Go-Through: Disabling Collision to Access Obstructed Paths and Open Occluded Views in Social VR

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Figure 1: One avatar with ego-centric view approaches a second avatar in VR: (A) far away (B) closer (C) very close to the avatar (D) standing insight the other avatar perceiving multimodal feedback: vibrotactile feedback in the moment one steps into another avatar, a beating heart, dimmed lightning.

ABSTRACT

Social Virtual Reality (VR) offers new opportunities for designing social experiences, but at the same time, it challenges the usability of VR as other avatars can block paths and occlude one's avatar's view. In contrast to designing VR similar to the physical reality, we allow avatars to go through and to see through other avatars.In detail, we vary the property of avatars to collide with other avatars. To better understand how such properties should be implemented, we also explore multimodal feedback when avatars collide with each other. Results of a user study show that multimodal feedback on collision yields to a significantly increased sensation of presence in Social VR. Moreover, while the loss of collision (the possibility to go through other avatars) causes a significant decrease of felt co-presence, qualitative feedback showed that the ability to walk through avatars can ease to access spots of interest. Finally, we observed that the purpose of Social VR determines how useful the possibility to walk through avatars is.

We conclude with design guidelines that distinguish between Social VR with a priority on social interaction, Social VR supporting education and information, and hybrid Social VR enabling education and information in a social environment.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Computer supported cooperative work**; **Interaction techniques**.

KEYWORDS

Virtual Reality, Social VR, avatar collision, avatar collision response, avatar collision feedback

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1 INTRODUCTION

Social VR allows several users - represented through avatars - to simultaneously interacts with each other in real-time in a shared virtual world [14]. Social VR has gained tremendous popularity in recent years, for example, it is used for team-based firefighter training [19, 30], for virtual education [44], for post-stroke rehabilitation [45], as interactive virtual messenger [27], as virtual conferencing application [17, 18], and for socializing using VR chat and event rooms, such as *VRChat*[1], *AltspaceVR*[2], *Rec Room*[3], *Facebook Spaces*[4], or *High Fidelity VR*[5]. Moreover, VR games, such as *Echo*

[1]https://www.vrchat.net
[2]https://altvr.com
[3]https://rec.net
[4]https://www.facebook.com/spaces
[5]https://www.highfidelity.com

Arena[6], *Coco VR*[7], *From other Suns*[8], or *Sprint Vector*[9] allow for multi-player game experiences, e.g., to solve tasks together or to compete in races.

While, due to the physics of reality and the resulting safety aspects, a real space can often only accommodate a limited number of people, a large number of users can visit Social VR at the same time. Restrictions of reality do not have to be adopted in VR and a dedicated design of rooms, physics, and locomotion can help to solve problems crowded places in the real word have. For example, it is hard to perfectly see da Vinci's Mona Lisa in the real Louvre. Usually, many people visit this museum and occlude each others' views, hinder others from getting closer to the painting, or even insight the room. In a virtual Louvre, users could walk their avatars through other avatars and everybody could virtually stand all in the front of the painting at the same time.

Of course, obstructed paths and visibility can also occur with a small number of concurrent users. If the virtual environment is very small and angled, the described crowding effects can also be observed in environments visited by only two simultaneous users.

This paper aims to increase the usability of Social VR. In a user study, we investigated the possibility that avatars can go through each other, e.g., to explore content in an exhibition. We are also interested in understanding how collisions or passing through other user's avatar should be designed. Therefore, we test how multimodal feedback about the collision of avatars is perceived. As the presence in VR and the social component in Social VR are essential, we look at how the possibility to walk through avatars affects the sense of presence and co-presence. We also analyze if collision or walking through avatars would effect the user experience when being in Social VR.

We contribute with design guidelines, which addresses the handling of COLLISION and MULTIMODAL FEEDBACK in Social VR.

2 RELATED WORK

This paper aims at improving Social VR through overcoming the limitations of obscured paths and hidden views. Thus, we discuss works which previously explored collision handling, collision response, and collision feedback in virtual environments as well as techniques that enable users in VR to better move through VR that contains obstacles.

2.1 Virtual Collision Handling and Response

The handling of the physical properties of virtual objects includes collision detection [10, 16, 35] and collision response [22]. The research on collision detection dealt with different methods and approaches for the detection of overlapping virtual objects, which methods and approaches offer the best performance for the detection and calculation of collisions with a large amount of virtual objects, and how to react to these collisions.

