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Gradual transitions and their effects on presence and distance estimation

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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. Based on this observation, it sounds reasonable that if subjects feel a high degree of situational awareness in a known VE, their ability for estimating distances may be much better compared to an unfamiliar virtual world. This raises the question, whether starting the virtual reality (VR) experience in such a virtual replica and gradually transiting to a different VE has potential to increase a person's sense of presence as well as distance perception skills in an unknown virtual world. In this case the virtual replica serves as transitional environment between reality and a virtual world. Although transitional environments are already applied in some VR demonstrations, until now it has not been verified whether such a gradual transition improves a user's VR experience.

We have conducted two experiments to quantify to what extent a gradual transition to a virtual world via a transitional environment improves a person's level of presence and ability to estimate distances in the VE. We have found that the subjects' self-reported sense of presence shows significantly higher scores, and that the subjects' distance estimation skills in the VE improved significantly, when they entered the VE via a transitional environment.

1. Introduction and previous work

Virtual reality (VR) environments provide one of the most sophisticated technologies for human–computer interfaces developed so far. Because immersive VR systems are able to present information as seen from a user's perspective, these graphical user interfaces provide a unique experience and have great potential as an enabling technology for immersive exploration in many domains. For instance, they enable architects and engineers to experience virtual models at true scale. Although VR research has gone through a long history of refinement, there are still only few applications that use VR technology effectively to solve problems.

1.1. Presence in virtual environments

For a broad class of problems a common measure of the quality of effectiveness is the level of *presence* evoked in users. Basically presence has been thought of as a person's "sense of being there" describing the phenomenon that she feels and behaves as if she were in the virtual world created by computer displays [12,13]. If it is important that participants exhibit behaviors similar to those that would have been induced by comparable circumstances in everyday reality, then presence is essential. An ideal example from the broad class of problems is the use of immersive VEs for virtual therapy, for instance to treat various phobias (for example, [7]).

It is a well-known fact that humans not only have a feeling of being transported to the place displayed by a VE, but they also tend to act as if they were really there. Hence, to increase the sense of presence, it is essential to make users feel that they are in the VE; the experience should be like a place visited rather than just a series of pictures seen [5,14]. In most fully-immersive VR systems, real-world information is blocked out, i.e., there is a separation between the user and her current situation. According to [14] users might feel a higher sense of presence in the VE if it is presented as persistent space that can be entered and exited, and moreover, if the transition into the VE involves some notion of travel or detachment from the real world.

In the past different approaches have been presented and examined in how far they contribute to each of these factors. Presence can be supported by exclusion of real-world cues since these might interfere or be inconsistent with the presented VE [14]. Furthermore, presence can be enhanced by incorporating a virtual representation of the user into the environment (a "virtual

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body") [15,16], especially providing actual limb motion [22]. In addition, multimodal feedback in a VE increases the sense of presence, in particular if not only haptic and tactile feedback, but also audio and olfactory stimuli correspond to events in the VE [3]. Moreover, properties of the visual display have an impact on the user's sense of presence [25]. For instance, a wider field of view, realistic physical simulations [21], stereoscopic display [8], low latency [11] and also dynamic shadows of objects in a virtual environment contribute to a user's sense of presence [6]. When it comes to moving in the VE, real walking has been shown to be a more presence-enhancing locomotion technique than other navigation metaphors, i.e., walkers have a higher sense of presence than "flyers" or users navigating by walk-like gestures [16,23].

1.2. Distance perception in virtual environments

Several experiments have provided evidence that users often have serious problems to estimate distances in virtual worlds and to orient themselves. For example, researchers have found a compression of ego-centric distance perception in immersive virtual environments—in some cases up to 50% or more, relative to distance perception in the real world [9,10]. Moreover, visual speed during walking is underestimated in VEs, and the distance one has traveled is also underestimated [1]. Perceptual distortion of such magnitude could present serious problems for different applications and decrease the effectiveness of a graphical user interface.

