banton et al. 2005] and that the distance one has traveled is also underestimated [Frenz et al. 2007].

Almost all of the studies to date that have compared distance perception of static targets in IVEs with perception in the real world [Witmer and Sadowski 1998; Willemsen and Gooch 2002; Messing and Durgin 2005; Gooch and Willemsen 2002], have found evidence that distances are perceived as significantly compressed in IVEs–in some cases up to 50%–relative to distance perception in the real world [Witmer and Sadowski 1998; Willemsen and Gooch 2002; Messing and Durgin 2005; Gooch and Willemsen 2002; Interrante et al. 2007; Loomis and Knapp 2003; Thompson et al. 2004]. Perceptual distortion of such a magnitude could present serious problems for different applications, in particular for architetural design and city planning, where an accurate perception of size and distance is essential. Distance compression effects have been shown for a wide range of displays and technologies, and considerable efforts have been undertaken to identify reasons for these effects. Previous studies have suggested that physical factors related to the ergonomics of head-mounted displays, such as the limited field of view of a head-mounted display in comparison to the field of view in the real world [Willemsen et al. 2004; Kuhl et al. 2006; Kuhl et al. 2008], may account for some of the apparent compression. However, an explanation for the larger portion of the observed compression effects remains unknown. Thompson et al. [Thompson et al. 2004] have demonstrated that also the graphical quality of the VE cannot account for the observed phenomenon.

In most of the previous studies on distance estimation, the visual stimulus has represented an artificial space that does not correspond to the space within which the VR user is actually, physically present during the experiment. Exceptions are the experiments performed by Messing and Durgin [Messing and Durgin 2005] in which sub-

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[*] e-mail: fsteini@uni-muenster.de
[†] e-mail: g_brud01@uni-muenster.de
[‡] e-mail: khh@uni-muenster.de
[§] e-mail: mlappe@uni-muenster.de
[¶] e-mail: ries0112@umn.edu
[‖] e-mail: interran@cs.umn.edu

jects saw the real environment presented by video streams on a HMD. Their results show that distances are underestimated even in known perceived environments, but the underestimation was linear. This raises the possibility that the problem of distance compression might have some of its roots in the cognitive interpretation of the visual stimulus. Interrante et al. [Interrante et al. 2006] suggest that if subjects are experiencing a cognitive dissociation between the virtual world that they are perceiving in VR, and the real world in which they are physically present, the resulting lack of presence might be having some effect on the subjects' interpretation of the distances that they are perceiving. In the experiments performed by Interrante et al. [Interrante et al. 2006], the subjects' perception of egocentric distances was tested in a high fidelity IVE, which could confidently be accepted as being a faithful representation of the actual space in which the experiment took place. Since the underestimation could not be reproduced in such a magnitude as reported in previous studies, i. e., subjects showed significantly less compression in comparison to the previous studies, they conclude that the problem of distance compression in IVEs may not necessarily be inherent to the technology, but may in fact stem, in significant part, from higher-level cognitive issues in the interpretation of the presented visual stimulus. Also, Mohler et al. have shown that when a subject sees a virtual representation of herself in the VE, her ability to estimate distances improves [Mohler et al. 2008]. In addition, a realistic representation of someone self has been shown to increase also the user's sense of feeling presence in the VE.

### Motivation

Based on this observation, it sounds reasonable that if subjects feel a high degree of situational awareness, their ability for estimating distances in such a known VE may be much better compared to an artificial virtual world. Recent experiments which analyzed the impact of using a virtual replica of the user's surroundings, have reported that the user's reported sense of presence is significantly increased. Steinicke et al. suggest using a virtual replica of the laboratory environment as starting point to the VR experience in order to increase a user's sense of presence [Steinicke et al. 2009]. In their experiments subjects saw a virtual replica of their real surroundings when they don the HMD. Then, subjects walked within a realistic, one-to-one copy of their real surroundings, in their case a virtual replica of the physical laboratory. After a certain time of familiarization in this so-called *transitional environment*, subjects were transferred to a different virtual world, where the main experiment took place. The results show evidence that such a gradual transition to the virtual world increases the user's self-reported sense of presence. According to Sanchez-Vives et al., presence has been thought of as a person's "sense of being there" describing the phenomena that we feel and behave as if we are in a virtual world created by computer displays [Slater and Steed 2000; Sanchez-Vives and Slater 2005]. In addition to the increase of the users' self-reported senses of presence, the results of these experiments suggest that subjects, who have entered the virtual world via a transitional environment, seem to move faster as well as more secure in comparison to those subjects who have entered the "actual" VE directly. Moreover, some subjects remarked that they had a better feeling for movements and that their space cognition of the unfamiliar environment had improved. From this viewpoint it sounds appropriate to examine if these subjective impressions can be verified objectively.

