Users' locomotor behavior in Collaborative Virtual Reality

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Figure 1: Overview of the experiment setup with examples of trajectories recorded for each participant.

ABSTRACT

This paper presents a virtual reality experiment in which two participants share both the virtual and the physical space while performing a collaborative task. We are interested in studying what are the differences in human locomotor behavior between the real world and the VR scenario. For that purpose, participants performed the experiment in both the real and the virtual scenarios. For the VR case, participants can see both their own animated avatar and the avatar of the other participant in the environment. As they move, we store their trajectories to obtain information regarding speeds, clearance distances and task completion times. For the VR scenario, we also wanted to evaluate whether the users were aware of subtle differences in the avatar's animations and foot steps sounds. We ran the same experiment under three different conditions: (1) synchronizing the avatar's feet animation and sound of footsteps with the movement of the participant; (2) synchronizing the animation but not the sound and finally (3) not synchronizing either one. The results show significant differences in user's presence questionnaires and also different trends in their locomotor behavior between the real world and the VR scenarios. However the subtle differences in animations and sound tested in our experiment had no impact on the results of the presence questionnaires, although it showed a small impact on their locomotor behavior in terms of time to complete their tasks, and clearance distances kept while crossing paths.

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MIG '18, November 8–10, 2018, Limassol, Cyprus
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ACM ISBN 978-1-4503-6015-9/18/11…$15.00
https://doi.org/10.1145/3274247.3274513

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Computing methodologies** → *Collision detection*; *Perception*;

KEYWORDS

Collaborative virtual reality, presence

ACM Reference Format:
Alejandro Ríos, Marc Palomar, and Nuria Pelechano. 2018. Users' locomotor behavior in Collaborative Virtual Reality. In *MIG '18: Motion, Interaction and Games (MIG '18), November 8–10, 2018, Limassol, Cyprus.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3274247.3274513

1 INTRODUCTION

Virtual Reality is not only a powerful tool for the game industry but also to many other fields such as design, architecture, engineering, and psychology. As HMDs have become available to the general public due to the low prices, the next generation of VR applications is moving towards collaborative VR. Collaborative VR requires information about other participants' whereabouts and behavior. This information enhances

interaction and coordination. When participants are simply playing a video game by siting down and moving their avatars with a joystick, their behavior is expected to be quite similar to when they interact with other NPCs (Non Player Characters). However if participants can move around (current HMDs can track a full room of approximately $4 - 6m^2$) it is important to understand how humans perceive the physical space around them while using an HMD, and how much they trust distances and movement of other avatars, when they know a real person is driving their movement.

Immersive virtual environments have proven to be a plausible platform to study human behavior. Being surrounded by virtual agents can provide high levels of presence [Llobera et al. 2010] [Pelechano et al. 2008] which leads to participants behaving as they would do in the real world. This observation has lead many research groups to use immersive VR as a platform to study human behavior [Olivier et al. 2014]. The next step will be to fully understand users' behavior in immersive collaborative VR, when being aware of the physical space being shared by other users. In our experience, when two people share both the physical and virtual space, communication emerges in a natural manner, i.e they talk to each other, and they virtually point at virtual objects to give verbal instructions [Andujar et al. 2018]. However we have also noticed that fear of physically colliding typically appears as they approach each other (e.g. due to not fully trusting their perception of distances in VR).

With this paper we wanted to study users' locomotor behavior running an experiment in which two participants share the same virtual space and need to collaborate to perform a specific task. The participants can see each other's avatar in the virtual environment and, as they move, their avatars will move accordingly. We track and store their trajectories during the experiment in both the real scenario and the virtual one. The virtual scenario was performed under three different conditions in terms of synchronism of animations and foot step noise. Differences between VR setups were very subtle and thus significant differences were not found from the questionnaires, although the quantitative evaluation of trajectories provided some small differences. Differences where found in behavior between the real world experiment and the VR one, which further emphasize our believe, that in order to develop high quality VR collaborative environments, it is necessary to fully understand how users adjust their locomotor behavior between the real and the virtual world.

2 RELATED WORK

Presence

For a long time there have been many researchers interested in studying how humans behave in a virtual environment, how they interact and navigate, and how those virtual environments can become more immerssive and enhance the level of presence [Slater and Sanchez-Vives 2016]. The concept of presence, is very relevant, because it has been proven that when humans experience presence in virtual reality, they tend to behave as they would do in the real world [Sanchez-Vives and Slater 2005]. This opens the door to using virtual environments as a powerful tool to study human behavior [Pelechano and Allbeck 2016] and decision making [Rıos et al. 2018]. It has been observed that when participants of a virtual experiment are given a task and can manipulate elements of the environment, their levels of presence and overall feeling of immersion are higher [Schubert et al. 2001]. Gupta et al. evaluated the impact of manipulating the instructions given to the participants to increase the engagement with a virtual crowd [Gupta et al. 2017]. Zibrek et al [Zibrek et al. 2017] studied perceived realism, affinity, co–presence and agency of virtual characters in immerssive VR based on their appearance and behavior. The work by Kyriakou et al [Kyriakou et al. 2017] studied plausibility of a simulated crowd in immersive and semi-immersive environments, and showed how handling correctly collision avoidance could enhance realism specially when adding basic social interaction (e.g. verbal salutations, gaze, and other gestures) by the virtual characters towards the user.