Jacobson and Lewis compared ghost (user passes through object), clunk (complete stop when collision occurs), and slip (the motion is deflected so that it slides around the object) methods as response for collisions with static objects, such as like walls in VR [22]. They found a significant difference in task completion time for the different methods using a desktop setup. The results show that the slippery mode is an efficient strategy to resolve collisions in virtual environments that are difficult to traverse. Collision with movable obstacles, other avatars, and user impression in term of sense of presence or co-presence was not investigated.

Blom and Beckhaus investigated how virtual collision methods (stop, sliding, no collision) and feedback (audio and audio-haptic) influence the perception of the realism of collisions and the virtual environment [4]. The results suggest that the presence of a collision response significantly influences the perception of the realism of the interaction and the environment. The stop-response method (the user stops when a collision occurs) leads to a maximum of realism of the collision and impressions of the solidity of the VE. The sliding method (the user sliding along the contact surface) also significantly improves perception of the solidity of the walls, but has a less global effect.

2.2 Virtual Collision Feedback

Often, the system provides feedback when the user's virtual representation, the avatar, collides with a virtual object. Various types of feedback on collision, like auditory or haptic feedback, have been investigated.

Auditory feedback has mainly been applied as sound informing about collision. Suma et al. compared locomotion techniques for VR and provided a buzzing sound in order to draw the user's attention to collisions [43]. In this study, sound was not a research objective and the same feedback was given for all compared locomotion techniques. Blom et al. investigated *soundfloor*, an audio-haptic interface that provided virtual collision feedback for a projected VR system [5]. However, their results did not show an effect of virtual collision response on performance, participants had a clear preference for contextual feedback.

Haptic responses have been used as alternative feedback to inform the user that a collision happened. Prior research investigated vibrotactile feedback to improve collision awareness [6, 7, 31]. Louison et al. compared vibrotactile feedback with pure visual feedback in a simple tracking task [31]. They found that the visual feedback leads to a significant higher root-mean-square error for the distance of the object of the tracking task compared to the haptic feedback.

Bloomfeld and Badler showed that the use of vibrating full-arm feedback improves performance over purely visual feedback when navigating through a virtual environment [6, 7]. Bloomfield and Badler also investigated localized, close-up vibration feedback applied to the user's right arm [8]. They compared visual (color change) and vibrotactile notification for collision awareness on virtual training tasks. Their results show that the use of full-arm vibrotactile feedback improves the performance compared to purely visual feedback for navigation in the virtual environment and allows the easy acquisition of new skills.

Herbst and Stark investigated the use of visual, vibrotactile, and auditory substitutions for force feedback in a judge task of the weight and the friction resistance of virtual objects [20]. They found that when a combination of substitute stimuli was presented

[6]https://www.oculus.com/echo-vr/
[7]http://cocovr.magnopus.com
[8]http://gunfiregames.com/games/fromothersuns
[9]https://survios.com/sprintvector/

task performance improved in regards to correct discrimination of weight and friction resistance and task completion time.

Lécuyer et al.investigated the effect of additional haptic, visual, and acoustic information on the user's performance during insertion tasks in VR [29]. They found that none of the additional information had a positive impact on task completion time. However, the participants' movements when colliding were more limited if additional information is provided. Participants then seemed to pay more attention to the collision, but they also took longer to solve the task. Moreover, the participants mostly appreciate the different types of haptic feedback. These types were haptic directed assistance (haptic multidirectional information), simplified haptic assistance (haptic unidirectional information), and haptic vibration alarm. Participants perceived the different types of haptic feedback as useful, pleasant, and capable of improving the realism of the simulation.

As described above, Blom and Beckhaus investigated the impact of virtual collision methods and feedback on users' perception of the realism of collisions and the virtual environment [4]. Their results show that the feedback corresponding to the collision situation in combination with the stop collision method (the movement of the virtual body is stopped at the contact point) results in the best perceived realism of the collision and the scenario.

Burke et al. compared various research papers on visual-auditory and visual-tactile feedback effects [12]. They found that such additional information generally improves user performance.

2.3 Collision Avoidance in Virtual Reality

A large body of research investigated collision avoidance between co-located users in VR. Collision avoidance aims at preventing users from physically colliding with each other through avoiding that their paths overlap or through making them aware of the position of other co-located users [1, 2, 15, 21, 33, 36, 38, 41] or nearby objects in the real environment [13, 23–25, 42].

Further research investigated how the avoidance of collisions between virtual characters influences the degree of realism. When aiming at a high degree of realism, the virtual characters should behave in a way that their paths in the virtual environment does not cross the path of others as clashes between other (observed) virtual characters as well as clashes between the own avatar and a virtual character in VR reduces realism of the scene.