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. Several experiments have shown that hardware issues can cause a small portion of the compression observed, however, an explanation for the larger portion of the effect remains unknown. In almost all previous studies the displayed virtual environment was different from the physical surroundings the user was present in during the experiment. Interrante et al. [9] suggest that the problem of distance compression in immersive virtual environments may stem, in significant part, from higher-level cognitive issues in the interpretation of the VE. In their experiments, subjects performed blind walking tests in a virtual replica of the subjects' real surroundings. Hence, subjects could be certain that the virtual world represented the environment in which they were physically present. In such a setup, the distance compression did not occur in such a magnitude as it has been observed in previous studies. 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.

1.3. Gradual transitions to the virtual world

The usage of a *transitional environment* between real and virtual world in order to increase the user's sense of presence or to improve the virtual experience in general is not a novel concept. Some projects have already used different concepts to provide a gradual transition from the real to the virtual world and in the opposite direction [22]. For example, Slater et al. [14] have performed an experiment called the "VirtualAnte" room, where subjects entered a virtual replica of the laboratory in which the experiment was taking place. Subjects moved through a door to a new virtual location and carried out the main experimental task. When they returned, box-shaped objects had been added to the virtual lab, and in the meantime one object, i.e., a telephone, had been moved within the real laboratory. After subjects returned to the real laboratory by taking off their HMD, they had to reveal their degree of surprise that the additional boxes were not there, and that the phone had been moved. Indeed, re-orientation to the real world is fast, but there is also a break from the virtual model back to real world. For example, participants are often disoriented and surprised about the direction they are facing when they take off a HMD.

Slater et al. [15] propose to use a virtual HMD within the virtual world in such a way that putting it on transfers a user to another virtual world. After taking off the last HMD, the user is returned to the VE from where she 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. [17] augmented a four-sided (three-walled) CAVE with a white curtain. This curtain was used for projection, and the participants could see a virtual CAVE with avatars inside. As a participant walked through the curtain, an avatar appeared for her on the curtain.

From this viewpoint it seems appropriate to provide users with a virtual replica of their real environment (usually the laboratory) such that they can accustom themselves to the characteristics of an immersive VR system, e.g., latency, reduced field of view or tracking errors, in a known environment. Furthermore, recent work suggests that a user has a higher situational awareness if the virtual environment equals the surroundings in which the user is physically residing when she is immersed in the VR system (cf. Fig. 1). After a certain time period, the user may enter the "actual" virtual environment, for example via a virtual door. This raises the question whether the benefits of a virtual replica such as a high situational awareness as well as an improved ability to estimate distances can be transferred to the actual VE. Until now it has not been verified whether the usage of a transitional environment increases the degree to which a user thinks that she is in the virtual environment and not the real world, or whether the distance estimation skills can be transferred from a transitional environment to the actual VE.

1.4. Virtual portals

In order to transfer subjects from the transitional environment to a remote virtual world such that they believe themselves to be in a new (but somehow "connected" environment), we have decided to use *virtual portals*. Portals are a common concept in science fiction and fantasy. The notion of 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 can transfer a user. A portal is commonly depicted as a graphical object, which consists of an interior and a frame. The interior defines the area the user has to pass through.

In our setup, when a subject is in the transitional environment, a button press on an input device – we use a WII remote controller – opens a virtual portal in the actual environment. In order to ensure that portals can be placed in arbitrary environments and at arbitrary positions in space, we use a multi-pass rendering technique exploiting the depth and stencil buffer available in almost all modern graphics cards [2]. 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 Fig. 2).