Virtual human gaze

Gaze can have an important role on Presence, and also on the way that a human participant would perform locomotion around a virtual agent. Recent work by Narang et al. studied how behavioral plausibility increases when virtual characters not only move in a natural way, but also gaze at the participant [Narang et al. 2016]. Randhavane et. al. observed that when a virtual agent would turn the head to stare at the participant, the participants would appear more responsive, exhibited more reactions and experienced higher presence [Randhavane et al. 2017].

Lynch et al. carried out a VR experiment where a real participant and a virtual avatar would negotiate collision avoidance through nonverbal cues [Lynch et al. 2018]. Their results showed that during an orthogonal collision, avatar's gaze direction did not affect the behavior of the participants. The locomotion of the virtual character was a sufficient information for participants to perform collision avoidance. Varma et al. studied collision avoidance along a hallway between a participant and a virtual agent [Varma et al. 2017] . Their results showed that both avatar's head orientation and eye gaze direction had an influence on the participant's collision avoidance manouver.

Proxemics

Interaction with small groups of virtual agents has also been studied to evaluate proxemics [Llobera et al. 2010]. Those experiments found that physiological arousal would increase as the virtual characters would approach the participant and also as the number of virtual humans would increase from 1 to 4. However their results showed that arousal levels were similar whether the participant was approached by virtual characters or by cylinders. This raises questions regarding the extent to which realistic visual appearance and animations are necessary and why. The work by Bönsch [Bönsch et al. 2018] studied personal distances depending on the influence of virtual agent's emotions, by altering their facial expression between angry and happy. This work showed that

participants would keep larger personal space when the virtual agents showed an angry emotion, and smaller distances when the virtual agents showed happy emotions. Iachini et. al. presented an Immersive Virtual Reality experiment to study participants' personal distance against a robot and a cylinder [Iachini et al. 2014]. They found an important difference on human behavior depending on the representation of the obstacle.

The work by Rojas et al. focused on simulating group behavior and then used immersive VR with a head mounted display to evaluate the model when the participant was included in the group [Rojas and Yang 2013].

Embodiment

Several researchers have studied the importance of embodiment in VR. This means having a self avatar representation that follows your movements [Spanlang et al. 2014]. Mohler et al studied how seeing a self avatar in immersive VR affects our perceived sense of distances [Mohler et al. 2010]. They discovered that participants who explored the virtual space while seeing a fully-articulated and tracked self-avatar subsequently made better accurate judgments of absolute egocentric distance to locations (within the 4 to 6m range), than those participants without a visual representation of themselves. Smith and Neff studied the influence of emobiment while performing collaborative tasks. Participants wore an HMD and a motion capture suit to animate the avatars. They were able to talk and discuss about the task they were performing in a shared virtual space. The results showed a similar behavior between real world and embodied virtual reality with no significant difference between them whereas a significant drop off in presence for no embodiment.

Collision avoidance

Immersive Virtual Environments have been used to develop platforms to gather data on human locomotion around virtual obstacles [Argelaguet et al. 2015], and collision avoidance maneuvers when avoiding another virtual agent [Olivier et al. 2018]. Bruneau et al. studied collision avoidance strategies against groups of agents based on their appearance and formation [Bruneau et al. 2015]. One of the problems they observed, is that many participants would not be able to avoid the virtual humans. This happened because in real life, when we are facing a frontal collision, we perform half of the avoidance behavior, and expect the other person to perform the other half. However in their experiment, virtual humans were not aware of the participant, and thus kept walking straight towards him/her. There have been studies on how participants in VR avoid collisions against obstacles, depending on their virtual representation [Scavarelli and Teather 2017]. According to their experiments, participants took shorter time to reach their destination when a virtual avatar was used instead of a bounding box, or an AR approach based on a camera overlay. Gérin-Lajoie et. al. presented an experiment to study the differences in the size of the personal space and locomotor behavior during the circumvention of a cylindrical obstacle between a virtual and a real environment [Gérin-Lajoie et al. 2008]. Their work showed that the size of personal space was not modulated according to walking speed during the circumvention of a static obstacle, though the participants slightly enlarged the size of their personal space in the virtual environment. Recent work by Silva et al. studied collision avoidance in VR against a cyl inder, and a virtual human with and without footstep sounds. They found differences on clearance depending on the appearance of the obstacle, but not on the use of footstep sounds [Silva et al. 2018].

Collaborative VR and collisions between users

Recently there has been an increasing interest to use collaborative virtual environments as a working platform for different fields. For example, several works [Frost and Warren 2000], [Rahimian and Ibrahim 2011], [Schmidt et al. 2015] and [Andujar et al. 2018] helped untrained participants to understand architectural concepts using collaborative virtual reality, enhancing the learning experience when compared against traditional presentation tools. There is also work studying different strategies to steer participants away from each other to reduce collisions [Azmandian et al. 2017]. Langbehn et. al. evaluated the use of semitransparent avatars to avoid collisions between users when small physical spaces are shared in VR [Langbehn et al. 2018]. Understanding how participants behave in a collaborative virtual environment can help us to improve the design of those virtual worlds, so that collaborative work can be more efficient and feel more natural. The work by Podkosova et. at. evaluated the differences in collision avoidance when two participants walked either in a frontal or side crossing. They ran experiments in different conditions: one where virtual and physical space where collocated, another one where physical space was different but each participant would see the other's avatar in the same VR scenario, and a third situation without VR [Podkosova and Kaufmann 2018]. The participants of this experiment would be hearing rain noise in their headphones, and each avatar was animated by capturing the participant's movement and applying full IK. In the videos of the experiment, it can be observed that the avatars' animation was not smooth, and it had quite a few artifacts, that in our opinion could reduce the sense of presence and thus had an impact on the participant's trajectories.

