Shadow-Avatars: A Visualization Method to Avoid Collisions of Physically Co-Located Users in Room-Scale VR

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Abstract

In a typical living room scenrario, the physical space might be shared by multiple virtual reality (VR) users. Although, they might collaborate in the same virtual environment, their *physical spatial relations*, i. e., distances and orientations between users in the physical world, might vary from their *virtual spatial relations*, i. e., distances and orientations between them in the virtual world. When physical and virtual spatial relations are not consistent anymore, collisions between users in the physical space could occur. However, the feedback about the positions of physically co-located VR users should be effective if required, but not disturbing otherwise. For such situations, we suggest to use *shadow-avatars*, which provide a visualization of the actual physical positions of co-located VR users to avoid collisions and accidents. For these shadow-avatars, we use a semi-transparent silhouette of a virtual human. We evaluated two different types of shadow-avatars in a user study and compared them with a baseline condition regarding presence, usability, and number of collisions. The results show that a continuously visible shadow-avatar is preferred by the users and a dynamically visible shadow-avatar generated significantly more collisions.

Keywords: Multi-User, Locomotion, Room-Scale, Collision Avoidance

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1 Introduction

When using consumer virtual reality (VR) hardware in a spatially limited everyday context, such as a living room, it might not only be possible but also necessary to leverage the same physical space for several users. Tracking systems, e. g., the lighthouse stations from HTC Vive, already allow the independent tracking of multiple head-mounted displays (HMDs). However, since VR users are fully immersed into a virtual environment (VE) they do not perceive the other co-located users in the physical world. Hence, to avoid collisions and prevent accidents, i. e., to make the VR experience safe for everyone, the physically co-located users have to be displayed in the VE in some situations. An obvious solution for this might be the use of avatars, which is unsuitable in most situations since an avatar usually suggests that there is another user that is part of this VE.

In general, two cases have to be differentiated: (i) the physically co-located VR users collaborate in the same VE, or (ii) the physically co-located VR users do not collaborate in the same VE.

In the latter case, the co-located users are not part of the VE of the other users, and would usually not be visible to each other. In the first case, we have to distinguish between the *physical spatial relations*, i. e., distances and orientations between users in the physical world, and *virtual spatial relations*, i. e., distances and orientations between them in the VE. In several situations, the physical and virtual spatial relations between users do not match, for example, their actual physical distances are different from distances between their avatars in the VE (see Figure 1). Such situations can happen due to several reasons, but most often it is caused by the difference between physical and virtual travel. For instance, virtual travel techniques, such as teleportation [3], move the user's virtual viewpoint while the user itself stays at the same position and orientation in the physical space. Furthermore, redirection techniques, such as redirected walking [7], are also based on a discrepancy between physical and virtual