Benford et al., for example, implemented a framework for supporting crowds in Collaborative Virtual Environments (CVEs) and developed several types of crowds with different effects on spatial awareness and communication behavior [3].

Sohre et al. investigated in an experiment the impact of collision avoidance behavior for virtual characters on user experience in an immersive virtual environment [40]. In one condition, the virtual agents automatically avoided collision between themselves and the participant through dynamically adapting their path so that they keep distance to the participant's avatar. In the other condition, the virtual agents avoided the collision with each other, but not with the participant. Their results shows that users experienced a higher level of perceived realism, presence, and a lower level of discomfort and intimidation when virtual agents walk around

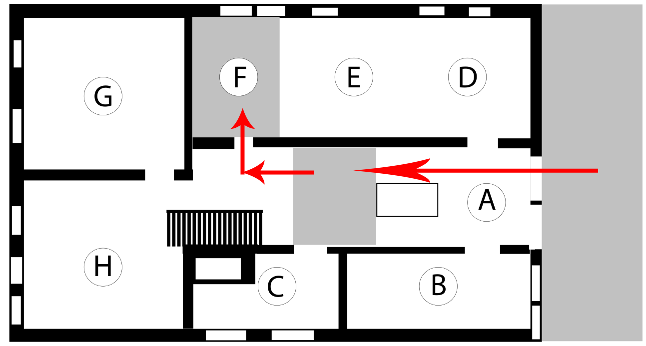


Figure 2: Floor plan of the ground level of the virtual museum. The grey areas were used during the experiment following the red arrows.

the participant than when they collide with them. Moreover, with collision avoidance participants took more direct paths.

Kyriakou et al. investigated the effects of collision between the avatar of a real user and the virtual crowd and their impact on perceived realism and ease of navigation in VR [28]. They found that preventing overlapping paths of the user and the virtual crowd makes the virtual characters, the environment, and the entire VR system appear more realistic and lifelike.

Bosch et al. investigated collision avoidance for small-scale immersive virtual environments with human-like virtual agents [9]. Their results showed that participants preferred collaborative collision avoidance: they expect the virtual agent to step aside to get more space to walk through while being willing to customize their walks.

2.4 Summary

Previous research covers techniques or responses when avatars collide with virtual objects.

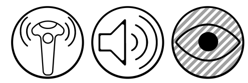
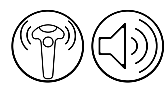
Moreover, while research on visual, auditory, haptic and multimodal feedback for collision response when colliding with virtual objects and walls has been done, no previous work looked into feedback on collisions between avatars.

Finally, previous work on collision avoidance explores avoidance of collision with co-located users or with virtual characters being in the same VR like one's avatar. While collision between co-located users has to be avoided to ensure safety, collision between virtual characters do not harm users; but has been shown to make the VR scene less realistic. Research that even forces collision and encourages to walk through other avatars to enrich the usability of virtual environments, for example, to access spots or to see content, has not yet been conducted. This paper addresses that research gap.

3 METHOD

In our study, we explored different techniques for collision handling when avatars in VR cross each other's way. As application we chose a virtual museum as it provokes several issues of Social VR. In virtual museums, avatars might stand in other avatars' way when

Table 1: Overview of the experimental conditions: collision and multimodal feedback

Visualization	Collision	Feedback	Multimodal Feedback
	COL_OFF	FB_OFF	
	COL_OFF	FB_ON	
	COL_ON	FB_OFF	
	COL_ON	FB_ON	

they want to reach exhibits or to look at objects occluded through other avatars.

We conducted the study implementing a Social VR that hosted two remote users. Our virtual museum was designed small enough to even rise issues of crowded places when only two avatars were in the room. For example, if one avatar was standing in front of an exhibit, the other avatar could not pass that location without colliding with the other avatar.

3.1 Experiment Design

Game engines allow to define physical properties of an object, in our case of the avatar. For example, collision can be switched on or off. If collision is switched on, objects (e.g., avatars) collide and cannot share the same position. If collision is switched off, objects (e.g., avatars) can share the same position, and an avatar can consequently walk through another. In our user study, we used that possibility to vary the collision in game engines.

Our study followed a 2x2 within subjects design with the independent variables COLLISION (COL_ON, COL_OFF), and MULTIMODAL FEEDBACK (FB_ON, FB_OFF), resulting in four conditions per participant. The dependent variables were PRESENCE, CO-PRESENCE, and USABILITY.