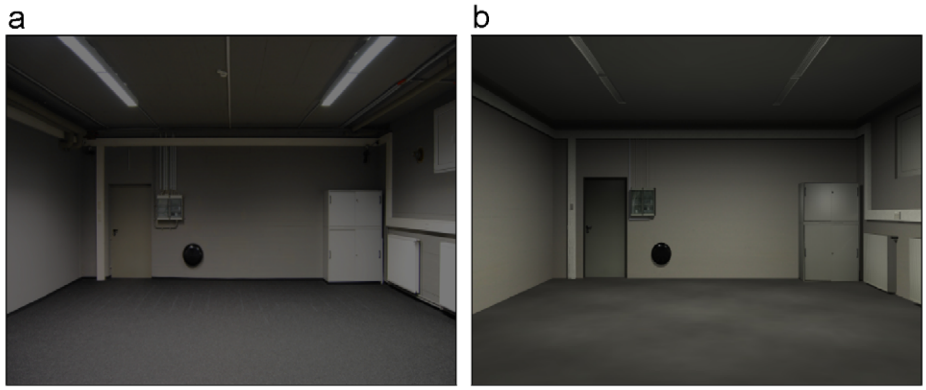

Fig. 1. (a) Photo of the laboratory environment and (b) computer-generated image of the transitional environment.

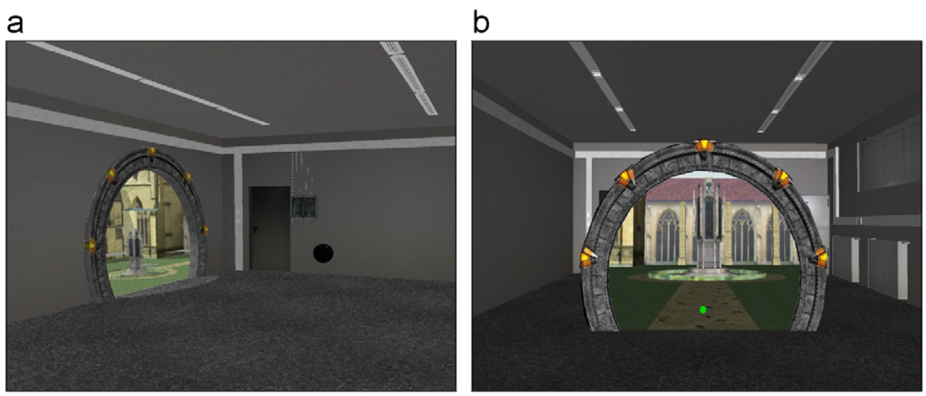

Fig. 2. Screenshots of different portal concepts: the virtual portal is (a) located on one of the walls of the transitional environment and (b) floating in the center of the virtual replica room.

We have implemented two different concepts for the placement of virtual portals: (1) attached to walls or (2) as floating objects. If the portal is floating in the transitional environment, a user can walk through the portal to get to the actual VE. However, if the portal is attached to a wall of the virtual replica a problem arises. Physical walls of the lab and virtual walls of the transitional environment are aligned in correspondence. Hence, a portal on a wall could not be passed. Therefore, after the user has pressed the portal button in the transitional environment, we applied motion compression approaches based on the results of [20]. We scaled the movements with a factor of 1.4. Thus, 1 m in the physical space is mapped to 1.4 m in the transitional environment. According to Steinicke et al. [20], such a manipulation cannot be observed reliably by a walking user. Hence, when subjects move to the virtual portal, they only walk 60% of the required virtual distance in the real world and are still located almost in the center of the physical laboratory space. Now the user can pass the portal without colliding with the physical wall. Furthermore, the same approach allows subjects to walk through a portal displayed on a wall in a VE to re-enter the transitional environment.

In this article we combine our previous works [19,18] and address the question if a transitional environment improves a user's VR experience. Therefore, we considered two aspects: a person's sense of presence and her distance estimation skills. We have measured presence in a virtual flight phobia experiment and distance estimation based on blind walking tests. Both experiments have been performed in a fully-immersive head-mounted display environment under two conditions: subjects were immersed in a VE immediately, or subjects visited a transitional environment represented by a virtual replica of our laboratory prior to the actual VE.

