Preventing Imminent Collisions between Co-Located Users in HMD-Based VR in Non-Shared Scenarios

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Abstract

This paper presents two experiments set in a multi-user HMD-based VR system where users navigate by real walking in a large real and virtual area. We investigate a case that could be used in a multi-user VR game or a training application: several users are walking in the same physical space without seeing each other in the virtual environment. Such a scenario involves the risk of collisions between users. In the first experiment, we investigate the strategy of stopping a walking user in a dangerous situation. In particular, we compare the effectiveness and the perceived difficulty of two visual and two auditory stopping signals. The results of this comparison show that the tested visual and auditory signals are equally effective in stopping users. With both visual and auditory signals, participants prefer the signal to contain a ”stop” command. In the second experiment, avatars are displayed at users' positions if the distance between users is dangerously small. The method is tested with four avatars of various degrees of anthropomorphism and in two different application scenarios. Our results suggest that the type of scenario influences users' preference of a notification avatar. It is sufficient to display an area occupied by other users in scenarios with specific goals and interactive content. If users are exploring a virtual world without having any other goal, they prefer to see human-like avatars as a possible collision notification.

Keywords: immersive virtual environments, multi-user Virtual Reality, collision prevention

1 Introduction

In recent years, HMD-based VR systems have been developed that allow their users to explore virtual environments (VEs) by physically walking in tracked spaces of large scale, of the size of a gym [1, 2], or even a football field [3]. Indeed, navigation by real walking has been extensively studied and proved to be beneficial for user experience. It has been shown to improve users' immersion [4] and to positively contribute to task performance [5, 6]. A number of VR applications require a multi-user setup in which navigation by walking is possible [2]. Systems have been developed that satisfy these requirements [1, 2, 7]. Our research concerns precisely these systems: multi-user, where users are fully immersed in a VE with HMDs and can walk or even run in a large physical area.

When building an application based on a large-scale setup with co-located users, scenarios are possible where VEs or at least parts of them are not shared by users. An example is a large collaborative scenario that takes place in a building with multiple floors. Such scenario can be used in a game or in a team rescue training application, for example for fire-fighters. Players start the game on the ground floor and spread out in different directions to explore the virtual building. Some of them go to different floors and therefore are no longer visible to the players who stayed on the ground floor. Meanwhile, all players stay within borders of the same tracking space. Since players do not see or hear what is happening in the real space around them [8], there emerges a danger that they walk or run into each other.

We focus on situations where walking players are dangerously close to each other and a collision is likely to occur within a short period of time. In such circumstances, a robust method is needed that would allow to prevent an imminent collision. One possible way to prevent an immediately approaching collision is to stop involved players. However, having to stop suddenly during the VR exposure can provoke breaks in presence and negatively affect user experience. Therefore, we suggest an alternative strategy: to allow the involved users avoid a collision on their own by temporarily displaying avatars at users' positions.

The effectiveness and plausibility of neither of these two approaches to the imminent collision prevention has been investigated before. This paper reports two experiments set up to explore the potential of both strategies. In *Experiment 1*, we use four different notification signals to stop users walking in VR. We then compare the signals in terms of their effectiveness and perceived difficulty. In *Experiment 2*, we use avatars to notify two users simultaneously exploring a VE about a possible collision at a near distance. We investigate how the visual appearance of notification avatars affects user experience. Four avatars reflecting various degrees of anthropomorphism are used to test our main rationale: a notification avatar should be distinct enough to allow successful collision avoidance yet it should not disrupt users' experience of individually exploring a virtual world.

The contribution of this work is the first to our knowledge experiment on imminent collision prevention conducted with pairs of walking in VR users. Its findings can be helpful for the development of multi-user VR applications with non-shared VEs.

2 Related Work

2.1 Collisions in VR

A large body of research on collisions in VR investigates collisions with static virtual objects. Blom and Beckhaus investigate the influence of the collision response on the perception of a VE [9]. Their results show that the stop handling method, coupled with feedback fitting the collision context, positively influences the perceived realism of collisions. Based on this work, Alfonso and Beckhaus suggest an aural notification method to prevent collisions with virtual geometry. In their study, constant directed sound feedback notifies users of the proximity of the walls in a virtual maze. Provided with such notification feedback, users collided with walls less frequently than without it. Both studies were performed in an immersive projective display (IPS) system with a wand used to navigate through the maze. However, virtual trajectories of users navigating in a VE highly depend on input and output devices [10]. Thus, a combination of a wand as navigation input and an IPS as an output device is likely to produce different results than a combination of real walking and an HMD.