PRESENCE was measured using the presence questionnaire (PQ) by Witmer and Singer [47] in its modified version [46]. CO-PRESENCE was recorded using the questionnaire developed by Poeschl and Doring [37]. USABILITY was recorded using the System Usability Scale (SUS) questionnaire [11]. We also used semi-structured interviews to better understand the reasons of the rating measured in the questionnaires. Our questions for the semi-structured interviews were:

- What did you like about the presented or missing feedback (feeling when touching/overlapping with the other avatar)?
- What did you NOT like about the presented or missing feedback (feeling when touching/overlapping with the other avatar)?
- What did you like about the presented or missing collision with the other avatar?
- What did you NOT like about the presented or missing collision with the other avatar?

3.2 Participants

We recruited 24 participants (16 males and 8 females) from our university with an age range from 22 to 56 years ($M = 31.08$, $SD = 9.57$). Two participants (two male) have never been in a VR before, seven participants (six male and one female) have been once or twice in VR. The remaining 15 participants (eight male and seven female) have been three or more times in VR.

3.3 Apparatus

As apparatus we used a virtual museum [26] in which two users could be at the same time to explore the virtual museum and to interact with exhibits. The VR interface were two HTC Vive HMDs with their controllers. The VR scene was rendered on a PC with an Intel i5-7400 CPU, 16 GB RAM and Nvidia GeForce GTX 1060 GPU. The virtual museum application was implemented in Unity [10].

The virtual museum had many small and cramped rooms and spots where only one visitor could stand in front of an exhibit. Thus, this scenario allows us to create situations of cramped spaces and obstructed paths with only two avatars being in one virtual environment.

The virtual museum is an authentic historic house that consists of three levels, the ground floor, the first floor, and the attic. The ground floor, shown in Figure 2, consists of the entrance hall (A) directly behind the entrance as well as five further rooms and a sleeping chamber as an intermediate level, which can be reached directly from the entrance hall via a ladder. On the right side of the entrance hall, there is access to the orderly room (B) and the old kitchen (C). On the left side, there is access to a long room. This room is divided by curtains into the dining room (D), a sleeping area (E), and another dining room (F). Behind the entrance hall, two further rooms follow (H, G), which document the history of the historic building.

The experiment took place in the ground floor and in the area in front of the museum marked with grey in the floor plan. We selected these areas as they are small and thus, best provoke collision when two visitors are there at the same time. The red arrows define the path avatars took during the experiment. The experiment always started outside in front of the museum.

To avoid clipping (seeing into the body of the own avatar), we omitted the visualization of the own avatar for the experimenter's as well as the participant's view, in a way that one could neither see feet, legs, arms nor hands except the VR controllers of one's avatar, while the other avatar was fully visible. Not visualizing the own avatar does not bias our results shown through previous work of Lugrin et al. [32] and Murphy [34]. Murphy showed that users can experience sense of ownership and control of there actions even if there is no visible body part of their avatars, and a large number of investigated VR games (86.5%) also dispenses the visualization of their own avatar [34]. Moreover, Lugrin et al. found that body ownership, immersion, emotional, and cognitive involvements as well as the perceived control and difficulty do not improve with a visible or partial visible virtual body [32].

For the remote user, we used an avatar from the Unity Asset Store. The movement of the avatar in the scene was realized through the touchpad of the Vive controller (touch up = move forwards, touch down = move backward, touch on the left = move to the left, touch on the right = move to the right). The orientation of the avatar's head and walking direction was controlled using the head orientation of the user. We used Photon Unity (PUN)[11] to transmit the position and rotation of the remote user so that they were visible to the other one in VR.

For the condition with collision (COL_ON), the physicality was implemented similarly to how we experience collisions in the real world. When the one user collided with the avatar of the other user, the movement of the avatars stopped and they could not virtually step into each other. A displacement in the form of transfer of energy to the other users' avatar was not implemented. For the condition without collision (COL_OFF), both users could walk through the other user's avatar and share the same position in the VR. Then the avatar of the other user was made invisible to avoid clipping problems and to allow the view through the avatar model.

The variations of MULTIMODAL FEEDBACK have been slightly differently implemented for the conditions with feedback (COL_ON) versus without feedback (COL_OFF), see table 1. We designed the feedback aiming at a natural response on the collision variations. When somebody collides with a person in the real world, we bump into each other, feel this action, and hear the collision of two bodies. Accordingly, the condition COL_ON provided MULTIMODAL FEEDBACK on collision consisting out of a short vibration of the Vive controllers as haptic feedback and a short sound as auditory feedback in the moment the two avatars collide. To create the most realistic sound possible, which sounds like the collision of two people, we experimented with different sound sources. Finally, we recorded a punch in a pillow. This sound has a total duration of 775 milliseconds. The recorded impact of the punch starts after 37 milliseconds. The vibrations of the controllers started synchronously with the occurrence of the impact of the punch and was held for 100 milliseconds.