3 THE EXPERIMENT

The goal of this experiment was to evaluate how two people interact in a collaborative virtual environment. From this experiment we were expecting to obtain information regarding collision avoidance strategies, preferred personal distances and velocities. We wanted to evaluate how humans collaborate in virtual reality when being represented by avatars, and how much the accuracy of the avatars movements and surround sound could have an impact on immersion and their overall performance.

Since the animations of the virtual humans can have an impact on plausibility, we decided to give priority to having natural looking animations as opposed to using IK were many artifacts may appear for example, due to blocking HTC lighthouses . Therefore we used natural and smooth walking

animations from Mixamo [Mixamo 2018] and then simply tracked the participant's left foot to drive the animation i.e. we determine if the participant starts moving the right leg first, and thus copy that behavior in his avatar by selecting the right frame of the animation cycle. The head tracker was used to determine the velocity of the avatar and apply time warping to the animation. Finally the right arm of the avatar was animated by applying IK based on the position and orientation of the VIVE controller.

3.1 Objectives and Hypothesis

Previous work on locomotor behavior in VR [Podkosova and Kaufmann 2018] showed significant differences in the clearance kept by participants between real and virtual scenarios. Their experiments consisted on a real situation with possibilities of frontal and crossing collisions, and then it was replicated with VR having the physical space shared (co-located) or not shared (distributed). In the VR case, avatars were animated with IK, and participants would hear simply rain noise in their headset. We hypothesize that non natural animations due to flaws in real time IK can have an impact on the trajectories. We also hypothesize that hearing footstep noises would lead to a more believable scenario. Our goal was thus to investigate whether having natural looking animations and footstep sounds would lead to smaller differences in clearance values between the virtual and the real scenarios.

For the VR set-ups, we hypothesize that having a self-avatar with synched foot steps would also lead to a locomotor behavior closer to the real world set up.

3.2 Scenarios

We had three different VR setups. Synchronized animations mean that the avatar will start moving the same leg as the participant, and then the animation clip will continue at the participants' speed. Not synchronized animations will start always with the same foot, thus not necessarily matching the participants movement. Synchronized foot steps sound means that the step noise will happen when the avatar's foot touches the floor. Finally not synchronized sound means that foot steps will not match the avatar's foot contact with the floor. With this possibilities we tested cases A, B, and C:

- A-nosync. Not synchronized animation and foot steps sound.
- B-mix. Synchronized animation with not synchronized foot steps sound
- C-sync. Synchronized animation and sound.
- D-noVR. Real life experiment no HMD.

The last case, D, corresponds to participants wearing the HMD on top of their heads for tracking purposes, but they see the real environment and they are not wearing headsets see Figure 4.

3.3 Design

At the beginning of the experiment, every participant chooses the avatar they want to represent themselves in the environment a male and a female avatar were available for that purpose. The avatar's height is then adjusted using the head tracker position. The virtual environment where the participants are immersed consists of a long corridor with a table and a board at each end. Pieces of a puzzle lie on the tables and the boards are empty see Figure 1 . The goal of the participants is to build the puzzle on the board at the other end of the corridor. When the experiment starts, the participants must take a piece from his/her table at a time, walk to the opposite side and hang it on the board. After that, each participant goes back to his/her table and the process starts again until the puzzle is completed on each board.

3.4 Apparatus

All the experiments were run in a 2x4m indoor lab area where the participants can walk from one side to the opposite. The tracking was performed using an HTC immersive virtual display and a VIVE controller was used to grab the pieces of the puzzle and hang them on the boards. Besides, a tracker on every participant's left ankle was attached to track the foot movement. The environment can be inspected by moving the head, and foot steps can be heard through the earphones that the participants wear during the simulation. Unity Game Engine was used to render the environment, control the pieces of the puzzles and animate the avatars.

We had one wireless HMD, and the other one required a wire which was hanging from a high point. This was enough to avoid cables tangling during the experiment, as only one participant had a cable.

3.5 Procedure

Before getting starting with the experiment, participants read and signed a consent form with information regarding the possibility of dizziness while performing navigation using an HMD, and were told that they could leave the experiment at any time if needed. Since physical walking movement was mapped one to one with virtual movement, none of the participants reported experiencing any dizziness.

When the simulation starts the participants are located in front of the tables facing each other. Both tables have a colored line in the center see Figure 2) and participants are told to use this line as a reference point to start and finish their trajectories. This was done to ensure a frontal collision avoidance in their paths. A sound indicates that they must begin the experiment, by grabbing a piece of the puzzle and taking it to the opposite board. Participants can take a piece by approaching the VIVE controller and pressing a button, then they need to hold it while carrying the piece. Participants are told to wait for the other person to be ready with his/her piece on the hand before starting to walk (but they are not told how to communicate with the other participant). Pieces are put in their right place automatically by simply stretching the hand and letting the button go. This was done to make the task easier and let participants focus on their walking task.