The remainder of the article is structured as follows. Section 2 describes the experiment that we conducted to measure the effects of a transitional environment on presence. Section 3 explains the experiment that we conducted to identify whether distance estimation can be improved by the usage of a transitional environment. Section 4 discusses the results of both experiments. The article concludes in Section 5.

2. Experiment 1: effect of transitional environments on presence

2.1. Materials and methods

In order to verify whether a transitional environment increases a subject's sense of presence we have conducted a virtual flight experiment under two conditions. Under the first condition (V–V) subjects immediately were immersed in a virtual airplane environment when they turned the HMD on. Under the second condition (T–V) subjects were transferred to the virtual airplane via a transitional environment. We wanted to analyze whether a gradual transition to the virtual world as used under condition T–V increases a subject's sense of presence in comparison to a subject's sense of presence under condition V–V.

2.1.1. Hardware setup and visualization environment

Both experiments were carried out in a $10\,m \times 7\,m$ darkened area of our laboratory. The subjects wore a HMD (eMagin 3DVisor

Z800, 800 × 600@60 Hz, 40 diagonal field of view) for the stimulus presentation. On top of the HMD an infrared LED was fixed. We tracked the position of this LED within the room with an active optical tracking system (Precision Position Tracker from WorldViz), which provides sub-millimeter precision and sub-centimeter accuracy. The update rate was 60 Hz 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 180 Hz. The InertiaCube was also fixed on top of the HMD. In the experiments we used a computer with Intel dual-core processors, 4 GB of main memory and an nVidia GeForce 8800 GTX for system control, rendering and logging purposes. In order to prevent any cues about the real world no communication between experimenter and subject was performed during the virtual flight.

The virtual scene (see Figs. 1(b) and 3) was rendered using OpenGL and our own software with which the system maintained a frame rate of 60 frames per second. As mentioned above we used two different virtual scenarios, i.e., a virtual airplane model (see Figs. 3(a) and (b)) and the transitional environment—which was a virtual replica of our laboratory (see Fig. 1). We combined the visual scene with different sound effects, e.g., engine noise, which were transmitted to the subjects via fully enclosed headphones. During the experiment the room was entirely darkened in order to reduce the subjects' perception of the real world. In addition we wrapped an opaque cloth around the subject's head.

2.1.2. Participants

7 male and 3 female subjects (age 23–53, ∅:32.6) participated in the experiment. Subjects came from backgrounds ranging from students to professionals with expertise in computer science, mathematics, psychology, geoinformatics, and physics. 3 subjects had no 3D game experience, 4 subjects had some, and 3 subjects had much game experience. Two of the authors served as subjects; all other subjects were naive to the experimental conditions. Four of the subjects had experience with walking in VR environments using an HMD setup. Subjects were allowed to take breaks at any time. Some subjects obtained class credit for their participation. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks and debriefing took 2 h. The entire experiment was performed within 2 days. We have used a within-subject design of the experiment. Five subjects have performed the experiment first with and then without transitional environment, whereas the other five performed the experiment in reverse order.

2.1.3. Measuring method

The main objective of this experiment is to show whether or not the sense of presence of a subject who has entered the virtual world via a transitional environment (condition T–V) is larger than a subject's sense of presence when she entered the virtual environment immediately from the real world (condition V–V). To measure presence we have analyzed subject's self-reported responses under both conditions based on the Slater–Usoh–Steed (SUS) presence questionnaire [24]. The questions are based on variations of three themes, i.e., sense of being in the VE, the extent to which the VE becomes the dominant reality, and the extent to which the VE is remembered as a place. Subjects had to rate each of six questions on a 1-to-7 Likert scale (where 1 means no presence, and 7 means high presence).

Indeed, subjective measures vary from person to person. However, in our experiment we were interested if and how strongly measures vary if the subjects have visited a transitional environment before. Each subject has performed the experiment under both conditions, and we analyzed relative differences.