Several studies compare collision avoidance behaviour of humans physically walking in the real world and in VEs. The results show a decrease of walking speed and an increase of the clearance distance when avoiding a collision with a static virtual object compared to its real counterpart, tested in an IPS environment [11] and with an HMD [12]. Furthermore, there is evidence of users keeping more distance to an anthropomorphic obstacle than to an inanimate object [11]. However, situations where physically walking users avoid moving obstacles or other users in immersive VR have not been studied. Research of Olivier et al. on pairwise interactions between walkers in the real world shows that walkers adapt their movement trajectories only when required [13]. It is proposed that walkers' collision avoidance behaviour can be described by a mutual function of their states noted as minimal predicted distance (the anticipated crossing distance at every moment of time). In the carried out user study, participants adapted their walking trajectories to avoid a possible collision only when the minimal predicted distance was lower than 1m. There is evidence that users are also able to predict whether they would collide with walking virtual humans or not and correctly choose their collision avoidance strategy [14], the study however being conducted in a desktop setup.

Situations with two users simultaneously walking in the same physical space while being immersed with HMDs in individual, non-shared VEs are addressed only by a few studies. An experiment with two users walking side-

Figure 1: From left to right: the stop sign used in *Exp.1*, the photo-realistic human avatar used as the figure signal in *Exp.1* and Human avatar in *Exp.2*, Spaceman, Robot and Shape avatars used in *Exp.2*, a pair of users in full gear during the Game task of *Exp.2*.

by-side with HMDs and headphones investigates whether users who do not see and hear their test partners in a VE could notice their proximity in the real world [8]. The results show that users do not notice each other at distances as small as 1m, especially if they are not actively trying to localize each other. Another work presents a collision prevention algorithm for several users walking in an immersive VE [15]. The algorithm is developed for a specific case where users are being steered away from the walls in the real room by a redirected walking method [16]. The method consists of two parts: collision prediction based on the redirected walking assumption and collision avoidance. Collision avoidance is performed by either steering users away from each other or by stopping them to avoid an imminent collision. The method is tested in a simulation on recorded paths of individual users walking in the tracking laboratory. Research on collision avoidance strategies used by walkers in the real world shows that collision avoidance is performed collaboratively and includes complex interaction between subjects [17]. Mutual collision avoidance behaviour of users walking in a VE has not been tested. However, it is likely to be based on similar principles. Therefore, we believe that it is crucial for an imminent collision prevention strategy to be tested with real walking users and not in a simulation.

2.2 Stopping Walking Users in VR

As to our knowledge, no previous studies in HMD-based VR investigate directly the task of stopping walking users. The aforementioned research on mutual proximity awareness [8] involves situations where users are stopped, with the use of a stop sign rendered in front of them. The effectiveness of this method is not reported. However, users are walking at controlled and low speeds of 0.3 m/s and 0.7 m/s. It is to expect that users are able to stop easily in such test conditions. Another work on non-shared VEs suggests to stop users when necessary by blanking their HMDs and displaying the word ”stop” [15]. The approach assumes the reaction time of 1 sec, however only used in a simulation. No different signals for stopping users are tested in any of the above work. Neither is it investigated how fast users can actually stop while walking in VR. Our intention is to fill this gap in *Experiment 1* where we separately test two visual and two auditory stopping signals.

2.3 Avatars in Immersive VR

Virtual humans can be used as agents steered by artificial intelligence and as avatars representing users in VEs. Effects of both agents’ and avatars’ appearance and responsiveness on presence, virtual body ownership and co-presence are well studied in immersive VR as well as in collaborative virtual spaces. Here, we only discuss work that is especially relevant to our research.

More elaborate avatars have higher success rate in social encounters [18]. Similarly, agents with higher responsiveness contribute to a higher degree of co-presence, or social presence perceived by users [19]. However, avatar realism does not seem to have a strong impact on the illusion of the virtual body ownership provided an immersive VE and full freedom of movement, in an experiment comparing a photo-realistic human avatar with a cartoon-like and a machine-like anthropomorphic avatars [20].