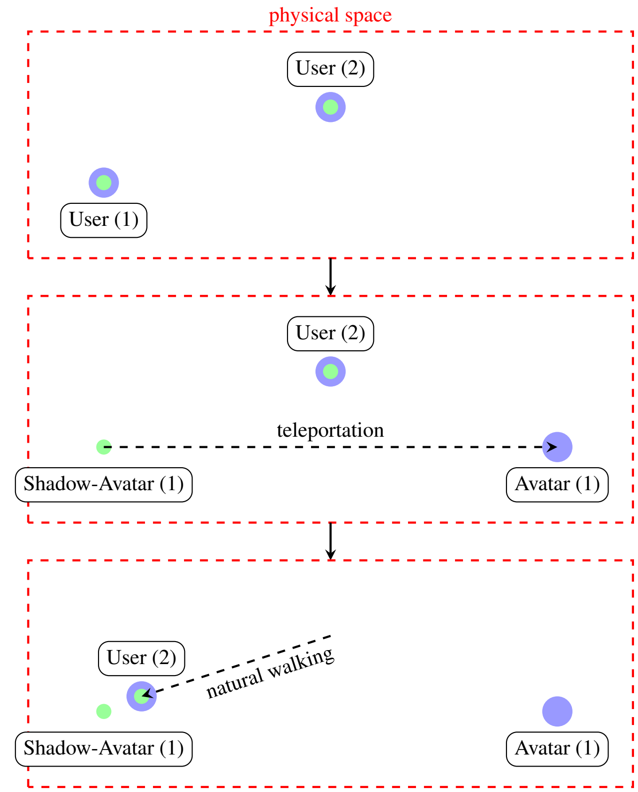

Figure 1: Illustration of the basic problem: Two users share the same physical space and collaborate in the same VE. The purple dots mark the users' virtual position and the green dots represent their physical position. In the beginning, both positions match. Then, user 1 changes her virtual position via teleportation but stays stationary in the physical space. User 2 would only see the representation of the virtual position of user 1 (avatar) and could collide with her physically when he walks around naturally in the physical space. Therefore, the shadow-avatar is needed.

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movements. Hence, virtual and physical positions do not match; even after small movements.

Therefore, in the VE there should be a distinction between the avatar, i. e., the user's virtual representation, which is displayed at the position in the VE, where the user has virtually navigated to, and the visualization of their physical location that is used only for collision avoidance. This collision avoidance method should warn the user in an effective way, but not break her sense of presence. Indeed, as long as no collision is imminent, the position and orientation of other physically co-located VR users is not important. In general, collision avoidance might be implemented visually as well as through audio or even haptic displays.

In this paper, we introduce shadow-avatars, which provide a visualization to prevent collisions between users by showing semi-transparent silhouettes of virtual humans representing them at their physical position. We tested two types of these shadow-avatars and evaluated them regarding presence, usability, and number of collisions.

The remainder of this paper is structured as follows. Section 2 presents related work. Section 3 describes the experiment and discusses the results. Section 4 concludes the work.

2 Related Work

Collaborative or Social VR is a topic in VR research since decades [2]. But there is almost no literature on collision avoidance of physically co-located VR users [5]. Simeone presented a solution to track and visualize non-participants that are not part of the VR experience but in the same room [10]. Redirected walking methods for two users that share a physical space were evaluated regarding their number of collisions [1]. Scavarelli et al. first introduced different collision avoidance techniques for physically co-located VR users [8]. They compared avatars, bounding boxes, and camera overlays in a user study. It turned out that each technique has different advantages and disadvantages. The camera overlay produced more collisions but was prefered by most participants. The bounding box had fewest collisions and the avatar offered quicker movement [8].

In their study, no collaborators were present in the VE. Therefore, participants stated that it may break presence to see an avatar when the user is actually not part of the VR experience [8].

Because of that, we propose shadow avatars in this paper. Shadow avatars might not be perceived as regular VR users because of their semi-transparent visualization.

3 Experiment

In our experiment, we evaluated two different types of shadow-avatars regarding their suitability as method for collision avoidance visualization. Therefore, we considered presence, usability, and number of collisions. In the experiment, for the safety of the participants, the shadow-avatars were just simulated, so that no actual collisions with another physical user could occur.

3.1 Participants

22 participants (8 female, 14 male, ages $18-31$, $M=23.9$) completed the experiment. The participants were students, who obtained class credit for their participation, or members of the local department of computer science. The most frequent response, i. e., the mode, when asked for the experience with VR in a range of 1 (no experience) to 5 (much experience) was 4 ($M=3.05$, $SD=1.29$). The experience with 3D computer games was individually different. When asked for played hours per week participants answered 9×0 hours, $6\times 1-5$ hours, $2\times 6-10$ hours, $4\times 11-15$ hours, and $1\times >15$ hours. The total time per participant, including pre-questionnaires, instructions, experiment, post-questionnaires, and debriefing, was around 30 minutes. Participants wore the HMD for approximately 15 minutes. They were allowed to abort the experiment at any time. Before the experiment, all participants provided informed consent and received detailed instructions on how to perform the experimental task. They filled out a demographic questionnaire and a questionnaire about their experiences with games and VR after the experiment.