2.1.4. Procedure

The virtual flight environment was the same under both conditions no matter whether subjects entered the virtual airplane directly or after they moved through the transitional environment first. In order to enforce subjects to stay the same timespan (≈ 10 min) in the VE, under this condition subjects had to walk 5 min in the airplane before the virtual flight began. Under condition T–V subjects had to walk 5 min in the transitional environment. In the following subsections we will explain both experimental conditions in more detail.

2.1.4.1. Condition V–V: virtual flight without transitional world. Before the virtual flight began, subjects had to walk to their assigned seat in a virtual airplane model (see Fig. 3(b)). Since we used two physical seats in the laboratory space, which were placed in correspondence to their virtual seat row, subjects perceived passive haptic feedback when they sat down. The accuracy between real and virtual seats was within centimeter range. A subject's view and the seat mock-up are shown in Figs. 3(b) and (c). After sitting down the virtual flight began. The flight took 3 min. Before, during and after the flight engine sounds indicated the state of the virtual flight acoustically. After the plane landed, subjects had to leave the plane via a virtual plank, which was presented by a physical plank providing passive haptic feedback. During the entire experiment noises transmitted via headphones supported the notion of a flight. We used sounds for background noise, instructions, take-off and landing. No communication between subject and experimenter was performed during the entire experiment. Before the experiment subjects were instructed to take off the HMD after they have gone across the plank.

2.1.4.2. Condition T–V: virtual flight with transitional environment. The materials and methods for condition T–V were similar to those for condition V–V. The virtual flight was identical to the virtual

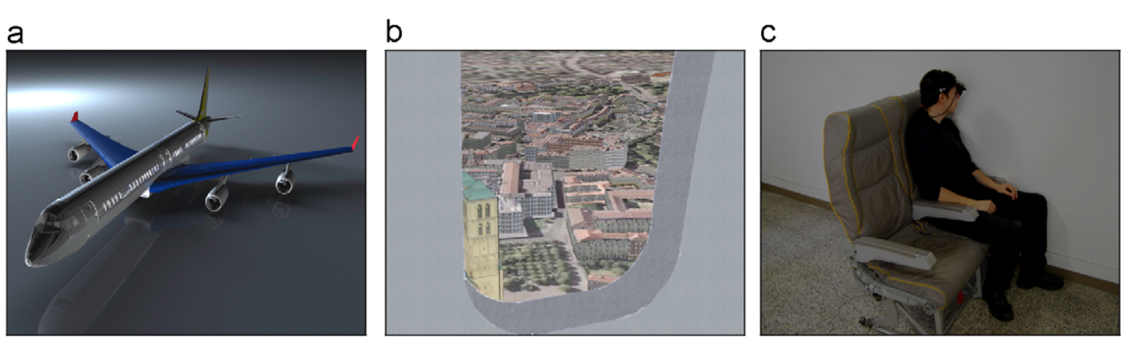

Fig. 3. Images from the virtual flight presence experiment showing (a) the used airplane mode, (b) the view through a window from a subject's perspective, who and (c) sits on a physical mockup.

flight presented under condition V–V, except that subjects had to walk to their seat immediately without walking through the airplane. Since we wanted to ensure that for both conditions subjects were immersed for the same period of time, they had to take their seat immediately, because they had already been in the transitional environment.

In contrast to starting the virtual flight experiment directly in the airplane, we used the virtual replica of the real environment for this condition. Hence, after having been equipped with the HMD, subjects saw a photorealistic model of the laboratory space used as transitional environment. In contrast to the situation in the virtual airplane, subjects could talk with the experimenter while they were walking through the transitional environment. We allowed this communication to indicate that they were not yet in the virtual world. Since the virtual model is a one-to-one copy of the real laboratory, subjects could walk around and touch objects like walls, doors, or cabinets. After approximately 4 min we told the subjects that they had to press a particular button, which was mounted on one of the walls of the laboratory, in order to open a portal to the virtual world, i.e., the airplane. The portal was displayed on the opposite virtual wall of the laboratory space (see Fig. 2 (a)) which initially was coincident with the corresponding physical wall and thus would prevent a walk through. Therefore, we have applied motion compression as explained in Section 1.4, which allows subjects to walk through the virtual portal without colliding with an obstacle obscuring the path in the real world.

