How Observers Perceive Teleport Visualizations in Virtual Environments

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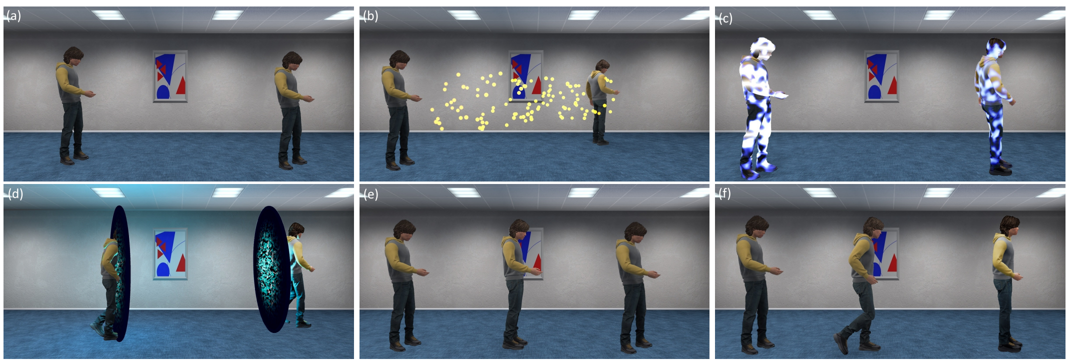

Figure 1: Our teleport visualizations depicted as sequences from start to end: None (the standard point & click teleport and the delayed variant) (a), particle trace (b), beam (c), portal (d), dash (linearly translating the avatar)(e), and walking (f).

ABSTRACT

Multi-user VR applications have great potential to foster remote collaboration and improve or replace classical training and education. An important aspect of such applications is how participants move through the virtual environments. One of the most popular VR locomotion methods is the standard teleportation metaphor, as it is quick, easy to use and implement, and safe regarding cybersickness. However, it can be confusing to the other, observing, participants in a multi-user session and, therefore, reduce their presence. The reason for this is the discontinuity of the process, and, therefore, the lack of motion cues. As of yet, the question of how this teleport metaphor could be suitably visualized for observers has not received very much attention. Therefore, we implemented several continuous and discontinuous 3D visualizations for the teleport metaphor and conducted a user study for evaluation. Specifically, we investigated them regarding confusion, spatial awareness, and spatial and social presence. Regarding presence, we did find significant advantages for one of the visualizations. Moreover, some visualizations significantly reduced confusion. Furthermore, multiple continuous visualizations ranked significantly higher regarding spatial awareness than the discontinuous ones. This finding is also backed up by the users' tracking data we collected during the experiments. Lastly, the classic teleport metaphor was perceived as less clear and rather unpopular compared with our visualizations.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

KEYWORDS

Teleport Visualization, Virtual Reality, Multi-User, Locomotion

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1 INTRODUCTION

Technological advances and decreasing costs lead to a growing popularity of virtual reality (VR) among researchers, developers, and consumers alike. The ability to immersively experience virtual environments as if actually present makes VR highly interesting for applications ranging from gaming and entertainment to training and education. [29] Furthermore, multi-user VR applications provide co-located or remote participants with the ability to collaborate and interact with each other in a shared virtual environment, which has been shown to be highly beneficial for a wide array of tasks such as liver surgery planning [8], moderated remote usability testing [6], and computer-aided design and construction [24]. In these multi-user VR environments, the users get virtually represented by 3D avatars to enable effective interaction and collaboration. Especially full-body avatars that realistically depict the user have been shown to be advantageous for the sense of presence, embodiment [22], trust formation, and task performance [17].

One of the most important design decisions for a VR system is which type of locomotion metaphor should be used for traveling greater distances in the virtual environment [19]. Smaller movements are usually handled well using “room-scale”, in which the actual movements get tracked and directly replicated. Typical locomotion methods for greater distances include (point&click) teleportation, redirected walking, walk-in-place, and steering (e.g., via joystick). All these techniques naturally have different strengths and weaknesses regarding aspects such as physical effort, precision, time, etc. [2]. The teleportation metaphor, for instance, is among the most popular ones, as it is relatively simple, quick, and proven to be unlikely to induce cybersickness [4, 5]. Cybersickness is a major concern for VR applications. It is similar to motion sickness and is believed to be mainly caused by a sensory mismatch between the visual and the vestibular and proprioceptive systems [15].

Using the standard teleport locomotion metaphor in multi-user environments, however, has one significant drawback: The inherent discontinuity of the process may disrupt multiplayer gameplay and lead to confusion for observers when the user('s avatar) seemingly vanishes or emerges from nowhere, as argued by Griffin and Folmer [14] and reported incidentally by Wang et al. [25]. Figure 2 depicts this scenario. Moreover, this behavior could be easily mistaken to be the result of network issues, in fact, it would strongly resemble a high-lag connection in online gaming. Ultimately, the chance for a loss of presence for the observers would be, presumably, significant. Especially so as it was already established that the abrupt change of location and the absence of any motion cues can lead to confusion and a loss of presence for the teleporting user himself [1]. Presence – the sense of being there/in the virtual environment – is a crucial factor for the quality of the VR experience, though [20, 21], and should be as high as possible. Prithul et al. [18], too, identified the issue of teleportation in multiplayer scenarios and anticipate detrimental effects to the presence of observers. Hence, they view it as an important direction for future research.

With this work, we want to tackle this issue and expand on the very sparse research on this topic. Typical dictionary definitions for something “confusing” are: “Something that is confusing makes it difficult for people to know exactly what is happening or what to do” [10], or “... because it is difficult to understand” [11]. Therefore, we have implemented several visualization methods to convey the deliberate act of teleportation to observing users in a shared virtual environment, similar to Thanyadit et al. [23] and Freiwald et al. [13]. Our main goal is to do a comprehensive evaluation of the effects of different teleport visualizations on observers. Specifically,

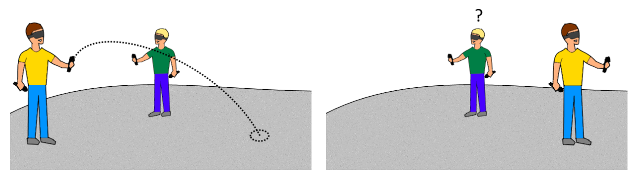

Figure 2: Depiction of the possibly confusing teleport locomotion in multi-user VR. Left: User teleports to a new location. Right: After the instantaneous, discontinuous teleport, the observing user lost track and is confused.

if the visualizations enhance spatial awareness, prevent confusion, and, thus, a loss of presence. Therefore, we have formulated the following research questions:

- R_1: Do visualizations help with preventing confusion caused by the teleportation process?
- R_2: Do visualizations help to retain presence when teleporting?
- R_3: Do continuous visualizations provide more spatial awareness?
- R_4: Which visualization is generally the best (e.g., presence, confusion, user preference)?
- R_5: Do the visualizations differ regarding the speed scalability?