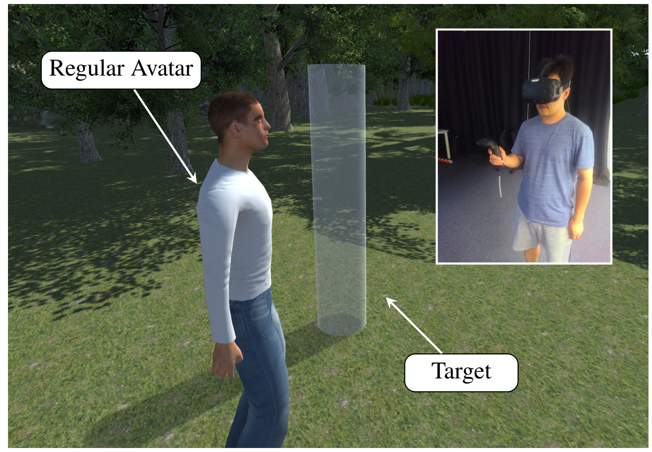


Figure 2: A scene from the VE of the experiment: the semi-transparent pillar in the center visualizes a target and the avatar on the left just crosses the walking path of the participant. The inset shows a participant of the experiment wearing an HTC Vive HMD.

3.2 Materials

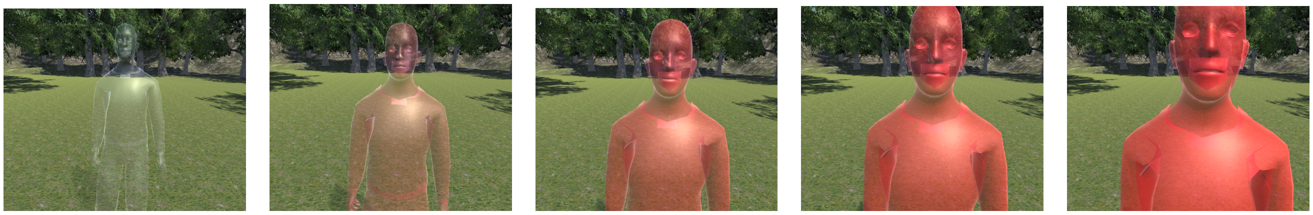
The experiment took place in a 6×10 m laboratory room. We instructed the participants to wear an HTC Vive HMD (see Figure 2 inset), which provides a resolution of 1080×1200 pixels per eye with an approximately 110° diagonal field of view and a refresh rate of 90 hz. Positional and rotational tracking was implemented by a lighthouse tracking system that is delivered with the HTC Vive. The lighthouse system was calibrated so that there was an available walking space of 4×4 m. An HTC Vive controller served as an input device via which the participants provided responses during the experiment. For rendering, system control and logging we used an Intel computer with 3.2 GHz Core i7 processor, 16GB of main memory and two Nvidia Geforce GTX 1080 graphics cards. The VE was rendered using the Unity3D engine 2017.1 and showed a natural outdoor scene including trees and grass to the participants of the experiment (see Figure 2).

3.3 Methods

We used a within-subjects experimental design. Each participant experienced three different conditions:

- C0 baseline condition without any avatar,
- C1 condition with avatar in combination with a continuously visible shadow-avatar, and
- C2 condition with avatar in combination with a dynamically visible shadow-avatar.

The baseline condition was the first condition for all participants while the order of the other two conditions was counter-balanced. In each condition, the participants had to navigate to several targets by natural walking. The targets were visualized as semi-transparent pillars (see Figure 2). Only one target was visible at a time. When participants reached the current target, it lit up green and the participants had to press a button on the controller. Then, it disappeared and the next target appeared. The distance between two targets was



(a) (b) (c) (d) (e)

Figure 3: The shadow-avatars that were used in the experiment: condition C1 used the avatar from (a) that was continuously visible throughout the condition, and condition C2 used a shadow-avatar that was only visible in a range of 1.25 m around the participant (a) and dynamically changed its appearance depending on the distance to the participant. The closer the participant came, the redder the avatar became (b-e).

3.5 m. In total, participants completed 16 walks per condition, i. e., walking 16 times the distance of 3.5 m.