In contrast to the collision of two bodies, we do not have natural experience how it looks and feels when two bodies step into each other. We designed feedback that still should suggest such a situation. We imagined that when standing inside another person, the sight might be dimmed, and we might hear and feel the other person's heartbeat. Consequently, the MULTIMODAL FEEDBACK for the condition COL_OFF consisted out of a darkened view for both users (see Fig. 1), auditory feedback representing the second's person heartbeat [12], and vibrations of the Vive controllers synchronized to the heartbeat of the corresponding audio, which was held for 100 milliseconds for each heartbeat. The feedback was provided as long as one user's avatar shared the same position with the avatar of the other user.

3.4 Procedure

After welcoming the participants, they received general instructions, signed a consent form, and fill in a demographic questionnaire.

During the study, one Social VR user was a participant and one was the experimenter. Participants experiences both situation, one

[10] https://unity.com

[11] https://www.photonengine.com/en/pun

[12] https://soundbible.com/1612-Slow-HeartBeat.html

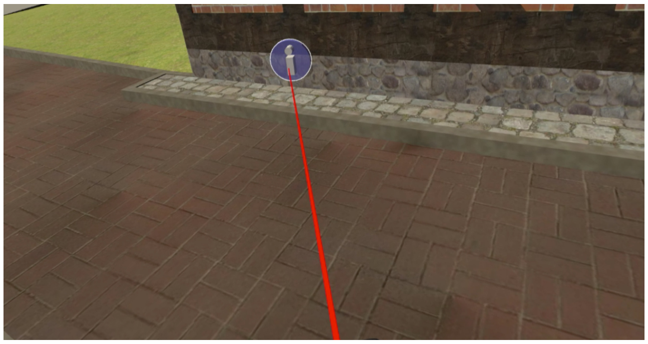


Figure 3: Selection of the info sign for object-related information

Figure 5: Display of object-related information

Figure 4: Display of object-related information

in which the experimenter provoked collisions with the participant and one in which the participants were encouraged to collide with the experimenter's avatar. All situations were experienced under our different conditions covering two variations of COLLISION (COL_ON, COL_OFF) as well as of MULTIMODAL FEEDBACK (FB_ON, FB_OFF).

Participants were equipped with an HMD and passed a short training phase in which they became familiar with the functionality of the prototype and the possibilities of interaction in the museum. In the beginning of the training, the position of the participants in VR was reset to the starting point, and the experiment has begun. The starting point was always set at the same point outside the virtual museum building for each condition and each participant. Then, the experimenter entered the VR as second visitor. During the training, the participants were asked to approach the building and to select one of the blue marked information signs (see Fig. 3) to see additional content (see Fig. 4, 5). This also served as training, as the participants later interacted similarly with the interactive signs during the conditions.

The experimenter could see when a participant interacted with content through highlighted signs or appearing content. Thus, the experimenter knew when the participant was exploring the exhibition, which we later during the conditions used to intentionally provoke collisions during times of content exploration to get quantitative and qualitative feedback on our approach.

Then, the experiment started. We counter-balanced the order of the conditions to avoid sequence effects. Every condition of the experiment followed a similar structure. This procedure ensured that participants experienced both, the actively as well as the passively caused collision, through, e.g., stepping into another avatar and experiencing another avatar stepping into them. First, before entering the building, the experimenter provokes collisions with the participant or stepped into them. These actions were taken so that the participant got experience with the collision handling of the current condition.

Then, participants were asked to follow the experimenter into the building. The experimenter stopped in the front door of the museum, and therefore, he blocked the participant's path through it. As the participants were asked to enter the door, they actively stepped through the experimenter's avatar or collided with him/her (with/without the feedback the conditions required).

Afterward, the participants were again asked to follow the experimenter, this time into the main room of the museum, where three large flags hang from the ceiling (see Fig. 4). Here, the participants were asked to choose an info sign and to select and read it. The experimenter again provokes a collision or stepped into the participants, approaching them from the direction best possible in the showroom (as that area is rather small). Then, the participants were asked to try to share the position of the experimenter (which again resulted in sharing the position or in a collision).

Then, the participant was escorted into a narrow space of the virtual museum and the process was repeated.

After completing this final part of each condition, participants were asked to remove the HMD and to fill in questionnaires. Before continuing with the next condition, participants got time to rest to avoid motion sickness and fatigue. In average, the experiment took about one hour, during that participants wore the HMD for approximately 20 minutes.