This raises the question whether the increased sense of presence as well as the subjectively improved skills of space cognition when using a transitional environment may also improve a person's skills to judge distances in the actual virtual world to which she is transferred from the transitional environment. Until now, it has not been considered if such a gradual transition to the VE has any impact on the user's ability to estimate distances in the virtual world. In this paper, we have conducted an experiment to examine if a person's distance estimation is improved when he visited a transitional environment (virtual replica of the laboratory environment) prior to the actual artificial VE.

### Assessing Distance Estimation

Several methods to assess a person's perception of distance have been proposed. The conceptually simplest approach is to let subjects make verbal estimates of the distance between themselves and a target location; however, studies have shown that verbal reports are generally less accurate than action-based metrics [Pagano and Bingham 1998; Loomis and Knapp 2003]. The most commonly used action-based metric for assessing egocentric distance perception is *blind walking*, for which studies have verified that people can accurately walk–at a brisk pace and without vision–to previously seen targets [Rieser et al. 1990]. Alternative action-based metrics include *triangulated walking* [Fukusima et al. 1997], which is often slightly less reliable than blind walking, but which can be used with relative accuracy to assess the perception of very long distances within restricted spaces. *Blind throwing* [Sahm et al. 2005] has been successfully used to dispel concerns that the indications of distance compression effects might be artifacts caused by subjects subconsciously hesitating to confidently walk without sight for fear of colliding with an obstacle. There are also subjective action-based metrics for assessing the perception of long distances without requiring any walking, in which subjects use a stopwatch to indicate their estimated walking time to a target. Since blind walking is the most accurate, reliable, and commonly accepted metric for assessing perceived distances in spaces within which it is possible to directly traverse the indicated interval, we use this metric in our experiment.

The remainder of this paper is structured as follows. Section 2 discusses transitional environments and virtual portals (as means to travel from the transitional environment to the virtual world). Section 3 describes the experiments that we have conducted to identify whether distance estimation is improved when the VR experience starts in a transitional environment. Section 4 discusses the results and their implications for the design of future VR environments. Section 5 concludes the paper and gives an overview about future work.

## 2 Transitional Environments and Virtual Portals

In this section we explain transitional environments and virtual portals as means to travel from the transitional environment to the actual virtual world.

### 2.1 Transitional Environment

The main idea of a transitional environment is to start the VR experience in a virtual replica of the surrounding physical space to accustom users to the characteristics of VR, e. g., latency, reduced field of view or tracking errors, in a known environment. When the user dons the HMD he sees a virtual replica of the laboratory space as illustrated in Figure 1(b). Tracked movements in the physical laboratory are mapped one-to-one to the transitional environment so that users can move through the virtual replica and touch walls like in the real world. After a certain time period, the user may enter the remote virtual environment, where the actual virtual 3D world is presented. Due to this start in a familiar environment, a gradual transition to the virtual world becomes possible.

Some work has demonstrated that the staging of the experience and

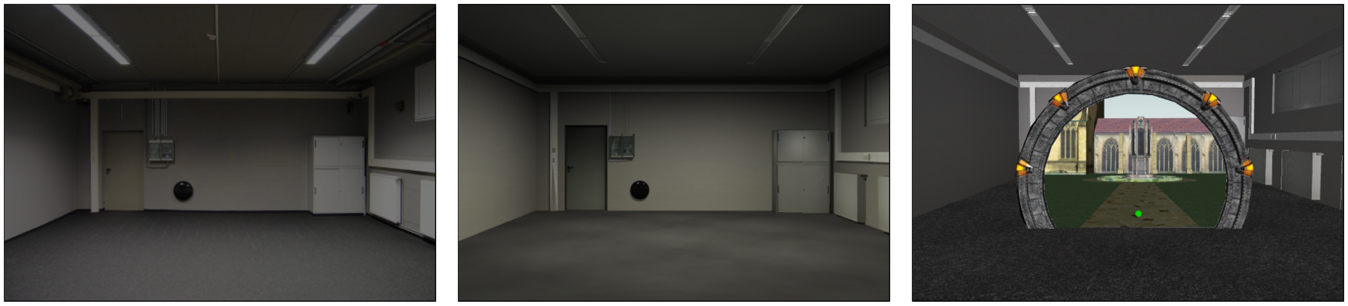
(a) (b) (c)