To answer these questions, we have conducted a subsequent study, in which we investigated the visualizations' effects on observers, i.e., regarding spatial awareness. To guarantee similar conditions and minimize confounding effects, we opted for a study design with a single observer that views pre-recorded teleportations. Moreover, we focused on near-field teleportation, i.e., room size, the usual scale of many VR applications. In contrast to previous work, we tested multiple scenarios (in/out of-FoV) and properties such as the spatial and social presence, the plausibility and intuitiveness of the visualization as well as the visualizations' speed scalability. With our user study and extensive evaluation, we provide valuable insights into this crucial but under-investigated topic.

2 RELATED WORK

Most previous work about locomotion in VR is concerned with designing novel advantageous locomotion metaphors –a comprehensive overview is given by Boletsis [4]– as well as examining and comparing them regarding factors of interest such as cybersickness, presence, user preference, and effectiveness. More information specifically about teleport locomotion can be found in the work by Prithul et al. [18]; generally, it is found to be highly performant and safe regarding cybersickness, but also prone to spatial disorientation in the absence of any motion cues and only limited path integration.

The observer's perception of the locomotion in multi-user environments is usually not considered, though. Even when looking at the related and interesting but distinct research topic of group navigation, where the focus lies on designing systems in which groups of people can navigate a common virtual space together, the findings about multi-user locomotion visualization are sparse. In this area, the main goals are finding and maintaining suitable formations, as well as, object avoidance, and improving the comprehensibility of the process to the group members. The latter is achieved by preview visualizations of where the individual users will be after the group navigation, of their individual paths, and of how the group as a whole will look like. The visualization of the locomotion process itself (to observers not in the group), usually, does not get considered. Recent examples from this area are the works by Chheang et al. [7], Weissker et al. [26, 28] and Weissker and Froehlich [27]. The latter presented a jumping-based group navigation metaphor focusing on usability and comprehensibility (for the navigator and the group). For this, the navigator has the ability to define the group formation and he and the group members get preview visualizations.

How locomotion by teleportation is perceived by others and how it could be favorably visualized is hardly researched yet. Accordingly, Prithul et al. [18] came to the same conclusion in their review about the teleportation metaphor. To our knowledge, the only works that explicitly looked into this topic are the ones by Thanyadit et al. [23] and Freiwald et al. [12, 13]. The latter first compared steering-based locomotion with teleportation, as well as avatar appearance, in a competitive multi-user, shared virtual environment. The task was to play a virtual match of snowball and hit the opponent as often as possible. While the player who was to be questioned was limited to the steering locomotion, the opponent either used steering too or teleportation. The authors found that the continuous steering locomotion ranked significantly higher regarding co-presence and perceived fairness, while the avatar's appearance had only a negligible effect. These results reinforce the assumption of a reduction in the presence and other adverse effects of teleportation in contrast to continuous locomotion methods. In the subsequent work, Freiwald et al. [13] did focus on the issue of discontinuous teleport locomotion in shared VR environments. To create a better experience and increase spatial awareness for observers, they proposed a system that temporally depicts special "smart avatars" that mimic the locomotion of the user to the observers. The idea is that these avatars do a continuous transition to the target destination, although the actual teleport is discontinuous. Four different transition techniques were implemented and evaluated regarding spatial awareness, attractiveness, and pragmatic and hedonic quality scores. Generally, the transitions consist of a walking animation, or depict some kind of trail. The proposed continuous transitions were rated higher for all these factors.

Thanyadit et al. [23], which, together with the later work by Freiwald et al. [12, 13], is the work most closely related to ours, did also identify the unique issues of teleportation in multi-user settings. Hence, they designed 4 substituted visualizations as a remedy, namely: hover, jump, fade, and portal. The former two are rather similar and resemble the continuous dash locomotion technique. The fade visualization slowly fades the avatar out and in, at the start and target location, respectively. The portal method uses separate portals to achieve a similar effect. The authors also identified general design requirements, being time efficiency, traceability, intuitiveness, and recognizability, and briefly discussed the visualizations. Moreover, they did a pilot study with 5 participants that found the hover visualization to be the preferred one.

Although their work featured multiple similar visualizations and evaluation properties as ours, they lack a large, formal evaluation. To this date, the only comprehensive evaluation of teleportation visualizations for observers is the one by Freiwald et al. [13]. However, in contrast to us, they did not test multiple scenarios, e.g., the influence of teleportation strictly in the observer's FoV compared to teleporting in/out of it, or the visualizations scaleability with speed/the teleportation time. Moreover, the visualizations' effect on the observers' spatial- and social presence as well as how plausible and intuitively understandable the visualization depicts the teleportation process were not evaluated, yet.

3 OUR TELEPORT VISUALIZATIONS

In order to investigate which visualization would be best suited to convey the teleportation process to observers in a multi-user setting, we decided to implement a variety of visualization methods. Important properties which we took into consideration were the degree of predictability and traceability the visualization provides, the time a convincing representation would take, the intuitiveness of the visualization, and the general plausibility. The first three properties are similar to the requirements Thanyadit et al. [23] proposed. The plausibility, naturally, is dependent on the exact setting and the user's representation itself, i.e., the kind of avatar. For our investigation, we focused on full-body avatars and a generic environment setting which should make the results more widely applicable. In addition to the standard point&click teleport that instantly changes the avatar's location, we opted to implement a teleport with particle trace, a portal metaphor, a beam particle effect, a quick dash, and a complete walking animation. As all these other methods take time, in contrast to the standard teleport, we also included a delayed teleport for a time-normalized comparison.

In the following, we briefly describe the individual visualizations.