In the case of the real experiment, where participants are not watching the virtual environment, we located a table at

each side of the real corridor with a cube on top (same sizes as in the virtual world). Participants were asked to simply grab the cube and take it to the opposite table. They had to repeat this task as many times as in the virtual world experiment.

We ran 4 experiments, with 2 participants per experiment. All participants were exposed to the four setups (A-nosync, B-mix, C-sync, and D-noVR), but in different order, following Latin squares to avoid having results influenced by neither learning nor tiredness (the order of each experiment was ADBC, BACD, CBDA, DCAB). For each setup, participants did 24 runs (to transport the 12 pieces and go back for the next).

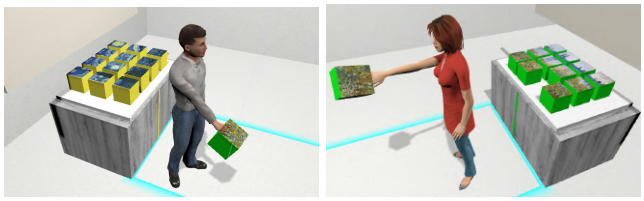


Figure 2: Participants' avatars holding puzzle pieces before starting to walk towards the opposite table.



Figure 3: Participants performing a crossing while holding pieces of the puzzle in their hands.

3.6 Participants

Participants were distributed in pairs, and a total of 4 pairs performed the experiment. All 7 male and 1 female aged from 20 to 40 had a lot of experience with computers and video games, but only 2 of them had good experience with virtual reality.

4 RESULTS

Each participant filled out a presence questionnaire after each VR scenario (see table 1). Questions were scored from



Figure 4: Participants performing a real crossing (without HMD).

Table 1: Questionnaire

Q#	*Question/Statement*
Q1	The overall quality of the visualization was good.
Q2	The quality of the VE makes it easy to perform the assigned tasks.
Q3	I consider the navigation in the VE to be intuitive.
Q4	At all times I felt in control of my avatar.
Q5	The virtual humans' movement and appearance looks realistic.
Q6	The surround sound helped me feel more immersed in the VE.
Q7	The experience in the virtual environment is consistent with experiences lived in real life.
Q8	I was able to predict the actions of the other avatar as a result of my own actions.

0 to 9 . Since we had 4 pairs of participants performing the experiments, we had a total of 24 questionnaires filled out. The scores given by the participants can be seen in Figure 5. The participants rated their experience with high values for realism of the environment, the overall behavior being consistent with the real one, and having a good control of their avatar (high levels of embodiment). When it comes to the realism of the avatar in appearance and movement, the average score was 5.7 with a larger standard deviation than for other questions. Overall, participants reported high levels of embodiment, they felt in control of their avatar, and found it easy to move around the virtual environment and predict the movements of the other avatar.

For the purpose of studying whether synchronism in animations and foot steps sound had an impact on presence and sense of avatar ownership, we set our null hypothesis to be

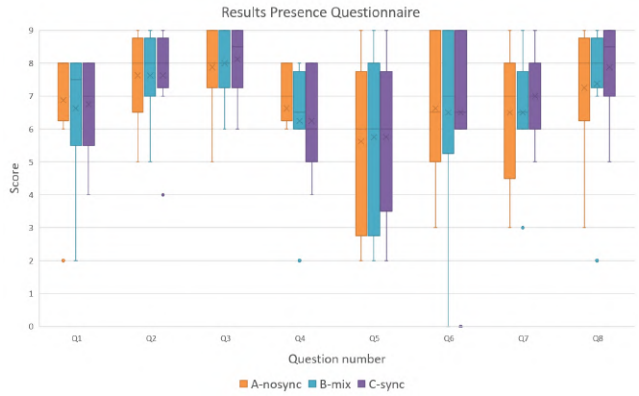


Figure 5: Results of the presence questionnaires.

that synchronism of animation and footstep noise would make no difference in the results of the presence questionnaires.

An ANOVA analysis was performed taking different dependent variables between the different scenarios ($p<0.05$): quality of visualization, quality of animations and control of own avatar. The results for each variable can be seen in table 2

	F	Fcrit	pvalue
Quality of visualization	0.0113	3.4668	0.9886
Control of avatar	0.1080	3.4668	0.8980
Realism of avatars	0.0064	3.4668	0.9935

Table 2: Anova results for the dependent variables

For each dependent variable F<Fcrit and p-value>0.05 thus, the variables had no statistically significant differences and the null hypothesis could not be rejected. Therefore according to the ANOVA performed on the results of the questionnaires, there seem to be no influence on whether animations and foot steps sound were synchronized with the movement of the participant. However, since presence questionnaires are a subjective way of measuring presence, we also run quantitative analysis on the data gathered from the users' trajectories, to obtain some objective measurements on their performance. For each participant we stored the information of their trajectories in terms of position and time. We studied speeds, clearance distances and time taken to complete the task.