**Figure 1:** *A transitional environment: (a) the real laboratory, (b) the corresponding virtual 3D textured model of the laboratory, and (c) screenshot of a virtual portal. While the user moves through the transitional environment, she can see the actual virtual world through the portal.*

introduction of a user to the system can impact her subsequent sense of presence [Slater et al. 1998]. In theme parks a similar concept is successfully used. For example, prior to a ride in a roller coaster passengers have to cross dungeons or fairy tale worlds to mentally prepare for the experience. The concepts of a gradual transition from the real to the virtual world and vice versa have already been introduced in some research projects. For example, Slater et al. have performed an experiment in the so-called "VirtualAnte" room, where subjects entered a virtual replica of the laboratory [Slater et al. 1998]. In their experiment, subjects moved through a door to a new virtual location and carried out the main experimental task. Slater et al. also proposed to use a virtual HMD within the virtual world in such a way that when the user puts on the virtual HMD she is transferred to another virtual world [Slater et al. 1994]. After taking off the last HMD, the user is returned to the VE from where he was transferred before. This procedure provides a *recursive* HMD-based virtual world. Transitional techniques might also be used in CAVE environments. For example, Steed et al. augmented a common four-sided (three-walled) CAVE with a white curtain [Steed et al. 2002]. This curtain was used for projection, and the users could see a virtual CAVE with avatars inside. As a user walked through the curtain into the CAVE, an avatar appeared on the curtain, representing the user.

A transitional environment is basically a virtual world which simulates the physical environment in which the user resides during the VR experience; usually such a transitional environment is given by a virtual 3D model of the laboratory (see Figure 1(a)). We modeled the transitional environment as a set of texture-mapped polygons. The texture maps were obtained from a mosaic of digital photographs of the walls, ceiling and floor of the laboratory. All floor and wall fixtures were represented true to original as detailed, textured 3D objects, e. g., door knobs, furniture and computer equipment. Figure 1(a) shows the physical laboratory, which is simulated by the virtual replica illustrated in Figure 1(b).

### 2.2 Virtual Portal

In order to transfer subjects from the transitional environment to a remote virtual world such that they believe to be in a new (but somehow connected environment), we needed a plausible way of travel. Inspired by TV series and movies, for instance, MGM's Stargate, but also 3D games such as the first-person action video game Portal [1], we have decided to introduce *virtual portals* [Bruder et al. 2009]. Portals are a common concept in science fiction and fantasy. The notion of such a portal in fiction is a magical or technological doorway that connects two distant locations, whether separated by time or, most commonly, space. They can be of two forms: either a person must step through the frame of an object (a mirror, a cupboard, a gateway etc.) which serves as a portal or, when they stand alone, the portal will commonly appear in a "magical" form, for example, a vortex of energy. In fiction, there are several places to which a portal transfers the user. Examples are the past or the future (time portal), or a different place in the same universe; in this case portals serve as alternative to tele-portation. Portals commonly are depicted as a graphical object, which consists of an interior and a frame. The interior defines the area the user has to pass. When a subject is in the transitional environment, a button press on an arbitrary input device–we use a WII remote controller–opens a virtual portal in the transitional environment. In order to ensure that portal objects can be placed in arbitrary models and at arbitrary positions in space, we use a multi-pass rendering technique exploiting the depth and stencil buffer available nowadays in almost all graphics libraries. By using this multi-pass rendering approach users can walk around in the transitional environment and view the world behind the portal through the interior of the portal (see Figure 1(c)).

## 3 Experiment

The goal of our experiment is to analyze whether a gradual transition via a virtual replica improves a person's space cognition, in particular his ability to estimate distances in the virtual world.

### 3.1 Materials and Methods

We used a between-subject design in which each subject participates under only one condition: under condition V-T subjects performed distance estimation tests first in a Virtual 3D city model and afterwards in the Transitional environment, i. e., virtual replica room. Under condition T-V subjects performed the distance estimation in the reversed order, i. e., in the transitional environment first and afterwards in the virtual city model. In order to get from from the virtual replica room to the virtual city model and vice versa, subjects walked through a virtual portal as explained in Section 2.2. Furthermore, we performed an exposure test in which subjects performed distance estimation tests in the real city environment, i. e., a parking lot at our campus. Distance estimation was assessed via blind walking over three different fixed paths of lengths 3m, 5m and 7m. No feedback was given during this test phase of the experiment.

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[1] The single player game Portal, in which a player must solve physical challenges by opening portals to maneuver objects and herself through space, was released by Valve Corporation in 2007.