- The standard point&click teleport (P&C, or just teleport from now on) instantly changes the character's location to the target destination without any visual feedback to observers, see Fig. 1(a). Although the teleport line/arc that the user himself usually can see could also be visualized for observers, we decided against it as this is not the usual practice. Additionally, we have a delayed implementation in which the character only arrives after the same amount of time as with the other visualizations (P&C S, or slow teleport).
- The particle trace (PTrace) visualization is implemented using a particle system and shows many continuously emerging (and slowly fading out) particle spheres along the path from start to destination, see Fig. 1(b). This trace of particles provides a motion cue to observers. This metaphor is inspired by several computer games using similar techniques, such as League of Legends (Pike character), as well as, the "dissolve" transition by Freiwald et al. [13].
- The beam effect is a warping- and glowing effect briefly applied to the character's material at the start and end of the teleportation, see Fig. 1(c). It resembles beam effects in many sci-fi movies (e.g., Star Trek) and computer games and is also part of the "dissolve" transition by Freiwald et al. [13] and similar to the "Fade" visualization by Thanyadit et al. [23]. It is non-continuous and rather quick.

- The portal metaphor is generally similar to the beam effect, see Fig. 1(d). However, instead of applying a visual effect on the character, a portal emerges through which he then steps. At the destination, another portal pops up from which the character reemerges. It is similar to the one by Thanyadit et al. [23].
- The dash visualization is similar to the one in [3] and the hovering metaphor in [23], see Fig. 1(e). The full-body avatar is quickly and continuously translated in a direct line to the destination, thus, providing the observer with motion cues, similar to the particle trace.
- The walking visualization is a fully-fledged, pre-recorded walking animation that is played and shown to the observers, see Fig. 1(f). This should help to increase the plausibility and be the most natural visualization, depending on the speed.

In general, the visualizations can be classified as continuous and non-continuous ones. We expect the former to feature higher tractability and presence but to be less time efficient (at least for the teleporting user) [9]. Example visualizations for this category would be the dash, the particle trace, and, on the far end of the spectrum, the full walking animation. Non-continuous visualizations would be the beam effect, the portal, and, on the other end of the spectrum, the extreme case of the standard teleport.

4 STUDY

To conduct a user study about the teleportation depiction and its effects (see the last paragraph of section 2), we have implemented all the aforementioned visualizations using the Unreal Engine 4.26.

4.1 Hypotheses

Based on prior work about locomotion in virtual reality, and our own considerations, we defined the following eight hypotheses to answer our research questions. From research question R_1, and the report by Wang et al. [25], and the definition of confusing (see Sec. 1) we directly derive hypotheses H_1 and H_2:

- H_1: A teleport visualization makes the locomotion process more intuitively understandable.
- H_2: A teleport visualization makes the locomotion process more plausible.

Similarly, to answer research question R_2, we formulate hypotheses H_3 and H_4:

- H_3: A teleport visualization has a positive impact on the perceived spatial presence.
- H_4: A teleport visualization has a positive impact on the perceived social presence.

It was already established that continuous locomotion tends to provide a higher presence for the teleporting user [9], thus, it arguably holds also for the observers.

To check research questions R_3, we decided to focus on the abilities to track and relocate a person, thus, we raise the hypotheses that

- H_5: Continuous teleportation visualizations increase the ability to track the person.
- H_6: Continuous teleportation visualizations increase the ability to quickly relocate the person.

This is a natural assumption to make, as a continuous visualization directly provides visual cues to the observer. Moreover, Freiwald et al. [13] reported higher spatial awareness for observers by using continuous visualizations for teleport locomotion.

As the walking animation is the most natural metaphor (at least when the speed is appropriate), we answer the research question R_4 by hypothesizing (similar to Freiwald et al. [13]) that

- H_7: The walking animation is preferred the most by the users.

Lastly, we would expect that the continuous visualizations have inherently a more limited range of distances/speeds in which they are convincing and effective. Therefore, to answer research question R_5, we formulate the hypothesis H_8:

- H_8: Continuous teleport visualizations exhibit a lower speed scalability.

4.2 Experimental Design

In our experiment, we opted to test two scenarios in a within-subject design. In the first one, the teleporting character starts in full view of the participant and teleports either from left to right or the other way around. The destination (and the full path) was always in view, too. We chose this teleport setup in order to have distances as large as possible in the FoV. The order in which the teleport visualizations were applied throughout the use case was randomized. Also, to reduce the predictability, possible mental fatigue and prevent confounding learning effects, the exact teleport angle, and therefore target destination, was slightly randomized. The distance was always the same, though. We decided to not use vastly different paths to provide comparable conditions. For the second scenario, we focused on a more advanced setting with a higher potential for a reduction in presence, namely, when the target destination is out of view of the observing user. The setup was principally the same as before, however, this time, the character's target destination was set up to be behind the observing user. Again, the visualizations' order as well as the exact target destination were slightly randomized, meaning the character sometimes teleported to the observer's back left or back right. Figure 3 depicts the setup for both scenarios. The participants always had to go through both scenarios, although the order was randomized.

Additionally, to investigate the effect of the visualizations' duration and their scalability regarding the teleportation speed/time, we decided to perform our experiment again with a faster teleport/visualization speed. When teleporting over greater distances, and one wants to prevent the user from waiting longer, the visualization has to be quicker. Empirical tests we conducted led us to use the durations of 1.42 seconds for the original, slower variant and 0.71 seconds for the faster one over a teleport distance of 2.88 meters. Thus, theoretically, the user had a speed of 2.03 m/s and 4.06 m/s. The animations were sped up accordingly from their original speed to match the durations. The eventual durations were always the same for each visualization during the experiment, with the exception of the standard teleport, which is performed instantly.

Although we employ a within-subject design for the two scenarios (in/out of the field of view) to get sound results with a reasonable amount of participants, for the second, faster experiment variant, we made sure to recruit new participants that did not take part

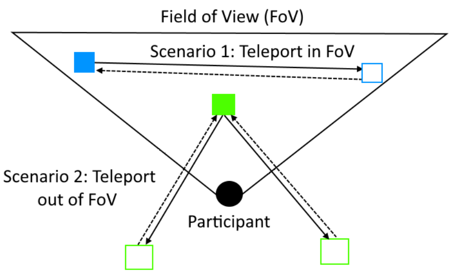

Figure 3: Top-down view of the scene of our VR experiment. Scenario one (in-FoV) is depicted in blue, and scenario 2 (out-of-FoV) in green. Both consist of a two-way teleportation to the destination (full arrow) and back (dotted arrow). The exact positions and angles were randomized.

in the original one to reduce the repetitiveness. This makes our study, ultimately, a mixed design study (a combination of a between-subjects design and a within-subjects design). We find this to be a good compromise.