In our notification method of *Experiment 2*, the purpose of avatars is to merely make collision avoidance easy for users without inviting them to interact or inducing the sense of social presence. A user seeing an appearing avatar should be able to remember that it represents another user and colliding with it should be avoided at any time. Ideally, the sense of being alone in the VE should not be lost even when users actively avoid collisions with each other. Following the approach presented in [20], we use the degree of anthropomorphism as a classification for notification avatars to test the above requirements.

3 System and Method

3.1 Experiment 1: Stopping Users

The aim of this experiment is to test whether a type of signal used to stop a user walking in VR has effect on how quickly the user stops. Additionally, we collect information on perceived difficulty of signals. This experiment has 4×1 within subject design, the stopping signal being the within group factor.

3.1.1 Stopping Signals

Two visual and two auditory signals are tested. The visual signals are a human figure and a stop sign depicted in Figure 1. The auditory signals are a voice staying ”stop” and a short clap sound.

The motivation behind using a stop sign and a stop sound is to give a short and simple command known to everybody. In a casual situation, it is natural to stop a walking person by talking to them. However, the visual system is likely to dominate other senses during a VR experience. We test a visual and an auditory stop command separately to investigate this reasoning. The figure of a virtual human used as the second visual signal is meant to remind of another user co-located in the shared tracking area. We assume that seeing such a reminder could make stopping easier. The position at which the figure is displayed should identify the location of a possible collision. Finally, the clap sound is used as a comparison for the auditory signal containing the stop command semantics (stop sound).

The position of the human figure is fixed in the VE whereas the stop sign is always shown at 1.5m distance in front of a user. This way, it is clearly visible even when the user keeps walking for some time after receiving the stopping signal. Both sound signals are non-spatialized.

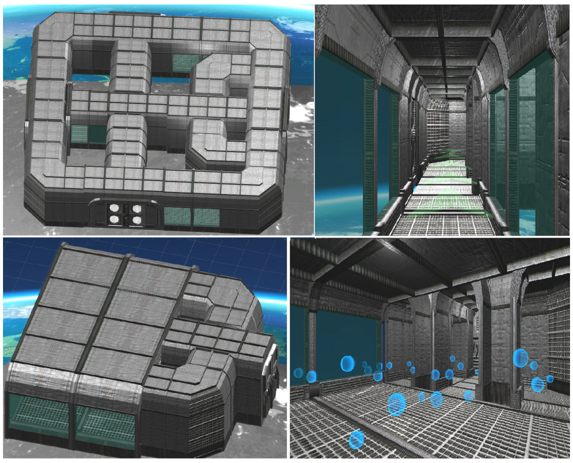

Figure 2: The VEs used in *Exp.1* (top) and *Exp.2* (top for Walk and bottom for Game).

3.1.2 Environment and Tasks

The used VE is shown in Figure 2. The VE is designed to look appealing enough to not disappoint participants but at the same time to be simple and non-distracting. The size of the VE is 8x11 m, corridor width is 1.2m.

The main task is to walk in a virtual corridor. Participants are instructed to stop as quickly as possible if they see objects appearing in front of them or hear a sound. Both sounds were played for each participant before the experiment. The task is performed by one participant at a time. They are asked to walk at a comfortable pace and to not slow down in the anticipation of a signal.

The signals are invoked by invisible triggers placed at different locations in the middle of the virtual corridor where participants are walking. When a participant reaches a pre-defined distance towards each trigger, a signal is given. Thus, the triggers represent a second user the collision with whom would need to be prevented by stopping the walking participant.

Each participant performed two walk-through sequences with all four stopping signals being given in each of them. The order of the signals was different between the sequences. The distance at which the triggers invoked the stopping signals was 2m in the first walk-through and 1 m in the second walk-through. Effectively, this difference only affects the human figure signal. This signal is implemented by displaying the figure at the location of the corresponding trigger, at 2m distance in front of a participant in the first walk-through and at 1m in the second one.

3.1.3 Measures

The main quantitative measure is the distance that a user walked before the full stop after a stopping signal had been issued (further ”stopping distance”). The stopping distance is measured as a difference between the tracked position of a user when the stopping signal is given and the position of the user registered when the user have fully stopped. Subjective data on the signal perception is also collected. In a post-test questionnaire, participants rate how difficult it was to stop following each signal. We call this measure ”stopping difficulty”. Participants also indicated their preferred signal, if any.