After walking through the portal subjects have been transferred into the virtual airplane model. This transfer phase has been indicated via a 3 sec animation sequence with compelling sounds. Afterwards, the part of the virtual flight under this experimental condition has been performed identical to the condition V–V, i.e., when subjects started in the airplane directly. But instead of taking off the HMD after having crossed the plank, subjects were instructed that they had to follow the gangway until another portal occured. They were told that they could return to the virtual laboratory by means of this portal, again by simply walking through it. Another animation sequence showed a flight back to the laboratory. After a subject had been transferred back to the transitional environment, i.e., the virtual replica of our laboratory, sounds related to the virtual flight have been turned off and subjects could talk to the experimenter. Subjects had to press the button again in order to turn off the portal and to finish the experiment.

2.2. Results

Subjective evaluation of the virtual flight condition without transitional environment shows that subjects had only a slight self-reported sense of presence. This is indicated by the average score of 3.63 (σ=0.70) of the SUS questionnaires; no high rates, i.e., 6 or 7, were chosen by the subjects. The absence of vestibular stimuli during the flight, which could be experienced in a flight simulator, may be one reason for the low level of presence. However, as mentioned in Section 2.1.3 we were not focused on the absolute sense of presence, but on the sense of presence in comparison to the condition where subjects were in the transitional environment first. Thus, we wanted to examine whether the scores for the SUS questionnaires for condition V–V differ significantly from condition T–V.

In comparison to the first condition, subjective evaluation of the virtual flight with the transitional environment condition shows that subjects still had a slight, but increased sense of presence. This is underlined by the average score of 4.31 (σ=0.57) of the SUS questionnaires; 3 subjects answered three questions

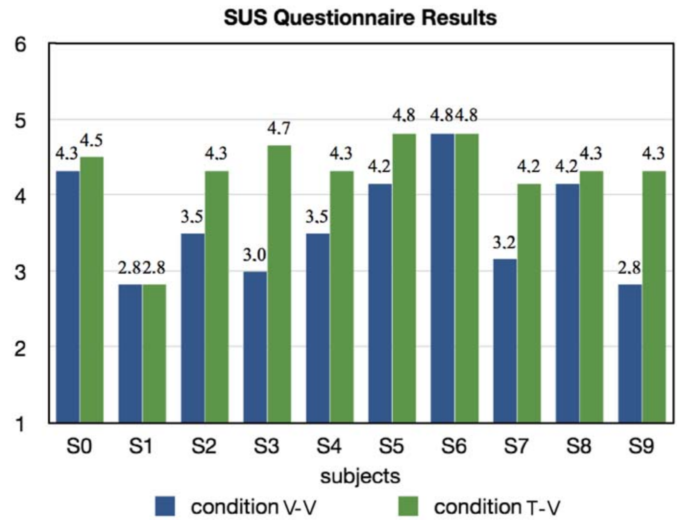

Fig. 4. Results of the SUS questionnaires for individual subjects S0,...,S9 under conditions V–V and T–V. Subjects S0, S2, S4, S7 and S8 first participated in the experiment using a transitional environment (condition T–V), the other subjects started first directly in the virtual airplane environment (condition V–V).

with 6. The virtual flight parts were identical for both conditions, but under condition T–V subjects had to walk through a transitional environment before and after the flight. The results of the SUS questionnaires shown in Fig. 4 indicate that the self-reported sense of presence has remained constant or has increased for *all* subjects. When the results are pooled the subjects' sense of presence increased by 19% under condition T–V. On average each subject increases her SUS scores by 0.68 (σ=0.59). The SUS scores for subjects, who have participated in the experiment under condition T–V first, show a higher sense of presence for both condition V–V (3.74 vs. 3.52) and condition T–V (4.32 vs. 4.28).