Independent of the scenario and variant, the participants were supposed to stand in the middle of the room and, to minimize distractions, were not represented by any avatars themselves. To guarantee comparable conditions for all participants and to minimize confounding effects between subjects and between different visualizations, we pre-recorded animations for the teleporting character to perform and opted to only have one observer at a time. For each of the different teleport visualizations, the procedure was the same: the character looks around briefly, executes the teleport by pointing the controller in the destination direction, the visualization is shown, and the character arrives at the target destination. Finally, the character turns around and teleports back to the original position. We chose this two-way teleportation path in an effort to maximize the effect size. The task for the participants was to simply observe and track the teleporting character, both, with the eyes as well as with a virtual laser pointer.

4.3 Setup

For our experiment, we created a 3D office scene in the Unreal Engine 4.26. As to not distract the participants, the 3D scene is rather minimalistic and free of clutter, yet, the lighting and the used meshes are of high quality. We implemented all the teleport visualizations that we described in chapter 3 and opted to use a high-fidelity MetaHuman avatar for the teleporting character. However, to keep the performance reasonably high, we had to lower the avatar's hair's fidelity. In order to record the animations, we opted for the OptiTrack motion capture system. Tracking of the participants' gaze direction was done using the HMD's built-in eye-tracking system.

4.4 Measures

For our experiment, we mostly relied on questionnaires. In a demographics (pre-)questionnaire, we asked the participants about the usual demographic data as well as their experience in VR and with games with avatars, cybersickness, etc. Moreover, we employed

Table 1: Our questionnaire about social presence (1./2.) and spatial presence (3./4.), which is based on the Multimodal Presence Scale [16]. Answers from "None" to "Very much" using a 7-point Likert scale.

1.	I felt like I was in the presence of another person in the virtual environment.
2.	The person in the virtual environment appeared to be sentient (conscious and alive) to me.
3.	The virtual environment seemed real to me.
4.	While I was in the virtual environment, I had a sense of "being there".

Table 2: Our questionnaire in which the visualizations had to be ranked according to the various criteria listed below. Each item begins with "Order the visualizations by".

1.	how plausibly they represented the movement.
2.	how intuitively they represented the movement.
3.	how well you could anticipate the destination of the other person with the help given by the visualizations.
4.	how fast you could find the other person after the locomotion took place.
5.	how much you liked them.

a custom social- and spatial presence questionnaire. We decided to limit ourselves to two questions each to reduce the repetitiveness and the time. The exact questions are listed in Table 1 and had to be answered using a 7-point Likert scale. The questions are a subset we carefully selected from the more comprehensive presence questionnaire by Makransky et al. [16]. Additionally, the participants had to rank the visualizations regarding several criteria, such as plausibility or target anticipation (see Table 2). To quantitatively measure the observers' ability to find or track the teleporting user, we tracked the time the participants looked (roughly) at the teleporting character and the time they pointed at the character. Lastly, we also employed a post-questionnaire to ask again about cybersickness and any comments.

4.5 Procedure

The study procedure, which is depicted in Fig. 4, started with the participants being informed about the study and its purpose and them giving their consent. However, the exact goal was not revealed to them; only that it involved multi-user VR. They agreed to the anonymous collection and processing of the data. Moreover, the experiment strictly followed the ethical guidelines of the university. Then, the participants were asked to fill out the (demographics) pre-questionnaire. After this, the participants were given a minute to familiarize themselves with the HMD and the virtual 3D environment. Additional training was not necessary due to the simplicity of the task. Eventually, the actual experiment (either the slow or fast variation) started with the first of the two scenarios in which the participants had to observe the teleportation visualizations (one after another). After each one, the participant was presented with a black screen on which the text questions about spatial and social presence appeared one after each other. The verbally given answers

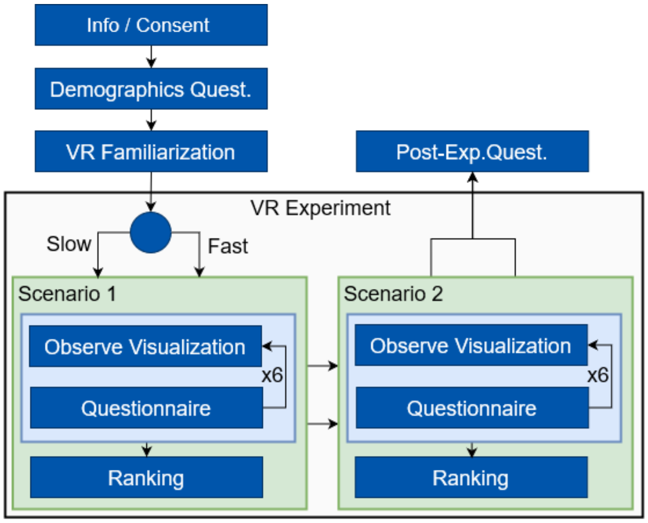

Figure 4: Diagram of the study procedure. Each participant experienced both scenarios (in-FoV/out-of-FoV) but took part only in either the slow or the fast experiment variant.

were written down by the assistant. This procedure then was repeated directly for the other of the two scenarios. After each of the two scenarios, the participants had to also perform the rankings. For these, the participants were presented with a gallery of enumerated images of all the visualizations, serving as a reminder, and had to order them, one time per criteria. Again, the verbally given answers were written down by the assistant. We decided to let the participants complete the questionnaires and rankings directly in VR. The reason is that recent research on using presence questionnaires in VR suggests that this reduces the time needed for adjusting between VR and the real world, reduces potential distracting cues from the real world, and, most importantly, reduces the occurrence of breaks in presence [21]. Finally, the participants filled out the post-experiment questionnaire.

5 RESULTS

5.1 Participants

For our study, we recruited $n = 52$ participants (76.9 % men, 23.1 % women). In our mixed design, a random half took part in the slow experiment variant and the other half in the fast one, but all participants experienced both scenarios. The participants' ages' ranged between 18 and 71 years with an average age of 30.98 (SD = 12.9) years. Asked about previous experience with VR, 36.5 % reported to have none or very little (< 5 times), 17.3 % stated to have moderate experience (5 to 10 times), and 46.2 % had extensive experience (> 10 times). Furthermore, 15.4 % of the participants stated to not have any awareness of the teleportation metaphor for locomotion (in general, not necessarily regarding VR), while 34.6 % reported to be not familiar with seeing another player as an avatar in virtual 3D worlds. Regarding previous experience with multiplayer games (first/third-person only), 23.1 % reported to have none or very little (< 5 times), 17.3 % stated to have moderate experience (5 to 10 times), and 59.6 % had extensive experience (> 10 times).