3.2 Experiment 2: Displaying Avatars

The goal of this experiment is to explore the strategy of displaying notification avatars at users' mutual positions if the distance between walking users is dangerously small. This experiment has 4×2 mixed design, with the within factor being the notification avatar and the between factor the type of the VE. The experiment is conducted with two participants at a time.

3.2.1 Avatars

Avoiding collisions with others while walking is a natural task daily performed by everybody. A human figure displayed at the position of an approaching co-located user would probably allow to avoid a collision in a most intuitive way. However, a human avatar is likely to produce an illusion of another person being in the same VE. A different solution would be to use a very generic non-human shape that would only identify a currently occupied volume in the VE. Such an avatar is unlikely to induce a feeling of the VE being shared with somebody else, although it would be less familiar to users and might cause confusion. To explore the range between these two limit cases, we introduce four levels of anthropomorphism and realism of the avatar, ranging from a photo-realistic human to a completely non-human shape.

We use two human avatars: a photo-realistic avatar from *Experiment 1* (further ”Human”) and a detailed but cartoon-styled and less realistic avatar (”Spaceman”). A lower level of avatar anthropomorphism is represented by a robot (”Robot”), obviously non-human, faceless and having simplified geometry. Finally, we use a semi-transparent cylindrical shape (”Shape”) that does not resemble a human at all. All avatars are shown in Figure 1.

Avatars are displayed at respective users' positions when the distance between two users reaches the minimum threshold set to 2 m. The avatar's position and rotation is set according to the position and head rotation of the user whose proximity the avatar notifies. Avatars' limbs are not animated. Participants did not have any self-avatars. Each participant tested all four avatars.

3.2.2 Environments and Tasks

Initially, we believed that a featureless avatar (such as Shape) would be the most appropriate for our notification strategy as it would not distract users from their activity in VR. However, preliminary test sequences showed that participants did not like this type of avatar at all.

We hypothesized that the suitability of a specific avatar type could be affected by the structure of the VE and by the task that users are accomplishing. Therefore, we test our notification strategy in two scenarios. In the first one (”Walk” task), users simply walk in a rather constrained VE. In the second scenario (”Game” task), the VE consists of a larger area without obstacles and users fulfil a specific goal.

Walk The Walk task is set in the same VE that is used in *Experiment 1*. Each participant has to move on the path indicated by arrows inside the virtual corridor. The paths for both participants from a pair have several common segments where they are likely to collide. If the distance between the participants gets as low as the threshold of 2m, each of them sees an avatar displayed at the other participant's position. This avatar disappears when the participants walk farther apart again. The task is completed when a participant reaches the end point of the path.

Each pair of participants from the Walk group performed four walk-through sequences, with a different notification avatar used in each.

Game The Game task is set in the VE shown in Figure 2, 8x8 meters large. The VE is filled with blue spheres. At each moment, one of these spheres is coloured in pink. Participants are instructed to collect spheres by walking into them. However, only the pink sphere can be collected. When a participant walks into it, it disappears and a new sphere turns pink. The game is finished when all spheres are collected.

The spheres are not shared between the players. Each participant sees the same initial set of spheres, and the same sphere is pink in the beginning. The next sphere turning pink for each participant is chosen in the following way. A position is calculated that is equidistant from both players. Then, all remaining spheres are found that are located within 2m from this equidistant point. One of these spheres is then chosen to change its colour. If there are no spheres found in this area, one of the remaining spheres is turned pink at random. With this approach, players are drawn to walk towards each other when trying to collect the next sphere but do not stay too close to each other during the whole game. As in the Walk task, players see avatars at each others' respective positions if the distance between them gets lower than 2 m.

Each pair of participants from the Game group performed one game sequence in which all four avatars were used. The notification avatar was chosen in a pseudo-random manner each time when the participants from a pair came closer to each other.

3.2.3 Measures

In *Experiment 2*, the primary measures are subjective questions. In a post-test questionnaire, participants are asked to rate how surprised, scared and disturbed they felt when they saw each avatar, as well as how well they could associate each avatar with their test partner. These questions are used to assess how disruptive the appearance of each avatar is for user experience. In addition, an in-depth discussion with each pair of participants took place.