4 RESULTS

We analyzed the quantitative and qualitative data in a similar structure aiming at (1) identifying significant effects and (2) finding explanations that provide deeper understanding for the quantitative results.

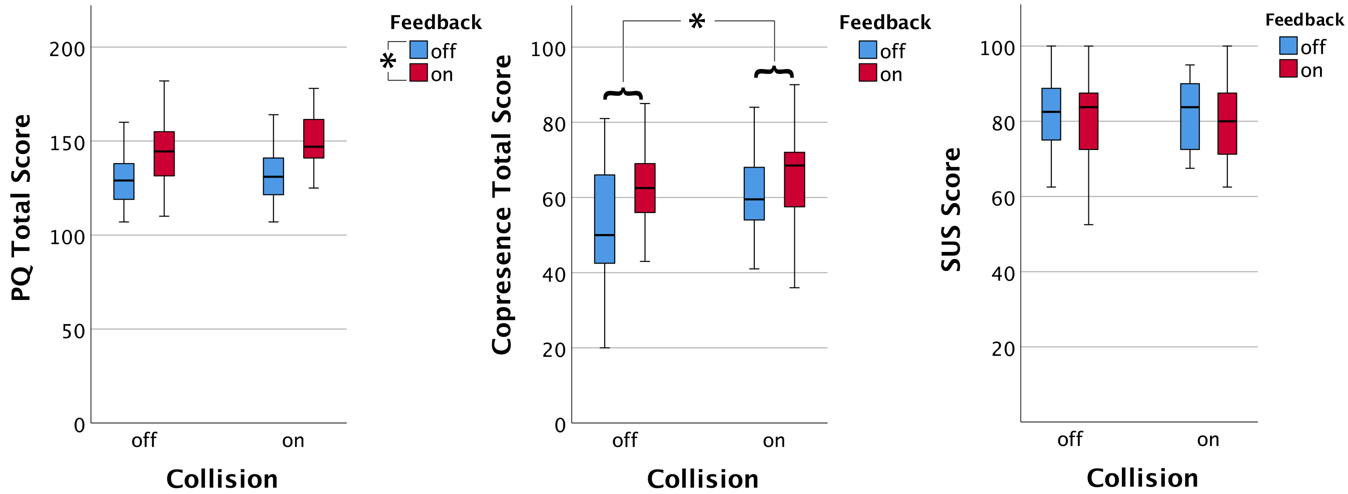


Figure 6: Presence Score (left), Co-Presence Score (middle), SUS Score (right).

4.1 Quantitative Analyses

Mann-Whitney U tests were used to indicate significant effects on the ordinal data presence, co-presence, and usability, with a Bonferroni correction applied, resulting in a significance level set at .025.

4.1.1 Presence. Descriptive statistics resulted in the following presence scores for collision: col_off$_{MEAN}$ = 137.29 (SD = 17.638), col_on$_{MEAN}$ = 140.90 (SD = 16.702) and for the multimodal feedback condition: fb_off$_{MEAN}$ = 130.729 (SD = 13.879), fb_on$_{MEAN}$ = 147.458 (SD = 16.160) (see Fig. 6).

Mann-Whitney U tests were used to identify differences in presence scores between the collision conditions col_off and col_on, and between the multimodal feedback conditions fb_on and fb_off. Mann-Whitney U test showed that *presence* was scored significantly higher for fb_on than for fb_off, $U = 118.0$, $z = -3.506$, $p < .001$, while no significant difference could was found between col_off and col_on, $U = 244.0$, $z = -.908$, $p < .364$.

4.1.2 Co-presence. Descriptive statistics resulted in the following co-presence scores for collision: col_off$_{MEAN}$ = 57.479 (SD = 14.835), col_on$_{MEAN}$ = 63.145 (SD = 12.508) and for multimodal feedback: fb_off$_{MEAN}$ = 56.75 (SD = 14.669), fb_on$_{MEAN}$ = 63.875 (SD = 12.323) (see Fig. 6).

Mann-Whitney U tests were again used to identify significant differences in co-presence score between the collision conditions col_on and col_off and between the multimodal feedback conditions fb_on and fb_off. The Co-presence score was significantly higher for col_on than for col_off, $U = 12.5$, $z = -5.684$, $p < .001$, while no significant difference could been found between fb_on and fb_off, $U = 180.5$, $z = -2.218$, $p = .027$.