5.2 Qualitative and Quantitative Data

For our presence data, which we gathered using questionnaires with 7-point Likert scales, we assumed the data to be normally distributed. This assumption was confirmed by Shapiro-Wilk tests that we performed for validation. To statistically evaluate our data, for each questionnaire item and separately for the scenarios and experiment variants, we then conducted 7-level repeated measure ANOVA to check for statistically significant differences between the visualizations. This was followed up by pairwise posthoc testing of all visualizations using dependent samples t-tests with Bonferroni correction, to find the exact visualizations with significant differences. As we did employ a different measurement method for our second questionnaire, namely relative rankings between the visualizations, we did assume to have not normally distributed data. This was confirmed by Shapiro Wilk-tests. Therefore, we employed the Friedman test, followed up by a pairwise Bonferroni corrected Wilcoxon signed-rank test. Lastly, for the tracked hit data, we had no definitive assumption for the distribution, which is why we again performed Shapiro-Wilk tests. As they were not normally distributed according to the tests, we employed the non-parametric evaluation process for this data. In order to compare the different scenarios (repeated-measure) and experiment variants (between-subject), we did perform separate 2-level tests, following the same general procedure. We always assumed the level of significance (alpha) to be 0.05, as usually done.

In the following, we describe the statistical details for the slow experiment variant in detail and show representative plots from the IFoV scenario. Then, we show relevant differences between the scenarios and variants. For the interested reader, all plots and data from all scenarios and variants can be found in the supplementary material.

5.2.1 Cybersickness. In regard to cybersickness, the average Likert Score increased slightly from 1.44 (SD = 0.84) before to 1.59 (SD = 1.09) after the experiment. Generally, most participants reported having none or just slight feelings of nausea, dizziness, or discomfort before and after the experiment. Only one participant started to have a strong feeling of cybersickness.

5.2.2 Presence. To measure the presence, we aggregated the two social presence and spatial presence questions, respectively. For the social presence in the "in the field of view" (IFoV) scenario and slow variant, the walking visualization got the highest ratings ($M = 4.42, Mdn. = 4.75, SD = 1.87$), while the slow teleport ($M = 3.25, Mdn. = 3.5, SD = 1.45$) and dash ($M = 3.25, Mdn. = 3.5, SD = 1.48$) got the lowest, see Fig. 5 (left). We found the data to be normally distributed and ANOVA ($p = 0.0001$) revealed significant differences between the visualizations. Posthoc testing revealed these to be between the slow teleport and walking ($p = 0.0038$), teleport and walking ($p = 0.0445$), and dash and walking ($p = 0.018$). Note, in our notation, the latter visualization is always the one that was rated higher. For the "out of the field of view" (OFoV) scenario, we got similar results and additional significant differences between dash and particle trace/beam/portal

($p = 0.0437/0.0326/0.0477$). The pair of teleport and walking barely missed the threshold with a p value of 0.0521.

For the spatial presence, we found the ratings generally to be slightly higher. In the IFoV scenario, the walking visualization was again rated the highest ($M = 5.19, Mdn. = 5.5, SD = 1.32$), the rest were closer together this time, and the portal was rated lowest ($M = 4.35, Mdn. = 4.0, SD = 1.43$), see Fig. 5 (middle). As before, ANOVA indicated significant differences ($p = 0.0007$), and posthoc testing revealed them to be only between the dash and the walking visualization ($p = 0.0105$). However, the pair of slow teleport and walking missed the threshold just slightly with $p = 0.0683$. In the OFoV scenario, the dash was rated lowest ($M = 4.23, Mdn. = 4.25, SD = 1.58$). ANOVA returned $p < 0.0001$ and posthoc testing revealed additional significant differences between the slow teleport/particle trace/beam/portal and walking ($p = 0.0273/0.0202/0.0358/0.0184$). The pair of teleport and walking missed slightly with $p = 0.0708$.

5.2.3 Plausibility and Intuitiveness. Regarding the questions of how plausible and intuitively understandable the visualizations were, we got rather similar results, also for both scenarios (IFoV/OFoV). In all cases, walking was rated the highest (i.e., plausibility, IFoV: $M = 5.42, Mdn. = 6, SD = 1.27$), and both teleports (i.e., plausibility, IFoV: $M = 1.77/2.54, Mdn. = 2/2.5, SD = 1.42/1.78$), as well as the dash (i.e., plausibility, IFoV: $M = 2.11, Mdn. = 1.5, SD = 2.08$), were rated the lowest, see for example Fig. 5 (right). The data was found to be not normally distributed. After the Friedman test, which indicated significant differences, we found them in posthoc testing to be between the walking visualization (rated higher) and all other ones regarding plausibility, for both the IFoV scenario ($p = 0.0002/0.001/0.0061/0.006/0.0169/0.0001$), and the OFoV scenario. In the case of intuitiveness, significant differences were found again for the walking visualization (rated higher) and all other ones (except the particle trace in the OFoV scenario)(IFoV: $p = 0.0002/0.0003/0.0184/0.02/0.0003$). Moreover, in the IFoV scenario, both teleports were rated significantly lower than the beam ($p = 0.0028/0.0374$), and in both scenarios, the slow teleport was rated lower than the particle trace (IFoV: $p = 0.0028$).

5.2.4 Target Anticipation and (Re-)Spotability. Our results regarding target anticipation as well as the ease of (re-)spotting the person after the locomotion show that the walking visualization was rated the highest for both criteria and both scenarios (i.e., target anticipation/spotability, IFoV: $M = 5.15/5.46, Mdn. = 6, SD = 1.12/1.07$), see for example Fig. 6(left). The dash and particle trace followed suit, while both teleports (i.e., target anticipation, IFoV: $M = 1.08/1.5, Mdn. = 1/1, SD = 1.2/1.6$, and spotability, IFoV: $M = 0.46/1.15, Mdn. = 0/1, SD = 0.65/1.12$) were rated lowest. The data was again not normally distributed. Significant differences were found between many visualizations: In the case of target anticipation, we found significant differences between the beam visualization and particle trace/dash/walking (IFoV: $p = 0.0014/0.0138/0.0003$), between the slow teleport and particle trace/portal/dash/walking (IFoV: $p = 0.0003/0.0387/0.0017/0.0002$), between teleport/dash and walking (IFoV: $p = 0.0002/0.0007$), as well as between teleport and particle trace/dash (IFoV: $p = 0.004/0.0002$). In the OFoV scenario, we found additionally the portal and walking ($p = 0.0037$) to be rated significantly different.