### 3.1.1 Apparatus

The approximate dimensions of the darkened laboratory room are $10m \times 7m$. The virtual environment was presented on a 3DVisor HMD (800 × 600 @ 60Hz, $40^\circ$ diagonal FOV) manufactured by eMagin. A cloth attached to the HMD blocked any peripheral vision of the external environment. On top of the HMD an infrared LED was fixed. We tracked the position of the LED within the room with an active optical tracking system (Precise Position Tracking of World Viz), which provides sub-millimeter precision and sub-centimeter accuracy. The update rate was 60Hz providing real-time positional data of the active markers. For three degrees of freedom orientation tracking we used an InertiaCube 2 (InterSense) with an update rate of 180Hz. The InertiaCube was also fixed on top of the HMD. An Intel computer (dual-core processors, 4GB RAM, *n*Vidia GeForce 8800) displayed the VE and was used for system control and logging purposes. The virtual scene was rendered using OpenGL and our own software with which the system maintained a frame rate of 30 frames per second.

During the experiment, the paths to be traversed were indicated by markers on the floor, which were located at the paths' start and end in the VE. The markers were placed such that no obstacle in the physical setup was in a 3m distance from the path. Participants wore earplugs to prevent the acquisition of any ambient auditory cues. Furthermore, participants wore a blindfold in the real world walk test to prevent any accidental acquisition of external visual input. In order to focus subjects on the tasks no communication between experimenter and subject was performed during the experiment. The subjects received instructions on slides presented on the HMD. A Nintendo WII remote controller served as an input device via which the subjects indicated the start and end of their walks.

### 3.1.2 Participants

11 male and 1 female (age 25-34, $\varnothing : 27.8$) subjects participated in the study. Most subjects were students or members of the departments (computer science, mathematics, psychology, geoinformatics, and physics). All had normal or corrected to normal vision; Two wear glasses or contact lenses. Eight of the subjects had experience with walking in VR environments using an HMD setup. Eight had much game experience. One author participated in the study, all other subjects were naïve to the experimental conditions. We arranged them into two user groups. Subjects in group T-V perform the experiment under condition T-V, and subjects in group V-T perform the experiment under condition V-T. We balanced the groups in terms of HMD as well as 3D game experience. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 2 hours. Subjects were allowed to take breaks at any time.

### 3.1.3 Procedure

As explained above we used two conditions for the distance estimation test. Under the first condition V-T, subjects performed distance estimation tests first in the virtual city model and afterwards in the virtual replica room. Under the second condition T-V, subjects performed the distance estimation in the transitional environment first and afterwards in the city model. Overall, three different distances (3m, 5m and 7m) were considered in the virtual replica room as well as in the virtual city model. Each distance was tested 6 times for each subject resulting in 18 trials per environment. The order of distances was randomized.

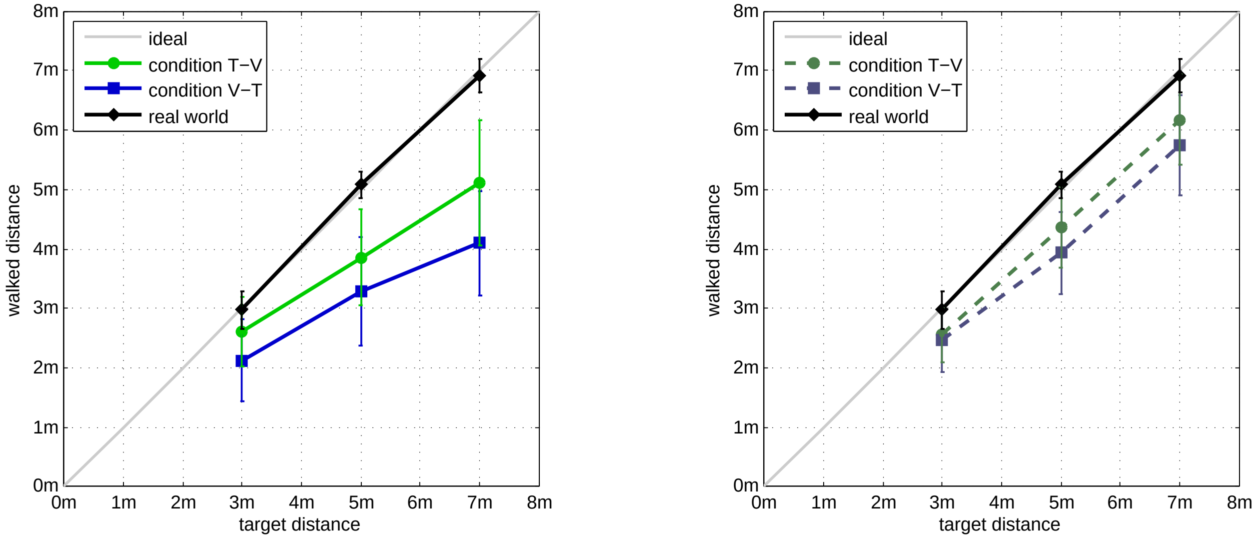
The experiment was divided into three main phases: a practice, test and baseline phase. The test phase was divided into two sub-test phases with a transition phase in-between. All of the subjects conducted the practice, training and baseline phases consecutively. Although previous studies had not found any significant impact on performance after prior practice either with or without feedback [Elliot 1987], we decided to include a practice phase so that we could be certain that the subjects were comfortable with performing the task. Furthermore, we wanted to reduce a bias caused by walking short out of caution. In the practice phase, subjects completed 5 practice walks with visual feedback on the HMD in our virtual laboratory. Under condition T-V subjects saw the virtual replica, under condition V-T they saw the virtual city model. In this practice phase we used randomized distances between 3m and 7m, which were different from the distances used during the test phase.