We can observe that the D-noVR setup took on average 34% shorter time than the VR setups, and the maximum speeds reached by participants were 28.67% faster than for the VR experiments. This indicates that even though human locomotor behavior (e.g.clearance and velocity) in VR tends to be similar to their real world counterparts, there are still differences that need to be taken into account. It is important to emphasize that the D-noVR setup had the exact same physical limitations as the VR scenarios, in the sense that participants were also carrying the weight of the HMD in their heads, and the cables either connected to the battery around their waist, or to the PC in the case of the non wireless HMD. Figure 7 shows the total time per experiment for the 4 setups and the 4 pairs of participants.Figure 8 shows the maximum velocities reached for each scenario and each pair of participants. We can observe that on average the maximum velocity for D-noVR was $1.145ms$, whereas for the VR experiments was $0.89ms$.

Note that the total experiment time depends on two things: (1) velocities at which participants follow their trajectories, and (2) time taken to coordinate with the other participant when to start walking again. Participants were told to wait for their partner to be ready (both holding the piece in their hand) before starting to walk. When participants run the D-noVR scenario, this time was close to zero, as participants had no difficulties grabbing the box and they would use mostly eye contact to start moving again. During VR experiments we observed an interesting behavior: since eye contact could not be used, they would either make a little gesture with their hand (moving the hand up and down again while holding the piece) or if they knew each other they would simply say something to their partner (e.g: "'ready?"'). This would require a few more seconds to start moving than for the D-noVR case. Also, on a few occasions, participants of the VR setup would accidentally drop the piece of the puzzle after grabbing it (letting the button go would make the piece fall, disappear and appear again on the table). This would introduce a further delay in their movement. In Figure 9 we can see two example graphs showing the velocities at which the participants moved through their trajectories for D-noVR and C-sync. The velocity peaks correspond to the middle of their trajectory between the two tables. The lowest values correspond to when the participants reach the table and stop to grab a new piece before starting the next trajectory. The long sections at close to zero speeds show either long waits for the other participant to be ready, or else delays due to a participant "'loosing"' a piece of the puzzle.

One interesting observation from the total time taken for each scenario, was that for 3 out of the 4 pairs the time taken to complete the experiment was $T_A > T_B > T_C > T_D$. From the time and velocity results, together with the participants' comments, it is obvious that participants in immersive VR behave in a more cautious way than when they are in the real world. No matter how realistic and accurate the scenario looks, users are still worried about colliding in the real world when wearing an HMD. This is something to keep into account when using immersive VR for collaborative tasks.

What we found more interesting however, was the fact that even though the ANOVA study on the questionnaire results did not show statistically significant differences between A-nosync, B-mix, and C-sync, the fact that the time taken for those experiments was the largest for the non synchronized scenario and the smallest for the synchronized one, makes us suspect that small anomalies in the animation or sound made participants to be more cautious when moving between tables and when coordinating the start of each trajectory.

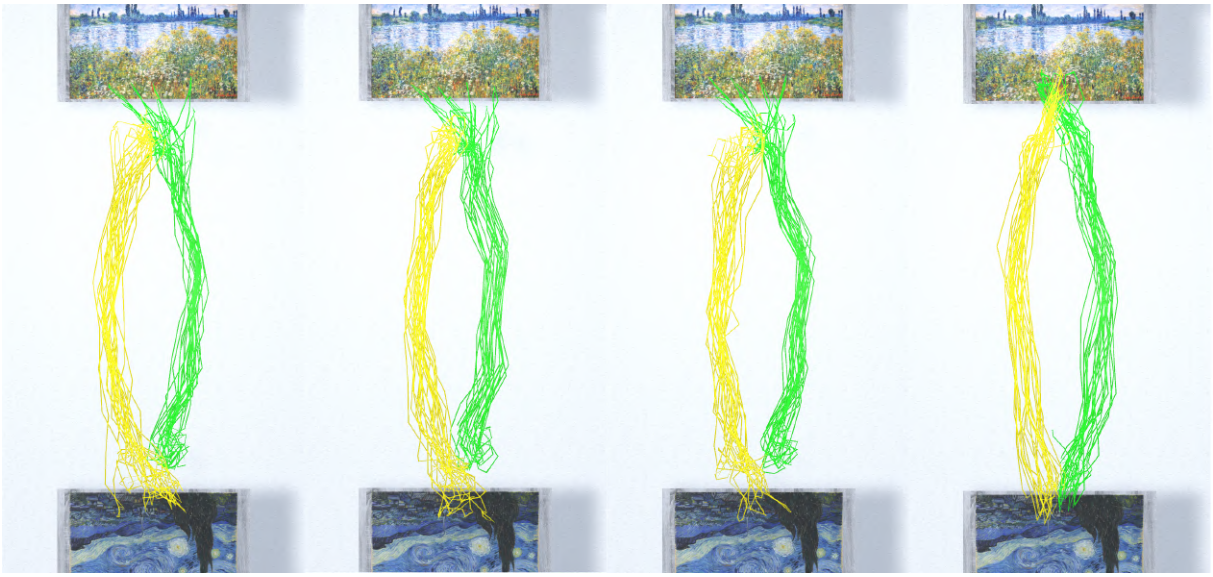


Figure 6: Examples of resulting trajectories for each of the experiment setups. From left to right: A-nosync, B-mix, C-sync and D-noVR

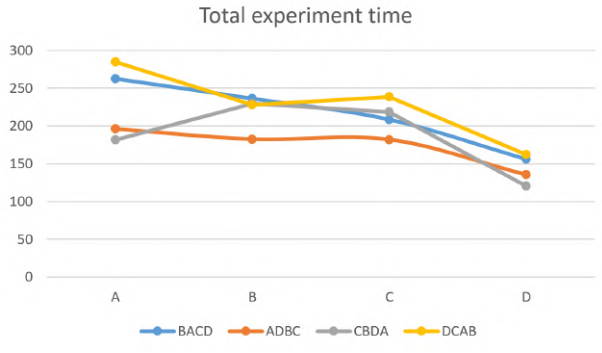


Figure 7: Total time (in seconds) taken for each scenario and for each pair of participants.