We performed a *t*-test of the means for the subjects' self-reported senses of presence under condition T–V and condition V–V and found a significant difference, which shows that the increase of the SUS scores from 3.63 to 4.31 is statistically significant ($p < 0.01$).

3. Experiment 2: effect of transitional environments on distance perception

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

3.1. Materials and methods

The apparatus as used in this experiment was identical to the one used in the first experiment. The only difference was the displayed virtual environment. In contrast to the first experiment, where we displayed a virtual airplane model behind the portal, we displayed a virtual 3D city model in this experiment. After donning the HMD subjects were told to adjust the displays of the HMD such that they could view the scene comfortably. 11 male and 1 female (age 25–34, $\varnothing$:27.8) subjects participated in the study.

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 transitional environment first and afterwards in the virtual city model. In order to get from the virtual replica room to the virtual city model and vice versa, subjects walked through a virtual portal, which we displayed as floating portal in this experiment. 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 3, 5 and 7 m. No feedback was given at any time during the test phase of the experiment.

3.1.1. Procedure

We tested three different distances (3, 5 and 7 m) 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 [4], 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. 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 3 and 7 m, 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 (3, 5, 7 m) 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 subjects walked the distance, they 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 the screen before walking.

When a subject believed that she reached the target, she 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 forced subjects to walk on circuitous paths, which we used to reduce feedback about their performance during the test phase.

After 18 trials (6×3, 6×5, $6 \times 7\,m^2$), a virtual portal appeared 2.5 m ahead from the subject's starting position in the center of the room (see Fig. 2(a)). We displayed the portal in the center of the virtual replica such that subjects could walk through the portal without artificial motion compression. 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. Fig. 2(b)), 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 5 and 7 m 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 (3, 5, 7 m) in randomized order.

In the baseline phase, we performed distance estimation tests in the real world in order to get a baseline for the subjects. The procedure was similar to the virtual distance estimation tests. Subjects saw markers on the ground at different distances (3×3, 3×5, 3×7 m) and had to walk blindfolded as in the test phase.

The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 2 h. Subjects were allowed to take breaks at any time.

3.2. Results

Fig. 5 shows 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 results 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. 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 2.97, 5.08, and 6.92 m for the 3, 5 and 7 m target distances. This corresponds to distance under- respectively overestimations of less than 2%.

Fig. 5(a) shows that there is quite a large amount of distance compression in the virtual city model under both conditions, increasing with target distance. The results show a slightly larger amount of compression in the virtual world compared to previous work [9]. This may be due to the small field of view of the HMD as well as the monosopic viewing situation. However, the amount of compression is greater under condition V–T, when subjects were in the virtual city model first. Subjects walked 2.13, 3.29, and 4.09 m for the 3, 5, 7 m target distances under this condition. This corresponds to distance underestimations of approximately 29%, 34% and 41%. 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 2.62, 3.86, and 5.11 m for the 3, 5, 7 m target distances. This corresponds to distance underestimations of approximately 12%, 22% and 26%.

Fig. 5(b) supports previous findings that distance compression effects are reduced in a virtual environment that 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