Prior to each trial in the test phase, subjects were instructed to position themselves at the starting position. Therefore, we guided subjects to the starting position by two reference markers on an otherwise white screen. One marker showed the actual position and orientation of the subject relative to the second fixed marker, which represented the target position and orientation. When subjects were located at the starting position, they had to press a button on the WII remote controller. Then, depending on the condition either the virtual replica room (condition T-V) or the virtual city model (condition V-T) was shown on the HMD. In the test phase we showed subjects a virtual marker in the corresponding distance (3m, 5m, 7m) in randomized order. Subjects were instructed to visualize, estimate and memorize the distance to the target. They could view the target as long as desired. Before the subject walked the distance, he had to press a button on the WII remote controller. Then, the HMD screen was blanked, subjects were instructed to close their eyes and to walk to where they thought the target location was. An experimental observer followed the subject's view on an external display to control that subjects blanked (by pressing the button on the WII remote controller) the screen before walking.

When a subject believed that he reached the target, he had to stop and press a button on the WII remote controller again. We measured the Euclidean distance between the subject's positions at the first and second button press, which indicated the start and end of the walk. Hence, a drift from the shortest route between start and target marker had no impact on the estimated distance. Afterwards, we guided the subject back to the starting position again by means of the reference markers as described above. The shown markers enforced subjects to walk on circuitous paths, which we used to reduce feedback about their performance during the test phase.

After 18 trials (6 × 3m, 6 × 5m, 6 × 7m), a virtual portal appeared 2.5m ahead from the subject's starting position. As mentioned above we used the portal as transition between the virtual replica room and the virtual city model, respectively, vice versa. Under condition T-V subjects saw the virtual city model (cf. Figure 1(c)), whereas under condition V-T subjects saw the virtual replica room through the virtual portal. In the transition phase of the experiment, subjects performed 6 transition walks through the portal. Therefore, we showed them target markers on the ground of the VE in a distance between 5m and 7m and instructed them to walk to the markers with eyes opened. When subjects reached the target marker they had to press a button on the WII remote controller and were then guided back to the starting position as explained before. We used these transition walks in order to highlight the relation between transitional environment and virtual city model in terms of space and metric. After the last transition walk, the virtual portal disappeared and subjects were in the other environment. Now, subjects had to perform again 6 test walks for each distance (3m, 5m, 7m) in randomized order.

In the baseline phase, we performed also distance estimation tests in the real world in order to get a baseline for the subjects. All subjects participated in this baseline test regardless of their exper-



(a) Distance estimation in virtual city (b) Distance estimation in virtual replica

**Figure 2:** *Target distance versus walked distance for the two conditions (T-V and V-T), using pooled results from all participants for (a) blind walking in the virtual city model and (b) blind walking in the virtual replica.*

imental group. The procedure was similar to the virtual distance estimation tests. Subjects saw markers on the ground at different distances (3 × 3m, 3 × 5m, 3 × 7m) and had to walk blindfolded as in the test phase.

Prior to and after the experiment subjects had to answer questionnaires, including Kennedy's Simulator Sickness Questionnaire (SSQ). Furthermore, we measured their self-reported sense of presence based on the Slater-Usoh-Steed (SUS) presence questionnaire [Usoh et al. 1999]. The total time per subject including prequestionnaire, instructions, training, experiment, breaks, and debriefing took 2 hours. Subjects were allowed to take breaks at any time.