4.1.3 Usability. Descriptive statistics led to following SUS scores for collision: col_off$_{MEAN}$ = 80.260 (SD = 12.582), col_on$_{MEAN}$ = 80.833 (SD = 10.136) and for multimodal feedback: fb_off$_{MEAN}$ = 80.678 (SD = 11.791), fb_on$_{MEAN}$ = 80.417 (SD = 11.053) (see Fig. 6).

Mann-Whitney U test were used to determine if there were differences in SUS scores between the collision conditions col_off and col_on and between multimodal feedback conditions fb_off and fb_on. The SUS score was neither significantly different between col_off and col_on, $U = 280.0$, $z = -.165$, $p = .869$, nor between fb_off and fb_on, $U = 266.5$, $z = -.444$, $p = .657$.

4.2 Qualitative Analyses

The qualitative data collected during semi-structured interviews was analyzed through closed coding using same categories as in the quantitative analyses: presence, co-presence, and usabilty to find explanations for the significant results identified through quantitative analyses.

4.2.1 Presence. The qualitative results indicate that multimodal feedback makes the situation more realistic, which yields to more presence (stated by 11 participants) and vice versa, no feedback on collision (fb_off) reduces the perceived realism, for example:

- *"It felt not realistic"* (P16, col_off).

Accordingly, when collision is activated (col_on) a majority of our participants (21) reported an increase in realism and naturalness:

- *"Not being able to go through another person adds realism"* (P24, fb_off).

Consequently, with a deactivated collision (col_off), our participants (9) reported a reduction in realism and naturalness:

- *"The overlapping did not feel natural and irritated me"* (P8, fb_on).

4.2.2 Co-presence. In terms of co-presence, nine participants mentioned that colliding with the other avatar gave a better feeling of being with another person in the same VR. That is in line with our quantitative analyses that indicated a significant increase of sensed co-presence if collision was provided (col_on):

- *"Liked, that its an object, that you cant pass. feels like another real person"* (P18, FB_OFF)).

Moreover, being with someone in the exhibition was appreciated and not perceived as distraction:

- *"You are undisturbed by other avatars and still have the feeling of not being alone."* (P19, FB_OFF)).

The lack of MULTIMODAL FEEDBACK decreased the awareness of a second person in the VR and was reported by five participants:

- *"Person could suddenly and unexpectedly come out in front of you, if I had not known that this is there, I would have been a little scared (visual feedback would have been nice to me)"* (P17, COL_OFF).

Likewise, feedback (FB_ON) helped six participants to better perceive the second person:

- *"It was clear that someone had collided with me" (translated)* (P17, COL_ON).

When lacking feedback (FB_OFF), and consequently no information about the collision or sharing of the same position was given, two participants felt even alone in VR:

- *"Felt very anonymous, especially when the avatar was behind you, you had the impression to be alone, since no feedback was triggered"* (P15, FB_OFF).

4.2.3 Usability. The qualitative information on USABILITY showed that if participants want to interact with content, such as reading the information boards, presence can become less important to them. Eight participants stated that missing MULTIMODAL FEEDBACK on collision can help to focus on the exhibition and its content. In that sense, feedback was perceived as disturbing by six participants while reading and exploring the exhibits:

- *"No feedback available. But it was also very pleasant. Senses were not distracted."* (P23, COL_OFF).

Similarly, eight participants indicated that they could better concentrate and more focus on the content and environment when no feedback was provided:

- *"The lack of feedback allows you to better focus on the environment."* (P19, COL_OFF).

Six participants interestingly perceived the appearing MULTIMODAL FEEDBACK as disturbing and annoying, especially when the additional information was selected and read, which leads to decreased USABILITY:

- *"It felt disturbing in that situation, more disturbing than without a feedback."* (P12, COL_ON),

Free and unrestricted movements, when bodies did not collide (COL_OFF) was appreciated and found beneficial as the other avatar did not block the path, which was stated by 14 of our participants:

- *"I liked that I was not stopped going to places."* (P10, FB_ON).

The benefit of walking through others' avatars might depend on the spatial dimensions:

- *"Missing collision was good in small rooms"* (P22, FB_ON).

Being not able to walk through other avatars (COL_ON) was negatively perceived by eight participants, no matter what feedback was provided:

- *"I didn't like that it prevented me from going to some places, and it distracted me from my experience while reading."* (P10, FB_ON).

5 DISCUSSION

We first discuss or results according our dependent variables: PRESENCE, CO-PRESENCE, and USABILITY. Afterward, we derived design recommendations for Social VR, and last, we reflected on the limitations of our experiment.