3.3 Technical Setup

The VR application for each participant (implemented in Unity version 5.3.2) is run on a Windows 7 laptop with an Intel Core i7 processor and an Nvidia GTX 980M graphics card, at an update rate of 45 fps. The used HMDs are Oculus Rift DK2. We use an inside-out optical tracking system. A camera attached to a user's HMD tracks markers on the ceiling of the laboratory. The size of the tracking area is 14x9 m. The camera position is calculated on the user's laptop. In *Experiment 2* that uses a multi-user setup it is distributed to a server machine over a wireless network. The equipment worn by participants is shown in Figure 1.

Participants did not wear headphones, so they could hear each other's and the test coordinator's steps and eventually voices. We were aware that such a setup would possibly lower participants immersion. Nevertheless, we decided that participants would feel safer and more confident if they could easily communicate with the experiment coordinator, and possibly also hear steps, especially in *Experiment 2*.

3.4 Participants

29 volunteers (10 female and 19 male) in the age from 21 to 48 years (median 25) took part in the study. 14 participants had no previous experience of VR. The remaining 15 had either tried Oculus Rift before or taken part in a different user study in VR, including the ones with real walking. We did not intend to make a distinction between naive and experienced users. However, we assessed the possible influence of previous experience of VR on the results. All 29 participants accomplished *Experiment 1*. 17 participants accomplished the Walk task and 12 the Game task of *Experiment 2*. Experience of VR ($p = 0.419$) and playing video games ($p = 0.845$) does not differ between these two groups in the Mann-Whitney test.

3.5 Procedure

Participants came to the laboratory in pairs. One participant did not have a test partner, so he completed *Experiment 2* together with the experiment coordinator (the Walk task). The study procedure had the following order:

1. General introduction and explanation of the procedure.
2. Free walking in the VE (the same as used in *Experiment 1*) to accommodate to the setup, separately for each participant from a pair.
3. Instructions for *Experiment 1*.

4. *Experiment 1* for the first participant from the pair.
5. *Experiment 1* for the second participant.
6. Questionnaire for *Experiment 1*.
7. Explanation of the general purpose of the study and a detailed explanation of the notification strategy for *Experiment 2*.
8. Instructions for *Experiment 2* (either Walk or Game).
9. *Experiment 2* with both participants (Walk or Game).
10. Questionnaire for *Experiment 2*.
11. Discussion about the experience in *Experiment 2* with both participants.

4 Results

4.1 Experiment 1

The results are obtained from the data of 24 participants. Data of the remaining 5 participants are excluded due to the missing values. Neither distance nor subjective difficulty data is normally distributed (in Shapiro-Wilk test). Therefore, we use non-parametric tests. The significance level used for all tests is $\alpha = 0.05$. Illustrating box-plots are shown in Figure 3.

Friedman's ANOVA does not show significant differences in the stopping distances for all four signals in the first walk-through (with the trigger distance 2m), p = 0.192. However, the differences are significant for the second walk-through (with the trigger distance 1m), p <0.001. In the follow-up pairwise comparisons with the Wilcoxon signed-rank test, the stopping distance for the figure signal (Median M = 0.5 m) is significantly shorter than for the stop sound signal (M = 0.78 m) (p <0.001, effect size r = 0.27). The difference in the stopping distance for the figure and the stop sign (M = 0.7 m) is marginally insignificant (p = 0.052, r = 0.15). We believe that the significance in the ANOVA result for the second walk-through is induced by the fact that the figure is displayed at a closer distance compared to the first walk-through. Indeed, the stopping distance for the figure is significantly shorter in the second walk-through (M = 0.5 m) than in the first walk-through (M = 0.7 m) (Wilcoxon signed-rank test, p <0.001, r =

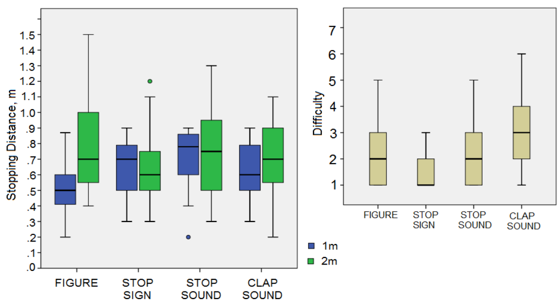

Figure 3: Results of *Exp.1*: stopping distance (left) and stopping difficulty (right). Median values, inter-quartile ranges and full ranges are shown.

0.51). Between-walk-through comparisons for the other signals are not significant, as expected. The tests are conducted on data without outliers.