We found rather similar significant differences regarding the (re-)spotability. Specifically, we found them for the IFoV scenario to be between the beam and all other ones except the teleport ($p = 0.0027/0.0001/0.0051/0.0002/0.0002$), slow teleport and particle trace/portal/dash/walking ($p = 0.0001/0.0003/0.0001/0.0001$), between teleport/portal/dash and walking ($p = 0.0001/0.0044/0.0006$), between teleport and portal/dash ($p = 0.008/0.0002$), and between teleport/portal and particle trace ($p = 0.0002/0.0125$). For the OFoV scenario, we also found rather similar significant differences.

5.2.5 Controller- and Gaze Tracking. In addition to the questionnaires, we employed controller and eye tracking to quantify possible differences in the trackability of visualizations. Fig. 6 (middle) shows representative results. Regarding the controller tracking, the particle trace (IFoV: $M = 79.4, Mdn. = 85.8, SD = 19.4$), dash (IFoV: $M = 83.4, Mdn. = 88.8, SD = 17.3$), and walking (IFoV: $M = 83.6, Mdn. = 88.3, SD = 17.9$) showed the highest results for both scenarios. The data was found to be not normally distributed. The Friedman test and posthoc testing revealed that, in the IFoV scenario, significant differences exist between the slow teleport and dash/walking ($p = 0.0015/0.0068$), between the teleport and particle trace/beam/dash/walking ($p = 0.021/0.0230.0003/0.0005$), between portal and particle trace ($p = 0.0464$), also between beam/portal and walking ($p = 0.03/0.0034$), and between portal and dash ($p = 0.0031$). We got rather similar results for the OFoV scenario. For the gaze tracking, the hit ratio was generally higher, and the differences between visualizations were smaller. However, walking (IFoV: $M = 88.4, Mdn. = 93.76, SD = 11.81$), dash (IFoV: $M = 86.6, Mdn. = 93.78, SD = 14.8$) and particle trace (IFoV: $M = 85.1, Mdn. = 90.59, SD = 15.15$) still ranked the highest. Significant differences were found for both scenarios between: slow teleport and dash/walking (IFoV: $p = 0.0028/0.0002$), teleport and dash/walking (IFoV: $p = 0.0193/0.0056$), and between portal and walking (IFoV: $p = 0.0176$). In the OFoV scenario, we got additionally: teleport/beam and particle trace ($p = 0.0034/0.0101$), beam and dash/walking ($p = 0.0031/0.0004$), and portal and dash ($p = 0.0042$).

5.2.6 User Preference. We found the walking visualization to be the most preferred one for both scenarios (IFoV: $M = 4.38, Mdn. = 5, SD = 1.88$), and the slow teleport (IFoV: $M = 1.31, Mdn. = 1, SD = 1.32$) and dash (IFoV: $M = 1.42, Mdn. = 1, SD = 1.68$) the least preferred ones, see Fig. 6 (right). The data was not normally distributed. We found significant differences between (IFoV) the slow teleport/teleport/dash and beam ($p = 0.0011/0.0425/0.0058$), also between slow teleport and particle trace/portal/walking ($p = 0.009/0.008/0.0045$), and between the dash and particle trace/walk ($p = 0.0424/0.0004$). For the OFoV scenario we got similar results but also found teleport and walking ($p = 0.0002$) to be significantly different.

5.2.7 Differences between Scenarios and Variants. We did also compare the individual results between the scenarios and experiment variants. For the former, we found the differences to be generally very small and not statistically significant. A representative example is shown in Figure 7 (top). Except for the single outlier of the slow teleport performing noticeably worse here, all other visualizations perform similar as in the IFoV scenario. Between the experiment variants, the differences were more noticeable, although they

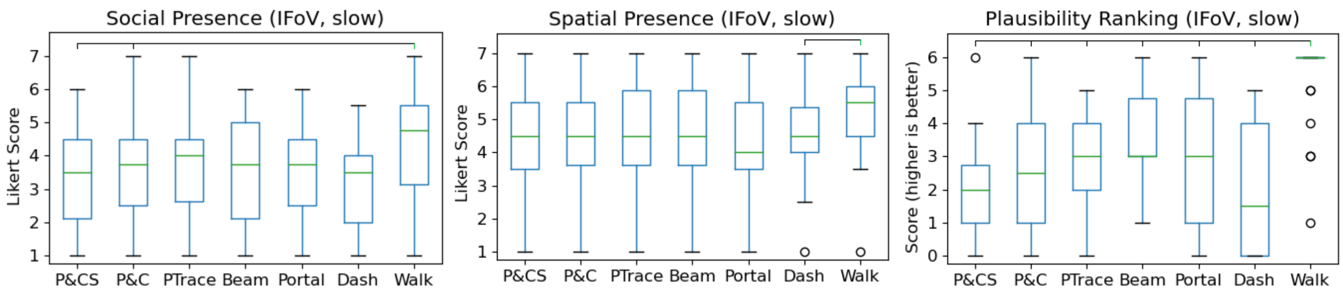

Figure 5: Social presence (left), spatial presence (middle), and plausibility ranking (right) results in the in-FoV scenario and slow variant. The walking visualization is (often significantly) rated the highest (note the aggregated significance bars; green highlights the superior visualization).

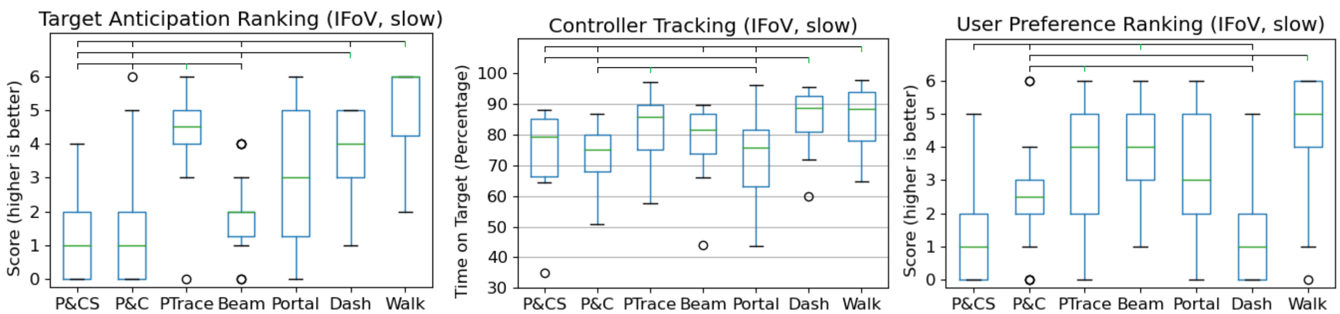

Figure 6: Results of the target anticipation ranking (left), and tracked controller hit rates (middle) in the in-FoV scenario and slow variant. Continuous visualizations are rated significantly better. Regarding the user preference (right), walking ranks the highest. For clarity, we highlighted only the most relevant statistical significances using aggregated bars.

were still mostly not statistically significant, see for example Fig. 7 (bottom). Generally, the differences between the visualizations are smaller in the faster variant, as high-ranking visualizations tend to perform slightly worse and low-ranking ones slightly better, see for instance the walk and dash (Fig. 7 (bottom)). The latter performed significantly better ($p = 0.015$), though, walking and particle trace performed still the best, absolutely speaking.