## 3.2 Results

Figures 2 show the averaged walked distances for the different target distances, pooled over all subjects for (a) the virtual city environment and (b) the virtual replica. The green circles show the results for the condition T-V under which subjects were first in the transitional environment and then in the virtual city model. The blue squares show the result for the condition V-T under which subjects were first in the virtual city model and then in the transitional environment. The error bars show standard errors for each tested target distance. Figure 3 shows separate scatterplots of the individual distance estimates obtained from each of the twelve subjects. The plots on the left side of Figure 3 show the results for the group V-T, the plots on the right side the results for group T-V. Lines are superimposed to illustrate the trend of the data. The black diamonds in the figures show the results of the blind walking experiment for the corresponding distances in the real world. The real-world results show that subjects were quite accurate in blind walking to targets previously seen in the real world. They walked on average 2.97m, 5.08m, and 6.92m for the 3m, 5m, respectively 7m target distances. This corresponds to distance under- respectively overestimations of less than 2%. There was no significant difference between both user groups in the real-world condition.

Figure 2(a) shows that there is quite a large amount of distance compression in the virtual city model under both conditions, increasing with target distance. However, the amount of compression is greater under condition V-T, when subjects were in the virtual city model first. Subjects walked 2.13m, 3.29m, and 4.09m for the 3m, 5m, 7m target distances under this condition. This corresponds to distance underestimations of approximately 29%, 34% and 41% respectively. When subjects entered the virtual city model from the virtual replica via a portal (condition T-V), the distance compression effect is significantly smaller. Subjects walked 2.62m, 3.86m, and 5.11m for the 3m, 5m, 7m target distances. This corresponds to distance underestimations of approximately 12%, 22% and 26% respectively.

Figure 2(b) supports previous findings that distance compression effects are reduced in a virtual environment which is an exact replica of a user's real physical surroundings. In this virtual replica subjects have estimated distances better than in the virtual city model. Again, the amount of underestimation appears to be greater under the condition V-T, when subjects were in the virtual city model first and then entered the virtual replica via a portal. Subjects walked 2.46m, 3.93m, and 5.74m for the 3m, 5m, 7m target distances. This corresponds to distance underestimations of approximately 18%, 21% and 18% respectively. When subjects started immediately in the virtual replica (condition T-V), the distance compression effect is smaller. Subjects walked 2.55m, 4.36m, and 6.17m for the 3m, 5m, 7m target distances under this condition. This corresponds to distance underestimations of approximately 14%, 12% and 11% respectively.

The amounts of distance compression observed in both virtual environments, i. e., virtual city model and virtual replica, are remarkably smaller for the condition T-V under which subjects were in the transitional environment first. When subjects first performed distance estimation in the virtual city model and then in the virtual replica, they show a larger compression effect in comparison to those subjects who performed the distance estimation directly in the virtual replica. Although the difference is not large, it raises the question whether the underestimation of the virtual world can also be transferred back to a virtual replica; but this has to be examined in further studies.