5.1 Presence

We found that the sensation of PRESENCE significantly increases when MULTIMODAL FEEDBACK is provided, which can be confirmed by the answers of the semi-structured interview.

Feedback, when bumping into an avatar, was related to the natural experience known from the physical world. This result is in line with the results of a pilot experiment by Slater and Usoh [39]. They indicated a reduction in the felt PRESENCE if the virtual world did not behave as expected and violated the laws of physics.

5.2 Co-Presence

Our results show that the awareness of other avatars significantly increases if the own avatar cannot walk through them. The analysis of the qualitative data supports these findings and shows that the users preferred to maintain the collision as such behavior feels more realistic and natural. Through the higher degree of realism, the feeling of being together with another person in VR increases.

5.3 Usability

However, we found no statistically significant differences in usability ratings, qualitative feedback indeed let suggest that if collision is provided and avatars can not go through each other, no feedback on collision is preferred. Such feedback was in the exhibition context perceived as disturbing information as the focus was on the environment (reading, exhibits) and not primarily on the other avatar.

Interestingly, if avatars could walk through each other, the feedback was perceived as less disturbing and even appreciated. One may assume that reading AND collision AND feedback on collision might cause cognitive information overload.

Consequently, when participants interact with content, such as reading museum content, they may perceive collision feedback (when somebody bumps into them) as distraction. When one reads an exhibition label and somebody bumps into them and collides, they cannot continue reading without noticing. To continue with reading seems here to be more important than getting informed about the collision.

5.4 Design Recommendations

Our findings show that there is no single answer to our research question if walking through other avatars creates more usable Social VR. Especially qualitative feedback helped us to understand that the purpose of the Social VR system as well as the goal the user has in a certain situation determines how collision and its feedback should be implemented. Therefore, we distinguish different types of Social VR and derive design recommendations for each of them separately.

5.4.1 Social VR focusing on social interaction. The prior intent of certain environments is the social interaction between the users. Awareness of the other user is necessary for social interaction. Sharing the same position hinders social interaction because users cannot see each other. The degree of perceived CO-PRESENCE increases when the collision is maintained, and the collision behavior corresponds to how we expect collision of bodies in the real world. We recommend to provide COLLISION to foster social interaction and to provide MULTIMODAL FEEDBACK to be aware of the other user.

5.4.2 Social VR focusing on education and information. In the physical world, many people visit education and information environments, such as libraries, museums, and universities. To ensure that people in such environments can focus and concentrate on the essentials, they are more willing not to disturb others. We found that collision can be perceived as disturbing and that the possibility to walk through an avatar to see the information that they block and occlude can increase the ability to focus on content and information. Even MULTIMODLAL FEEDBACK on a collision can be perceived as a distracting and disturbing factor. In order to focus on information, we recommend avoiding both, collision and MULTIMODAL FEEDBACK in information spaces and learning environments.

5.4.3 Hybrid Social VR focusing on social education and information. Learning environments can serve hybrid purposes and enable social interaction in a virtual education space. For example, users may discuss information and collaborate during their learning experience. Depending on the users' goals, such environments should be able to adapt to the respective needs, tasks, and, intends. We recommend to situation-dependent apply the specific design recommendations of Social VR focusing on social or educational aspects depending to the current situation.

5.5 Limitations

In our experiment, we investigated Social VR in small virtual environments with two avatars. We assume that our results scale also for many avatars in larger environments. Future is required to investigate if our guidelines can purely be adapted for large and crowded Social VR or if further issues have then to be considered, such as handling with noise when many avatars are in the same space.

As collision cannot be switched off in physical reality, our results cannot be used for VR with co-located users.

6 CONCLUSION

In this paper, we have investigated whether the possibility of walking through avatars (versus colliding with them) can increase the usability of virtual environments, especially when users aim at accessing certain spots in small rooms and perceiving content, which is a typical case in virtual exhibitions and museums.

Results of a user study show that colliding with others' virtual bodies can increase the sensation of presence if multimodal feedback on the collision is given, which references to our real-world experience when bumping into each other.

While in cramped spaces, the ability to walk through someone is beneficial for locomotion, the possibility of going through another body leads to a lower perceived CO-PRESENCE. Such behavior decreases the sense of being with another person in VR. Thus, it depends strongly on the user's intention and on the preformed task, whether or not collision is desired.

Therefore, we derived purpose-dependent recommendations on how to design collision between avatars and the respective feedback considering the user's intent in Social VR. Through these design recommendation, we hope to help researchers and practitioners to design and to develop better, useful, and enriched Social VR in which users can socialize as well as perceive content dependent on their current desire and need.

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