6 DISCUSSION

Our results show, that the walking visualization is consistently rated higher in social presence than the others, including the teleport, and the difference to the latter to be statistically significant. For the spatial presence, the results were closer together, but, still, the walking visualization was always rated highest. In the more critical OFoV scenario, significant differences to many other visualizations were found, while in the IFoV scenario, this threshold was mostly not reached, although the tendencies were present, too. These results indicate that the visualization of the teleport does have a positive effect on spatial as well as social presence. Thus, we can partly confirm our hypotheses H_3 and H_4. We can only confirm it partly, as this seems to be highly dependent on the actual visualization, and just having one not necessarily improves the presence. Generally, the spatial presence was consistently higher than the social one, which is understandable, as it might be more affected by the teleportation of the other user. Another reason could be that the social presence was lower to begin with, as there is no actual social interaction in the experiment. A more complex, dynamic, and engaging environment may be needed to induce more presence, possibly, leading to more differences between the other visualizations. User feedback we collected after the experiment, points in the same direction, as 2 participants stated that a more detailed environment would be helpful for presence and 8 participants did remark that the avatar's look, animation, or interaction with each other was lacking (e.g.: "dead eyes", "animations unnatural", "no eye contact", "no handshake"). The comments about the avatar and its animation are interesting, as we recorded them with motion tracking. Possibly, the actual physical transition between standing and walking was too abrupt and unnatural, as it was specifically intended for the teleport action. Another reason is probably that even the slow experiment variant was sped up from the actual recording.

Regarding the plausibility and intuitiveness of the locomotion process, our results clearly show that the walking visualization is consistently rated the highest, most often significantly, compared to all other ones. Moreover, the standard and delayed teleport, as well as the dash were consistently rated the lowest. These results confirm our expectations that a full walking animation is perceived as very plausible and intuitive while vanishing and emerging without any motion cues (teleport) is absolutely not. That the dash is rated low in this regard is understandable, too, as just translating a static

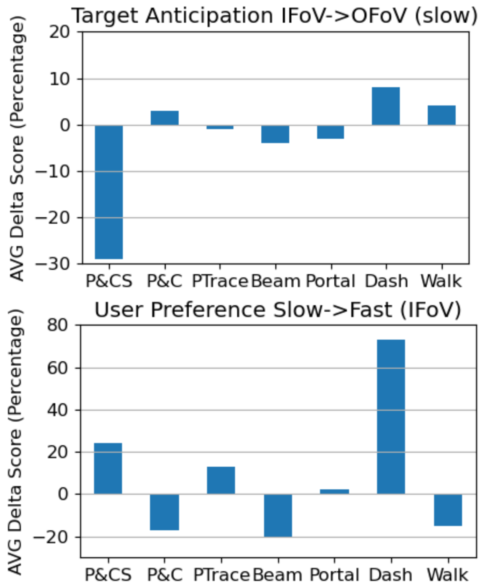

Figure 7: Relative delta scores of the visualizations between the IFoV/OFoV scenario (top) and slow/fast variant (bottom) In the former, the differences are mostly small but continuous visualizations tend to perform better. In the latter, we observe more noticeable differences leading to an equalizing effect (e.g., walk decreasing, dash significantly increasing).

avatar can look weird or jarring. With these results, we can confirm our hypotheses H_1 and H_2 that teleport visualizations, in general, make the locomotion process more intuitively understandable and plausible, thus, reduce potentially occurring confusion. The degree to which the visualizations improve plausibility and intuitiveness is, again, clearly dependent on the visualization itself.

The results about target anticipation and the ease of re-spotting the avatar after the locomotion show, as expected, that continuous visualizations perform significantly better than discontinuous ones, especially compared to the visualization-less teleports. The walking animation performed best overall, and, interestingly, the portal was the best out of the discontinuous ones. The latter result may be because the portal itself indicates the direction of locomotion, while the beam and the teleport variants do not give any hints. With these results, we can confirm our hypotheses H_5 and H_6, that continuous teleport visualizations are advantageous for tracking and relocating a teleporting user, thus, increasing spatial awareness. These findings are in line with the ones by Freiwald et al. [13]. These results moreover implicitly reinforce hypotheses H_1 and H_2, as easier tracking and increased spatial awareness of the other user's location should reduce confusion, too.

The quantitative results of the controller and gaze tracking, generally, paint the same picture and confirm the results regarding target anticipation and (re-)spotting. The continuous visualizations had the highest hit rates, often significantly higher, reinforcing hypotheses H_5 and H_6. Generally, the hit rates were higher for the gaze tracking than the ones from controller tracking and showed smaller differences between visualizations. This is understandable, as it is plausible that it is faster to change the eye gaze direction to the target location than the handheld laser pointer. Arguably, it is also easier to follow the movements of the avatar with the gaze. Interestingly, with this data, the portal performed worse than the beam, while the qualitative results were the opposite. This may be due to the portal object distracting from the avatar.

Our results show also that the walking animation is clearly the most preferred visualization and the teleport variants and the dash were rated lowest. Moreover, the differences in ratings were often significantly high. This result, together with the fact that the walking animation was rated best in all other tested categories, too, more than confirms our hypothesis H_7, that this is the best teleport visualization. Our results confirm the findings by Freiwald et al. [13], that continuous visualizations (walking/particle trail us, walking/dissolve them) are significantly more preferred than the standard teleport.

6.1 Comparison of IFoV and OFoV Scenarios

Interestingly, the results for the easier "in the field of view" and more critical "out of the field of view" scenarios are more similar than we expected. For instance, the tracked hit rates decreased in the OFoV scenario, especially for discontinuous methods such as the teleport versions. However, the differences were not as high as we would have expected. Also, the continuous visualizations tended to perform better, relative to the others, regarding the target anticipation in the OFoV scenario, which is reasonable. See for example Figure 7 (top). However, again, the difference between scenarios is smaller than assumed. This may indicate that the standard, visualization-less teleport is problematic in even simpler scenarios such as our IFoV scenario, which makes the visualizations even more important.