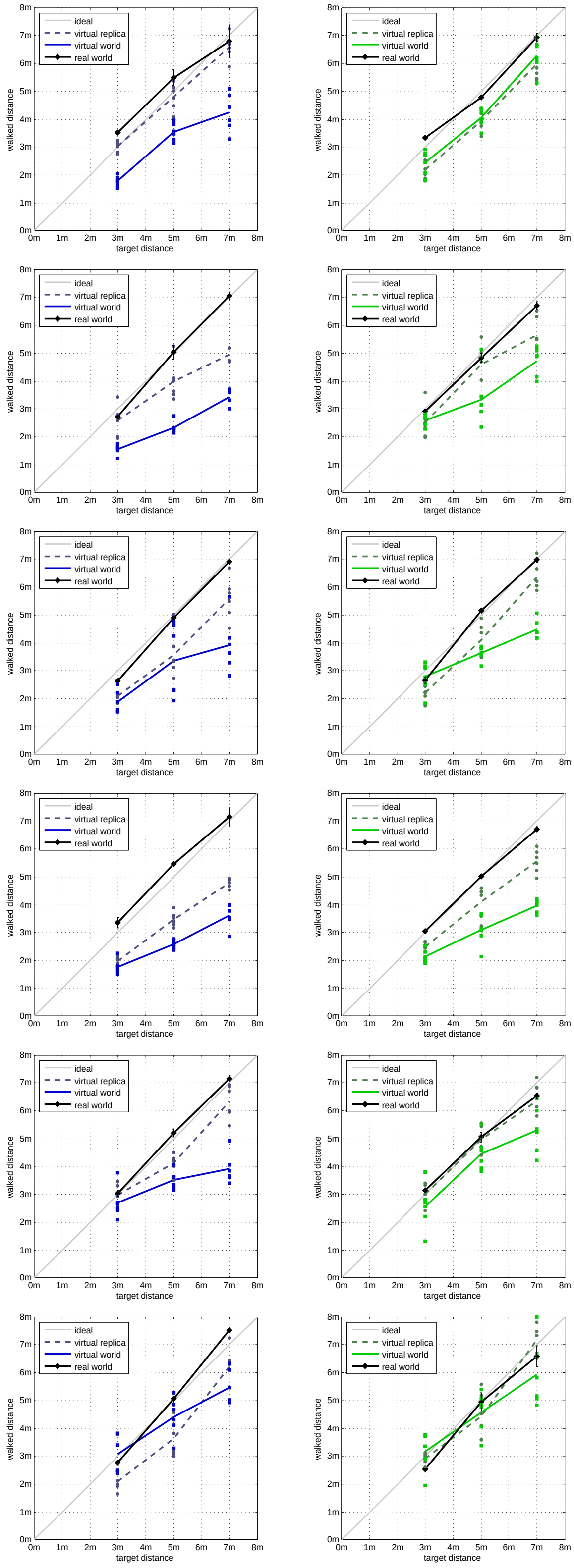


**Figure 3:** *Individual scatter plots of target distance versus walked distance over all trials for each subject (the plots on the left side show the results for the group V-T, the plots on the right side the results for group T-V; author's data is shown in bottom right figure).*

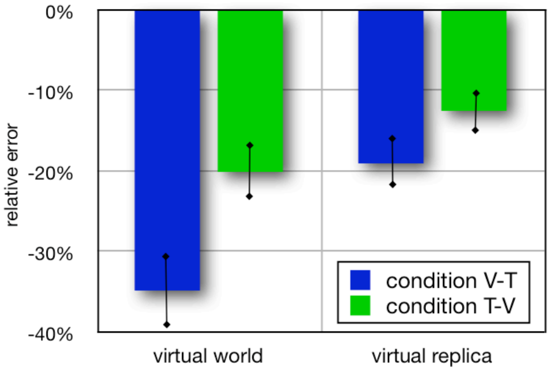


**Figure 4:** *Bar chart showing the average relative errors in distance estimation by subjects under condition V-T (blue) and condition T-V (green) in the virtual world and in the transitional environment, i. e., the virtual replica.*

To account for any effects from learning we also compared the distance estimation from the phase before the transition during the test phase versus the phase after the transition. Hence, we pooled the results from distance estimations from group T-V in the virtual replica, and the estimations from group V-T in the virtual city model, and compared them against distance estimations from group T-V in the virtual city model, and estimations from group V-T in the virtual replica. The results show that there was a slight (4%), but not significant, increase of the distance estimation skills.

Figure 4 shows the data for each VE, i. e., virtual city model and virtual replica, under both experimental conditions V-T and T-V, as the percentage of error collapsed across walked distance. In conformation with previous findings our subjects significantly tend to "walk shorter" in immersive virtual environments presented via head-mounted displays than they do in the real world. According to the results found in [Interrante et al. 2006], this compression effect is significantly larger for an arbitrary virtual world compared to the underestimation in a virtual replica. In the left chart, there is a large, statistically significant difference in the average distances traversed in the virtual world under the condition V-T, as compared with the condition T-V. When subjects entered the virtual world via a transitional environment (group T-V), they walked on average 15% farther in that VE in comparison to those subjects who entered the actual virtual world directly. Indeed, they still walked too short, but they performed significantly better than subjects from the group V-T. In the right chart we see that there is also a difference in the average distances traversed in the virtual replica under the condition V-T, as compared with the condition T-V. In this case, subjects walk shorter when they performed the distance estimation in the virtual world first, before they entered the virtual replica. Subjects starting in the virtual replica first (group T-V), walked on average 8% farther than subjects from group V-T. This may support the hypothesis that subjects are also transferring errors in distance estimation back to the transitional environment; they performed better, when they started directly in the virtual replica.

We analyzed our results using ANOVA. We found a significant ($\rho < 0.01$) increase of the subjects' walked distances under condition T-V in comparison to the distances subjects walked under condition V-T . We could not find statistical significance of the increase of the subjects' walked distances in the virtual replica when they started directly in the virtual replica in comparison to the walked distances when they were in the virtual city before ($0.05 < \rho < 0.1$).