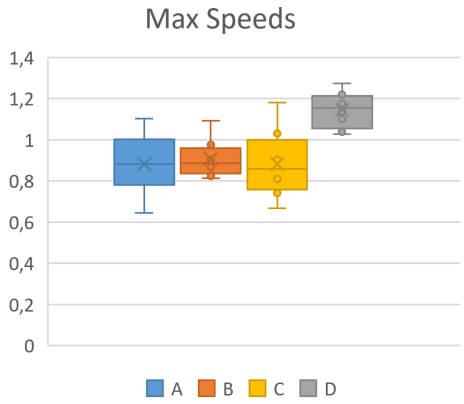


Figure 8: Maximum velocities reached for each scenario and each pair of participants.

Figure 6 shows the trajectories of two participants performing the experiment with the three VR setups (A-nosync,B-mix,C-sync) and no VR (D-noVR). Each participant's trajectories are represented by either color green or yellow. From the symmetry of the paths we can observe that each participant performed half of the collision avoidance maneuver, just like in the real world. One interesting thing that we observed for all 4 pairs of participants, is that they seemed to choose a side for the collision avoidance, and stick to it for the whole length of the experiment. We believe that this is the result of doing a collaborative task. When we are facing a collision in the street, there are several ways in which humans coordinate to choose side. The most typical one is social standards (for example: if we drive on the right, then we also avoid others by moving to the right). In our experiments it seemed like the participants would take such a decision on the first trajectory and only on very few occasions would change the side to avoid collision during the experiment.

Finally we computed clearance distances when crossing paths, to evaluate whether there was any difference between virtual reality and the real world, and also whether animation and noise synchronization had an impact on the clearance distances kept while participants would cross paths. Distances were computed between the head trackers for each run where participants walked past each other with or without a piece of puzzle in their hands. Figure 10 shows the minimum average distance for each of the 4 pairs of participants. As we studied each set of participants separately, we did not observe a clear scenario for which distances would be consistently larger or smaller across pairs of participants. However, as we can see

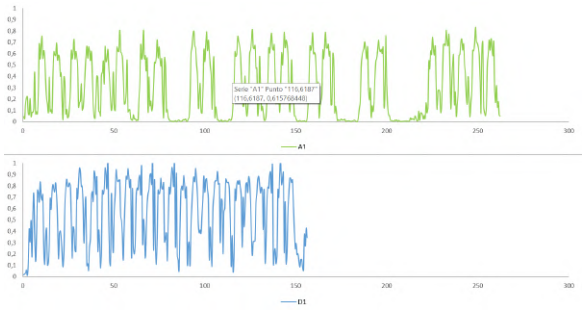


Figure 9: Example of speeds during an experiment for the D-noVR and A-nosync scenarios.

in the graph, if we compute the average throughout all the participants and experiment setups, we can observe a trend that indicates that distances kept for the D-noVR case were the smallest (0.72m). For the three VR setups, we observed that on average the clearance distance kept for C-sync was smaller (0.77m) than for the other two scenarios A-nosync (0.796m) and B-mix (0.795m). Therefore, it seems that people in the real world would keep smaller distances during a crossing, than when encountering the same situation in a virtual environment. Within the VR cases, it seems that when animations and sound were sync, the distances kept were also slightly smaller, although the results for all three VR cases were very similar. The difference in the average clearance between real and VR cases was 5cm, which is much smaller than what was observed in previous work [Podkosova and Kaufmann 2018], where the difference was as high as 28.4cm (these work had animation artefacts due to real time IK and participants were hearing rain noise during the experiment). This finding makes us believe that consistent animations for self-avatars create VR scenarios where participants behave closer to the real world counterpart.

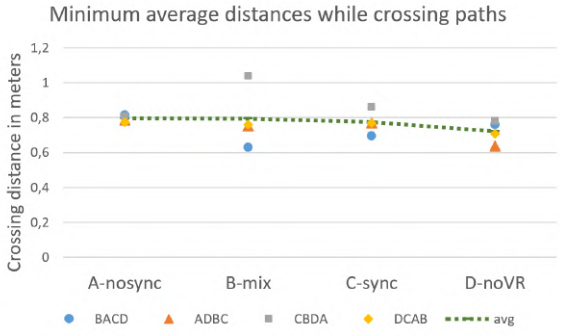


Figure 10: Average clearance distances kept while participants would cross paths.