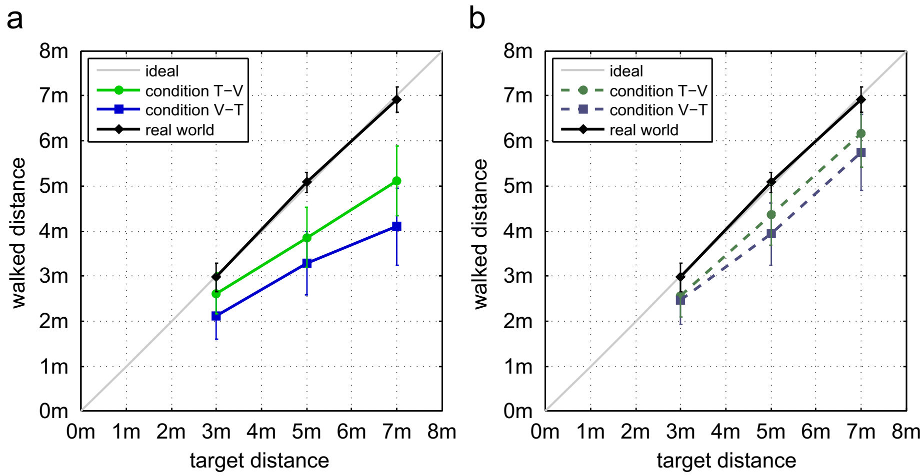

Fig. 5. Target distance versus distance walked under the two conditions (T–V and V–T), using pooled results from all participants for (a) blind walking in the virtual city model and (b) blind walking in the virtual replica. (a) Distance estimation in virtual city and (b) distance estimation in virtual replica.

2.46, 3.93, and 5.74 m for the 3, 5, 7 m target distances. This corresponds to distance underestimations of approximately 18%, 21% and 18%. When subjects started immediately in the virtual replica (condition T–V), the distance compression effect is smaller. Subjects walked 2.55, 4.36, and 6.17 m for the 3, 5, 7 m target distances under this condition. This corresponds to distance underestimations of approximately 14%, 12% and 11%.

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.

To reduce any effects from learning we also compared the distance estimation from the phase before the transition 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.

We performed a *t*-Test of the means for the subjects' walk distances under condition T–V and condition V–V. We found a significant ($p<0.01$) 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 for 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 ($0.05<p<0.1$).

4. Discussion

The experiments indicate that the usage of a transitional environment has the potential to increase a user's sense of presence as well as the user's ability to estimate distances.

Self-reported comments from subjects in the first experiment show that a subject gets more immersed into the virtual flight experiment under condition T–V, i.e., when she has entered the airplane via a transitional environment. We were surprised about the positive feedback concerning the application of virtual portals. The post-questionnaire has shown that subjects really preferred the usage of portals, which transferred them to the virtual world. As mentioned above the strongest impact of the usage of a transitional environment regarding the users' presence could be manifested by the subjective measurements. Self-reported comments of subjects indicate that they prefer the usage of a transitional environment. For instance, one subject remarked:

> "After walking and flying through the wormhole, I really got the feeling of being transferred to another world."

This was a typical comment of subjects. The metaphor of a wormhole supports their notion of being transferred to another world. Some subjects noted that acoustics were very important when they left the transitional environment and entered the virtual world.

In the second experiment, we found that 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 VE represents the same environment that they are physically occupying, to a virtual 3D city model. These results 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."

Hence, we found evidence that subjects can transfer their distance estimation skills from the transitional environment to a virtual world. Combining these results with the finding that users have a higher sense of presence when using a transitional environment suggests that the problem of distance compression in VEs may not only be inherent to the technology, but may stem also 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 a user's sense of presence as well as enhanced distance estimation in virtual worlds.

5. Conclusion and future work

In this article, we have analyzed the effects of a gradual transition from the real world to a virtual world on a user's sense of presence and distance estimation in an immersive VR environment. We have conducted two experiments. In the first experiment, we found evidence that the usage of transitional environments increases the users' sense of presence in the VE. In the second experiment, 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 immersive VE. For these reasons, we believe that a transitional environment has great potential to enhance the overall VR experience. Our findings agree with the assumption of Interrante et al. [9] 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 to 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. Due to many comments of the subjects about the benefits of virtual portals and their compelling sensation, we will examine these concepts. As opposed to using virtual transitional environments, one could also consider a physical mock-up as real transitional environment. For instance, the laboratory could be decorated as a waiting room at the gate before the user starts the virtual flight. It has to be examined in how far this approach, which is already applied in theme parks, further contributes to a user's sense of presence. The results of the experiments presented in this article have brought up evidence that gradual transitions have great potential to improve the overall VR experience.

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