Significant differences are found in the scores of the stopping difficulty of the signals (Friedman's ANOVA, p <0.001). The stopping difficulty is estimated on a 7-point Likert scale, where 1 indicates that a signal is very easy and 7 - very difficult. The follow-up pairwise comparisons with the Wilcoxon signed-rank test show that the clap sound (Median score M = 3.0) is perceived as significantly more difficult than the stop sign (M = 1.0) (p <0.001, effect size r = 0.21) and the figure (M = 2.0) (p = 0.037, r = 0.15). The actual stopping distance is however not larger for the clap sound than for any other signal as seen from the stopping distance comparison.

Neither VR experience no gender is significant for the stopping distance or difficulty scores of any of the signals (in Mann-Whitney U tests).

13 participants indicated the stop sign and 8 the stop sound as the preferred stopping signal. Three participants found the human figure to be the easiest signal. However, participants reported to have often "walked into" the figure shown in front of them (at 1m distance) in the second walk-through and judged it as being too close. Clap sound was not preferred by any of the participants, a result that well coincides with it being found significantly more difficult than the visual signals. Seven participants indicated that they found the visual signals generally easier, five said the same about the auditory signals.

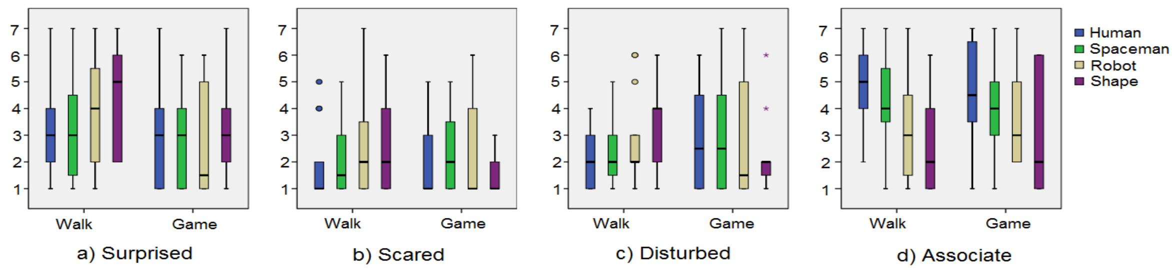

Figure 4: Box-plots of the results of *Exp.2*. Medians, inter-quartile ranges and full ranges are shown.

4.1.1 Discussion and Limitations

The results of *Experiment 1* show that auditory and visual (displayed at 1.5 to 2 m distance from a user) signals are on average equally effective in stopping walking users in immersive VR. A visual signal displayed as close as at 1 m distance is likely to make users stop faster. On average, participants walked between 0.6 m and 0.8 m before the full stop after a stopping signal had been given. Thus, in a situation where users are walking without seeing each other on paths that potentially lead to a frontal collision, they should be stopped no later than when the distance between them reaches 2m. Our test is limited to an immersive but not interactive VE where the only task is to walk and stop when a signal is given. Therefore, our results are likely to indicate users' fastest possible reaction. Even though the tested signals are similarly effective, they are differently perceived by users. A sound signal not carrying any command (the clap sound) is found to be more difficult than visuals. The absolute majority of participants prefer a stop command to be used, although their preferences are divided between this command being visual or auditory. In a VE filled with dynamic content and various game sounds, the best practice for quickly stopping users might be a combination of a visual and an auditory signal. However, a follow-up study in such a sensory-intense VE might be required to confirm this conclusion.

4.2 Experiment 2

4.2.1 Questionnaire Responses

Figure 4 shows box-plots of responses on questions to which extent each avatar surprised, scared and disturbed participants and how well they could associate it with their test partner. All answers are given on a 7-point Likert scale where 1 is "not at all" and 7 is "very much". Scores are not normally distributed (in the Shapiro-Wilk test), except for the Associate question for Human, Robot and Spaceman. Non-parametric tests are thus chosen. The analysis is performed on data without outliers. The significance level used for all tests is $\alpha = 0.05$.