5 CONCLUSIONS AND FUTURE WORK

The results of this work show that animation synchronism and footstep sound do not seem to have a strong impact in terms of presence and feeling of avatar control. However, in our experiments, incorporating natural animations and footstep sound resulted in smaller clearance values in VR than previous work in the literature. Quantitative evaluation of trajectories reported some differences which reflect how users behave in immersive VR depending on how much they feel that it accurately represented the real world. We believe that the reason why we did not observed a larger impact on the results was twofold (1) both the animation and footstep differences across scenarios were very subtle (participants reported not noticing any difference whatsoever after running each scenario), and (2) the sync animation was exclusively based on a left foot tracker to determine which foot started the animation, and the head tracker to determine the velocity of the avatar for time warping purposes. This decision was made so that we could run natural looking animations (simply coordinating the leg movement and speed) but avoiding artifacts that tend to appear when full IK is used. The disadvantage of this technique is that the animations are not completely mimicking the participant's movement, which makes less obvious the differences between sync and no-sync animation. The differences in foot step synchronism were very subtle, since the non-sync was played with an offset but respecting the frequency. We would like to study whether having more exaggerated difference in the no-sync sound could have a stronger impact. However, recent work by Silva et al. also found no impact on using footstep noise[Silva et al. 2018].

This paper presents our initial findings regarding participants behavior when performing a collaborative task in both immersive VR and non VR setups. The fact that participants are aware of the presence of another person sharing the physical space, seems to make them cautious about their movement and tends to reduce velocities. We also observed that by sharing the physical space, collaboration in terms of talking to each other emerges naturally. Gesturing also emerged as a convenient interaction technique even though it had not been agreed on before hand. As the use of VR is extending and collaborative VR offers a whole new world of working possibilities, more studies will be necessary to fully understand how user behavior differs between VR and the real world. From this we can gain experience and provide advice on how collaborative VR should be handled to achieve a natural working environment for designers to discuss ideas, engineers to instruct how pieces of machinery should be replaced, and of course for even better gaming experiences.

In the future we would like to run experiments with both participants wearing wireless HMDs, because we believe that the participants in our experiment, after doing the D-noVR scenario, were aware of the cable and this may have had an impact on their movement (even though it presented no physical limitation). We also want to further explore to what extent animation and sound quality can affect the participants' behavior, since our initial findings show that even subtle differences seem to have a small impact in the participant's velocities and avoidance distances.

ACKNOWLEDGMENTS

This work has been partially funded by the Spanish Ministry of Economy and Competitiveness and FEDER under grant TIN2017-88515-C2-1-R.

REFERENCES

Carlos Andujar, Pere Brunet, Jeronimo Buxareu, Joan Fons, Narcis Laguarda, Jordi Pascual, and Nuria Pelechano. 2018. VR-assisted Architectural Design in a Heritage Site: the Sagrada Família Case Study. In *EUROGRAPHICS Workshop on Graphics and Cultural Heritage (EG GCH)*. Eurographics.

Ferran Argelaguet, Anne-Hélène Olivier, Gerd Bruder, Julien Pettré, and Anatole Lécuyer. 2015. Virtual proxemics: Locomotion in the presence of obstacles in large immersive projection environments. In *Virtual Reality (VR), 2015 IEEE*. IEEE.

M. Azmandian, T. Grechkin, and E. S. Rosenberg. 2017. An evaluation of strategies for two-user redirected walking in shared physical spaces. In *2017 IEEE Virtual Reality (VR)*, Vol. 00. 91–98.

Andrea Bönsch, Sina Radke, Heiko Overath, Laura M. Asché, Jonathan Wendt, Tom Vierjahn, Ute Habel, and Torsten W. Kuhlen. 2018. Social VR: How Personal Space is Affected by Virtual Agents' Emotions. In *Proceedings of IEEE Virtual Reality Conference 2018*.

Julien Bruneau, Anne-Helene Olivier, and Julien Pettre. 2015. Going through, going around: A study on individual avoidance of groups. *IEEE transactions on visualization and computer graphics* 21, 4 (2015), 520–528.

Peter Frost and Peter Warren. 2000. Virtual reality used in a collaborative architectural design process. In *Information Visualization, 2000. Proceedings. IEEE International Conference on*. IEEE, 568–573.

Martin Gérin-Lajoie, Carol L Richards, Joyce Fung, and Bradford J McFadyen. 2008. Characteristics of personal space during obstacle circumvention in physical and virtual environments. *Gait & posture* 27, 2 (2008), 239–247.

Naman Gupta, Anmol Singh, and Sachit Butail. 2017. The effect of instructional priming on postural responses to virtual crowds. In *Virtual Humans and Crowds for Immersive Environments (VHCIE)*. IEEE, 1–8.

Tina Iachini, Yann Coello, Francesca Frassinetti, and Gennaro Ruggiero. 2014. Body space in social interactions: a comparison of reaching and comfort distance in immersive virtual reality. *PloS one* 9, 11 (2014), e111511.

Marios Kyriakou, Xueni Pan, and Yiorgos Chrysanthou. 2017. Interaction with virtual crowd in Immersive and semi-Immersive Virtual Reality systems. *Computer Animation and Virtual Worlds* 28, 5 (2017).

Eike Langbehn, Eva Harting, and Frank Steinicke. 2018. Shadow-Avatars: A Visualization Method to Avoid Collisions of Physically Co-Located Users in Room-Scale VR. In *IEEE Workshop on Everyday Virtual Reality*.