In conditions C1 and C2, two avatars crossed the walking path of the participant: One regular avatar and one shadow-avatar (see Figure 3). In condition C1, the shadow-avatar was continuously visible and did not change its appearance. In condition C2, the shadow-avatar became only visible within a range of 1.25 m around the participant and dynamically changed its appearance depending on the distance to the participant: the closer the participant came, the redder the avatar became. We decided to use two avatars in each condition, the regular avatar and the shadow-avatar, because we wanted to simulate the mentioned scenario where physically co-located users share the same VE, and thus, two types of visualizations are necessary (see Section 1). In each walk, one of both avatars in the scene crossed the walking path of the participant. Which avatar crossed the scene was randomized, but both avatars occured equally frequent. The exact crossing position and its point of time were randomized. We mentioned that the avatars might cross the walking path of the participants but we did not instruct them how they should behave in case of a collision. We assumed that they would unconsciously avoid collisions with avatars when the visualization of the avatars induces social presence to the participants. This way, a lower number of collisions indicates a more suitable avatar visualization.

The number of collisions with both avatars, the regular and the shadow-avatar, was measured. A collision was counted when the distance between participant and avatar was less than 0.5 m. Furthermore, we measured the time per walk. The baseline condition, which did not include any avatars, was just used to measure time and walking paths in a regular VR setup. We measured VR sickness, sense of presence, usability and user preferences using questionnaires. The participants filled out the Kennedy-Lane simulator sickness questionnaire (SSQ) [6] before and after the experiment. In addition, the participants filled out the igroup presence questionnaire (IPQ) [9] after each condition and the system usability scale (SUS) questionnaire [4] after condition C1 and condition C2. Furthermore, they were asked to give qualitative feedback.

3.4 Results

Figure 4 shows the results of the user preferences. 17 participants preferred the continuously visible shadow-avatar and 5 participants preferred the dynamically visible shadow-avatar.

Table 1 shows the mean number of collisions with regular and shadow-avatars in the different conditions. A Shapiro-Wilk test showed that the data is not normally distributed. We analyzed the results with several Wilcoxon tests at the 5% significance level. We found no significant effect of the type of avatar (regular vs. shadow) on number of collisions in condition C1 ($p = .726$) but in condition C2 ($p = .018$). This means, participants collided significantly more often with the dynamically visible shadow-avatar than with the regular avatar. We found no significant difference between continuously and dynamically visible shadow-avatars ($p = .119$).

Condition	Regular Avatar	Shadow-Avatar
C1 (continuous):	M = 1.81	M = 1.95
	($SD = 1.4$)	($SD = 1.86$)
C2 (dynamic):	**M = 1.68**	**M = 2.45**
	($SD = 1.98$)	($SD = 1.68$)

Table 1: Mean number of collisions with regular and shadow-avatars in conditions C1 and C2. Significant differences are marked in bold text.

Table 2 shows the mean walking times in the different conditions. A Shapiro-Wilk test showed that the data is not normally distributed. We analyzed the results with several Wilcoxon tests at the 5% significance level. We found no significant effect of the type of avatar (regular vs. shadow) on walking times in condition C1 ($p = .592$) but in condition C2 ($p = .02$). This means, participants needed significantly longer when the dynamically visible shadow-avatar crossed their path than when the regular avatar crossed their path. Furthermore, we found a significant difference between continuously and dynamically visible shadow-avatars regarding walking times ($p = .01$)

Figure 5 shows the results of the SUS questionnaire. We measured a mean SUS-score of 84.43 ($SD = 11.47$) for the continuously visible shadow-avatar and a mean SUS-score of 76.36 ($SD = 11.89$) for the dynamically visible shadow-avatar. A Shapiro-Wilk test showed that the data is not normally distributed. We analyzed the results with a Wilcoxon test at the 5% significance level. We found a significant effect of the type of shadow-avatar on usability ($p = .001$).

Condition	Regular Avatar	Shadow-Avatar
C1 (continuous):	M = 6.18	**M = 6.08**
	($SD = 1.0$)	($SD = 0.96$)
C2 (dynamic):	**M = 6.28**	**M = 6.67**
	($SD = 1.27$)	($SD = 1.45$)

Table 2: Mean walking times in seconds in conditions C1 and C2 and seperated by walks that were crossed by the regular avatar or by the shadow-avatar. Significant differences are marked in bold text.