In the Walk group, Friedman's ANOVA indicates significance of the avatar type in the scores for Surprised ($p = 0.04$), Disturbed ($p = 0.003$) and Associate ($p = 0.006$). The follow-up pairwise comparisons performed with the Wilcoxon signed-rank test do not show significant difference for all pairs. However, the effect sizes calculated based on the pairwise comparisons range from medium to large in many cases. For the Surprised question, the largest effects are for Human-Shape ($r = 0.46$), Spaceman-Shape ($r = 0.39$) and Robot-Shape ($r = 0.32$). For the Disturbed question, again, the largest effects are produced in comparisons with Shape : Human-Shape ($r = 0.43$), Spaceman-Shape ($r = 0.33$) and Robot-Shape ($r = 0.5$). For the Associate question, effect sizes grow with the increase of the difference in the degree of anthropomorphism of the compared avatars: from small for Human - Spaceman ($r = 0.16$) , Spaceman - Robot ($r = 0.18$), Robot - Shape ($r = 0.19$), to mediam for Human-Robot ($r = 0.34$), Spaceman-Shape ($r = 0.37$), to large for Human-Shape ($r = 0.54$). In the Game group, Friedman's ANOVA shows significant differences in the scores for Scared ($p = 0.036$), with no significant differences in the pairwise comparisons.

In the between-group analysis, the only significant result is Shape being 2 points less disturbing for the Game group than for the Walk group (Mann-Whitney U test, $p = 0.011$, $r = 0.53$). Between-group comparisons for Shape show medium effects for the Surprised ($r = 0.34$)

and Scared ($r = 0.39$) questions.

4.2.2 Interview Data

In the Walk group, 8 out of 17 participants strongly preferred to see Human avatar notifying them about the proximity of their test partner. Another 4 participants preferred any human-shaped avatar. Only one of the participants preferred to see Shape, whereas 5 participants strongly disliked it.

In the Game group, 9 out of 12 participants preferred to be notified by Shape. However, none of them disliked any other avatar.

The participants who preferred human and human-like avatars said that human figures looked natural and expected. They also helped to avoid the person whose location they notified as they indicated the direction of movement. The non-human shape was described as ”unnatural”.

Those participants who preferred the Shape avatar felt less distracted from fulfilling their task and ”did not want to look” at Shape for too long while the visuals of human-like avatars attracted their attention. They said that Shape's semi-transparency allowed to see what was going on in the game in the area behind it.

4.2.3 Discussion and Limitations

The notification strategy used in *Experiment 2* proved successful for imminent collision prevention: all participants could avoid their test partners when they saw notification avatars for short periods of time. The results show that the type of VE and tasks performed in it strongly affect users' preferences for a notification avatar. A human avatar is desired in an exploration task whereas a featureless non-anthropomorphic shape is better suited for a scenario with specific goals. This observation follows from interviews with participants as well as between-group comparisons of test scores for the Shape avatar. The core idea of our notification strategy is to provide a non-distracting yet effective guidance for collision avoidance. The results suggest that the strategy might be better suited for scenarios similar to our Game task, where users' attention is concentrated on tasks but not the VE itself. While notification avatars are effective for collision prevention in exploration scenarios they inevitably attract users' attention. This fact is reflected in the significant differences found by Friedman's ANOVA for avatar comparisons in the Walk group. In situations where users' attention is attracted to a notification avatar they prefer it to have a familiar human appearance. In scenarios with other goals than exploration, on the contrary, participants preferred the avatar to have as few visual details as possible, following our initial hypothesis.

The limitation of our experiment is the size of the participants' sample. Especially in the Walk group, we believe that more data would allow to find statistical significance in post-ANOVA pairwise comparisons that produce effects of medium to large size. The impact of the degree of avatar anthropomorphism could then be established in a more detailed manner.

5 Conclusion

In the user study reported in this paper, we examine two strategies for the prevention of imminent collisions in large-scale multi-user VEs navigated by real walking: stopping users and notifying them of each other's presence by displaying avatars. In the stopping strategy, visual and auditory signals are found to not differ in their effectiveness. Nevertheless, users report differences in the perceived difficulty and the preferences for the stopping signal. A stop command in either visual or auditory form is preferred by the majority of participants. Our results for the notification strategy suggest that the application scenario should be taken into account in the choice of notification avatars. More specifically, interactive and goal-oriented scenarios require abstract and featureless notification avatars, while human-like avatars are preferable for exploration scenarios.

The findings of both experiments can serve as guidelines for the development of scenarios with non-shared VEs in HMD-based multi-user setups. The development of an unnoticeable for users collision prevention algorithm remains an avenue for future work. We believe that such an algorithm would be especially beneficial for exploration scenarios in constrained VEs where a simple notification method has a larger impact on user experience.

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