Joan Llobera, Bernhard Spanlang, Giulio Ruffini, and Mel Slater. 2010. Proxemics with multiple dynamic characters in an immersive virtual environment. *ACM Transactions on Applied Perception (TAP)* 8, 1 (2010), 3.

Sean Lynch, Julien Pettré, Julien Bruneau, Richard Kulpa, Armel Cretual, and Anne-Hélène Olivier. 2018. Effect of Virtual Human Gaze Behaviour During an Orthogonal Collision Avoidance Walking Task. In *IEEE Virtual Reality*.

Mixamo. 2018. https://www.mixamo.com/

Betty J Mohler, Sarah H Creem-Regehr, William B Thompson, and Heinrich H Bülthoff. 2010. The effect of viewing a self-avatar on distance judgments in an HMD-based virtual environment. *Presence: Teleoperators and Virtual Environments* 19, 3 (2010), 230–242.

Sahil Narang, Andrew Best, Tanmay Randhavane, Ari Shapiro, and Dinesh Manocha. 2016. PedVR: Simulating gaze-based interactions between a real user and virtual crowds. In *Proceedings of the 22nd ACM conference on virtual reality software and technology*. ACM, 91–100.

Anne-Hélène Olivier, Julien Bruneau, Gabriel Cirio, and Julien Pettré. 2014. A virtual reality platform to study crowd behaviors. *Transportation Research Procedia* 2 (2014), 114–122.

Anne-Hélène Olivier, Julien Bruneau, Richard Kulpa, and Julien Pettré. 2018. Walking with virtual people: Evaluation of locomotion interfaces in dynamic environments. *IEEE transactions on visualization and computer graphics* 24, 7 (2018), 2251–2263.

Nuria Pelechano and Jan M Allbeck. 2016. Feeling crowded yet?: crowd simulations for VR. In *Virtual Humans and Crowds for Immersive Environments (VHCIE)*. IEEE, 17–21.

Nuria Pelechano, Catherine Stocker, Jan Allbeck, and Norman Badler. 2008. Being a part of the crowd: towards validating VR crowds using presence. In *Proceedings of the 7th international joint conference on Autonomous agents and multiagent systems-Volume 1*. 136–142.

Iana Podkosova and Hannes Kaufmann. 2018. Mutual Collision Avoidance During Walking in Real and Collaborative Virtual Environments. In *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games (I3D '18)*. ACM, New York, NY, USA, Article 9, 9 pages.

Farzad Pour Rahimian and Rahinah Ibrahim. 2011. Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design. *Design Studies* 32, 3 (2011), 255–291.

Tanmay Randhavane, Aniket Bera, and Dinesh Manocha. 2017. F2FCrowds: Planning agent movements to enable face-to-face interactions. *Presence: Teleoperators and Virtual Environments* 26, 2 (2017), 228–246.

Alejandro Rıos, Daniel Mateu, and Nuria Pelechano. 2018. Follower Behavior in a Virtual Environment. In *Virtual Humans and Crowds for Immersive Environments (VHCIE), IEEE*. IEEE.

Francisco Arturo Rojas and Hyun Seung Yang. 2013. Immersive Human-in-the-loop HMD Evaluation of Dynamic Group Behavior in a Pedestrian Crowd Simulation That Uses Group Agent-based Steering. In *Proceedings of the 12th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry (VRCAI '13)*. ACM, New York, NY, USA, 31–40.

Maria V Sanchez-Vives and Mel Slater. 2005. From presence to consciousness through virtual reality. *Nature Reviews Neuroscience* 6, 4 (2005), 332.

Anthony Scavarelli and Robert J. Teather. 2017. VR Collide! Comparing Collision-Avoidance Methods Between Co-located Virtual Reality Users. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)*. ACM, New York, NY, USA, 2915–2921.

Susanne Schmidt, Gerd Bruder, and Frank Steinicke. 2015. A Layer-based 3D Virtual Environment for Architectural Collaboration. In *Proceedings of the EuroVR Conference-2015*.

Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments* 10, 3 (2001), 266–281.

Wagner Souza Silva, Gayatri Aravind, Samir Sangani, and Anouk Lamontagne. 2018. Healthy young adults implement distinctive avoidance strategies while walking and circumventing virtual human vs. non-human obstacles in a virtual environment. *Gait & posture* 61 (2018), 294–300.

Mel Slater and Maria V Sanchez-Vives. 2016. Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI* 3 (2016), 74.

Bernhard Spanlang, Jean-Marie Normand, David Borland, Konstantina Kilteni, Elias Giannopoulos, Ausiàs Pomés, Mar González-Franco, Daniel Perez-Marcos, Jorge Arroyo-Palacios, Xavi Navarro Muncunill, et al. 2014. How to build an embodiment lab: achieving body representation illusions in virtual reality. *Frontiers in Robotics and AI* 1 (2014), 9.

Kamala Varma, Stephen J Guy, and Victoria Interrante. 2017. Assessing the Relevance of Eye Gaze Patterns During Collision Avoidance in Virtual Reality. (2017).

Katja Zibrek, Elena Kokkinara, and Rachel McDonnell. 2017. Don'T Stand So Close to Me: Investigating the Effect of Control on the Appeal of Virtual Humans Using Immersion and a Proximity-based Behavioral Task. In *Proceedings of the ACM Symposium on Applied Perception (SAP '17)*. ACM, New York, NY, USA, Article 3, 11 pages.