6.2 Comparison of Slow and Fast Experiment

As to the comparison of the slow and fast experiment variants, we did observe that the presence scores were mostly slightly lower in the fast one. We found the tracked hit rates to be generally lower, too. The hit rates of the continuous visualizations, which were higher previously, were the most affected while the hit rates of the teleport variants were less affected. Thus, in the faster variant, the hit rates between the visualizations were closer together. Interestingly, the ratings about target anticipation and (re-)spotability stayed roughly the same. Regarding the plausibility and intuitiveness, however, we found that the advantages of the walking visualization decreased while the dash got better, relatively (the teleport variants to a lesser degree, too). Thus, we observe a homogenizing effect again. In contrast to the slow experiment variant, we found the particle trace to have the highest scores regarding user preference in the IFoV scenario, as it was rated higher and the walking animation lower, see Figure 7 (bottom). The rankings for the portal and especially the dash increased, too. We see the same tendencies for the dash and walking visualizations in the OFOV scenario, making the particle trace and walking the most preferred visualizations overall. To summarize, the advantages of the visualizations decreased in the fast experiment variant, and the differences between the visualizations shrunk, e.g. dash catching up and walking coming down. We can therefore state that the speed scalability of the visualizations varies. However, we cannot confirm our hypothesis H_8 that continuous ones are principally worse. The fact that the walking animation loses so much regarding user preference, plausibility, and intuitiveness while the dash's ratings increase, is understandable, as the walking animation is more sped up, thus looking less natural. We find it also plausible, that the continuous visualizations fare worse in tracked hit rates, as these had the highest ratings in the slow variant, and it gets arguably harder for the observer to track the avatar/visualization when moving faster. Moreover, we see that the higher the locomotion speed, the lesser the advantages of the visualizations, especially when they get more unnatural (i.e., the simply sped-up walk animation). We find this logical, as there is less time that the teleporting user is not visible to the observer, and there is less time for a continuous visualization to show the motion cues.

We refer, as mentioned earlier, to the supplementary material for tables of all the statistical data and all plots (especially regarding the OFoV scenario and fast experiment variant).

6.2.1 Guidelines for Teleport Visualization. To summarize, we found the walking animation and the particle trail visualizations to be, for nearly all aspects, clearly superior to the standard teleport. The other visualizations showed more mixed results, in some aspects providing benefits and in others not. In the following, we want to give a couple of guidelines that we distilled from the findings:

- Continuous visualizations tend to perform better, especially regarding spatial awareness, thus, would be a general recommendation to employ.
- The walking animation performed best overall, thus, is our recommended visualization, as long as it can be used at reasonable speeds.
- If the visualization has to be performed faster, or the walking animation for other reasons cannot be depicted in a natural way, the particle trace would be our alternative recommendation, as it performed well, too.

7 LIMITATIONS

We opted to use a high fidelity but also a minimalistic virtual environment, decided to have a single pre-recorded character teleporting through the scene, and limit ourselves to a single observer with the simple task of just observing and tracking the other person moving. We did this, in order to limit distractions of the participants, focus on the primary question of how the visualizations affect the observer, and minimize confounding effects between the users, the environment, and the scenario. This setup, however, may have not been engaging and long enough to build high levels of presence, reducing the possible positive effects of the teleport visualizations. Also, the teleportation path may have been too short, linear, and predictable, hence, it would be interesting to do a similar experiment over larger distances. With our design choices for this first study, we are, naturally, also unable to fully replicate and investigate actual multi-user conditions with multiple users teleporting and multiple users observing. Having multiple users teleporting at the same time could possibly alter the requirements and suitability of the individual visualizations, as paths could be intersecting. Similarly, in a more complex and dynamic environment, other dynamically moving objects could get in the way, or target destinations may be not conventionally reachable. This would make real-time path planning and visualization and possibly more general visualizations necessary. Also, having multiple elaborate but non-personalized teleport visualizations that have the same appearance for various users at the same time could make the scene more distracting and unclear again. Also, It should be considered, that the natural-looking walking animation, in an actual application, might be confused for roomscale or other forms of locomotion instead of a teleport visualization. Handling these concerns was not the focus of this work, though. If this distinction to other forms of locomotion is required, an additional effect could be applied for clarity. Moreover, more complex, collaborative tasks than just one-way observation would be highly interesting to investigate, too, as then it may be more relevant if the observer recognizes the teleport as such and if and when he/she is aware of the destination and traveling path.

Another limitation of our current work is that we, for now, focused solely on the visualizations' effects on the observers but not on the teleporting user himself. For instance, the teleporting user probably will prefer a quick teleportation process to minimize waiting time, while observers, in contrast, would prefer to have some duration to observe motion cues and increase immersion.

8 CONCLUSIONS AND FUTURE WORK

With this work, we presented a user study to investigate suitable visualizations to depict the deliberate act of teleportation to observers in multi-user VR. The goal was to evaluate if they enhance spatial awareness, reduce confusion and, thus, help to retain as much presence as possible. For our study, we implemented seven different visualization techniques, continuous and non-continuous ones, into a virtual environment using the Unreal Engine 4. In our experiment, we compared the visualizations and their effects on observers. The properties we examined were perceived social presence, spatial presence, confusion, speed scalability, and spatial awareness. We found that teleport visualizations can have significant positive effects on social as well as spatial presence, but do not necessarily have to. Continuous visualizations significantly increased spatial awareness. Moreover, various visualizations were rated significantly higher regarding plausibility and intuitiveness, which indicates less confusion. Results show that the type of visualization affects the speed scalability and that a walking animation is the overall best-performing, user-preferred visualization, followed by the continuous particle trace. These findings not only hold when teleporting out of the observer's view but also when the start, path, and target are all in view. On the other hand, the advantages of the visualizations decrease, when increasing the teleportation/locomotion speed.

In the future, we plan to conduct a similar study in a more complex, interactive environment with multiple users teleporting and observing and with collaborative tasks between users. With this, we would have a more engaging experience that induces a higher presence and we would be able to provide a deeper investigation of the advanced requirements and effects of the visualizations and the issues arising from teleportation in multi-user VR environments. Furthermore, we plan to investigate the depth perception of the visualizations and how the teleportation visualizations affect the teleporting user's presence and usability, as well as how this changes with different teleportation/visualization speeds.

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