The mean IPQ-score for the sense of feeling present in the VE was 4.35 ($SD = 0.48$) for the baseline condition, 4.27 ($SD = 0.66$)

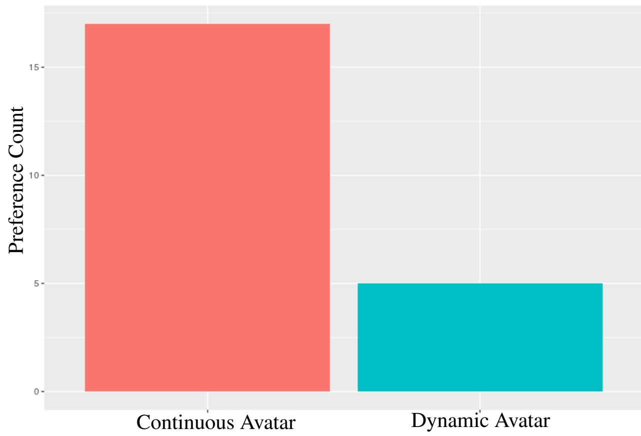


Figure 4: The continuously visible shadow-avatar was clearly preferred by the participants.

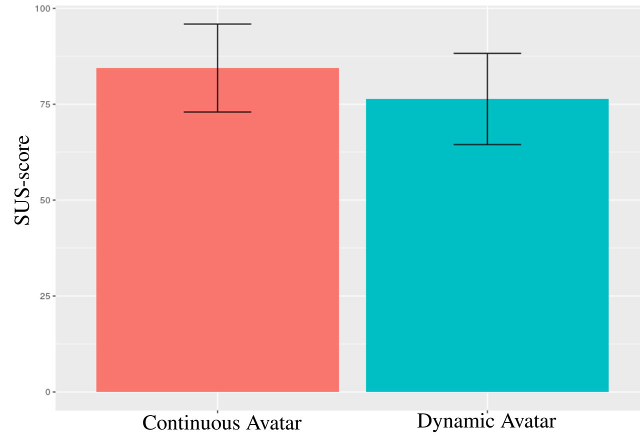


Figure 5: We found a significant effect of the type of shadow-avatar on usability.

for the continuously visible shadow-avatar and 4.26 ($SD = 0.59$) for the dynamically visible shadow-avatar. A Shapiro-Wilk test did not indicate that the assumption of normality had been violated. We analyzed the results with an ANOVA at the 5% significance level. We found no significant effect of the type of shadow-avatar on presence; $F(2,63) = .164, p = .849$.

We measured a mean SSQ-score of 11.56 ($SD = 20.08$) before the experiment, and a mean SSQ-score of 12.58 ($SD = 17.86$) after the experiment A Shapiro-Wilk test showed that the data is not normally distributed. Hence, we analyzed the results with a Wilcoxon test at the 5% significance level. We found no significant difference of the SSQ-score ($p = .526$).

3.5 Discussion

The results suggest that it might be advantageous to use continuously visible shadow-avatars. They were preferred by most participants and showed a significantly higher usability. Moreover, continuously visible shadow-avatars produced significantly less collisions than regular avatars and needed less walking times. Although, we did not find a significant difference between continuously and dynamically visible shadow-avatars, we could not observe an effect between dynamically visible shadow-avatars and regular avatars as well. The better performance of continuously visible shadow-avatars might be due to the better predictability. The participants could see the shadow-avatar all the time and did not have to fear a spontaneously appearing obstacle. This might also be the reason why they walked slower in the condition with dynamically visible shadow-avatars.

However, we did not find any significant difference between the conditions regarding the sense of presence. Hence, it seems as if the continuously visible shadow-avatar did not disturb the participants' feeling of being in a virtual environment.

During the qualitative feedback session after the experiment, multiple participants stated that they liked the color adjustments of the dynamically visible shadow-avatar. But they just felt more safe when they could see the potential obstacle the whole time. Probably, a combination of these two types of shadow-avatars might be an appropriate approach: The shadow-avatar should be continuously but faintly visible and increase its intensity when a user comes closer.

4 Conclusion

In this paper, we introduced shadow-avatars as visualization method for avoiding human collisions when physically co-located VR users share the same VE. Two different types of shadow-avatars were compared in a user study and results suggest that these shadow-avatars should be continuously visible to the VR users. In future work, a combination of both approaches should be evaluated since this was recommended by participants' feedback. Furthermore, the study might be repeated with multiple real users which can collide physically.

Acknowledgments

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