The results from the user questionnaires did not show any significant differences. Subjects from group T-V revealed their self-reported sense of presence on average with $3.36$ based on the SUS questionnaire, whereas the answers of subjects from group T-V averaged on $3.53$. We expected this low self-reported sense of presence due to the consistently displayed guidance screen, which definitely caused numerous breaks in presence during the experiment. Subjects from group T-V estimated the difficulty of the tasks with $0.67$ in average on a 4-point Likert-scale, subjects from group V-T with $0.5$ ($0$ corresponds to very easy, $4$ corresponds to very difficulty). Furthermore, we have asked subjects about their fear of colliding with physical objects. The subjects revealed their level of fear on a four point Liker-scale ($0$ corresponds to no fear, $4$ corresponds to a high level of fear). On average the evaluation approximates $0.83$ for group T-V and $1.9$ for group V-T, which shows that the subjects felt quite safe. However, subjects tended to feel less comfortable when they started directly in the virtual world. Further post-questionnaires based on a comparable Likert-scale show that subjects from both groups only had marginal positional and orientational indications due to environmental audio ($0.15$) or visible ($0.0$) cues.

We measured simulator sickness by means of Kennedy's SSQ. The Pre-SSQ score averages for subjects from group T-V to $71.06$ (group V-T: $33.66$) and the Post-SSQ score for subjects from group T-V to $112.2$ (group V-T: $123.42$). Simulator sickness is an important, but common issue of VR systems, in particular in HMD experiments over a long period of time.

## 4 Discussion

When users were transferred from a transitional environment to a virtual city model they exhibited less compression of perceived distance than when they entered the virtual city directly. This suggests that users can transfer their distance estimation skills from the transitional environment, in which they can be certain that the displayed IVE represents the same environment that they are physically occupying, to a virtual 3D city model. The fact that we used random locations in the city environment–some locations were occupied with buildings and trees, others were more open space–lead us to believe that the improved distance estimation skills will hold across a variety of conditions if the user is gradually transitioned from the real world via a transitional environment to the virtual world.

We found evidence that subjects can transfer their distance estimation skills from the transitional environment to a virtual world. Combining these results with the previous finding that users have a higher sense of presence when using a transitional environment suggests that the problem of distance compression in IVEs may not necessarily be inherent to the technology. In fact, the results show that distance compression effects may stem essentially from higher-level cognitive issues in the interpretation of the virtual world in which users are immersed.

In summary, the usage of transitional environments has great potential as starting point to a VR experience, since two major issues of VR systems are addressed: namely, increase of user's sense of presence as well as enhanced distance estimation in virtual worlds. Self-reported comments of subjects also indicate that they prefer the usage of a transitional environment. For instance, one subject remarked:

> *"After walking through the portal, I really got the feeling of being transferred from the laboratory to the city."*

This was a typical comment of subjects using a virtual portal to get from a transitional environment to an arbitrary VE. The metaphor of a portal supports their notion of being transferred to another, but connected world.

The results, which show enhanced distance estimation when a transitional environment is used, were also confirmed by comments of the subjects. Four subjects remarked that it was definitely easier for them to estimate distances, and that they found it easier to orient themselves in the VE. In general, subjects have remarked that estimation and performance of motions have improved after they had visited the transitional environment. One subject observed:

> *"It was definitely easier for me to judge my movements [...], when I was in the virtual laboratory before."*

## 5 Conclusion and Future Work

In this paper we have analyzed the effects of a gradual transition from the real world to a virtual world on distance estimation in immersive virtual reality systems. We have conducted blind walking experiments, and the results suggest that when users start their VR experience in a transitional environment, they can improve their ability to estimate distances in an IVE system. Previous work has shown that the usage of transitional environments also increases a user's self-reported sense of presence [Steinicke et al. 2009]. For these reasons, we believe that a transitional environment has great potential to enhance the overall VR experience. In particular, the improved ability of users to estimate distances is of major interest for many application domains requiring accurate space perception, for example, architectural design or city planning.

Our findings agree with the presumption of Interrante et al. [Interrante et al. 2006] that distance perception in a virtual environment could be affected by the extent to which a person is willing to accept the VE as being functionally equivalent to the real world. This raises the question whether the improved distance estimation is due to an increase of the user's sense of presence or as mentioned above due to other higher-level cognitive issues in the interpretation of the presented virtual world.

In the future we will pursue these questions more deeply and explore more strategies to increase a subject's sense of presence as well as enhance spatial perception in VEs. We are particularly interested in the challenge to identify if other skills, which may be better in a virtual replica than in an arbitrary VE, can be transferred to the virtual world. The results of the experiments presented in this paper have brought up evidence that gradual transitions enhance the VR experience and make virtual reality environments more effective.

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