Follow Me: Confirmation-based Group Navigation in Collocated Virtual Reality

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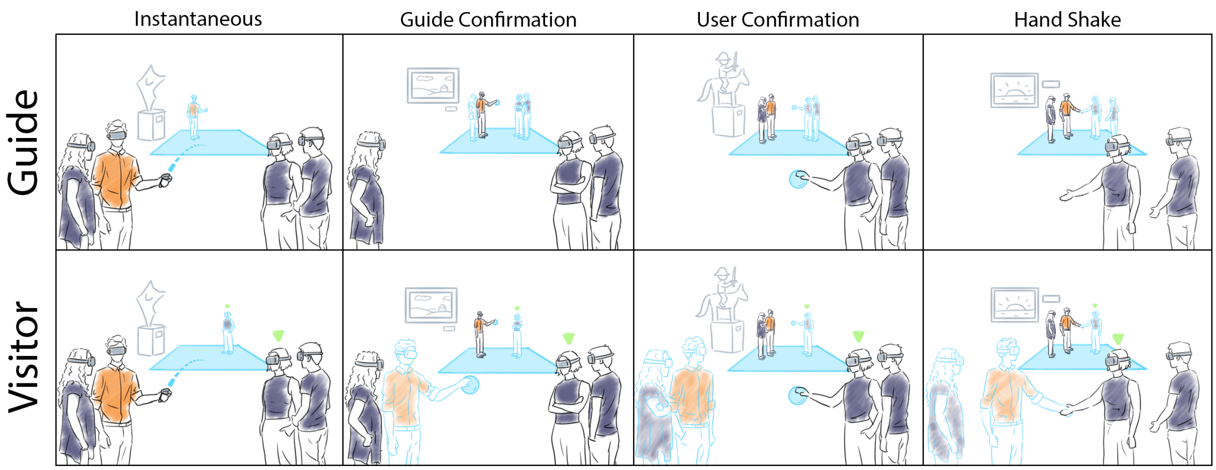

Figure 1: Illustrations for the baseline (*Instantaneous*) and the proposed two-phase confirmation-based group navigation techniques (*User Confirmation*, *Guide Confirmation*, *Hand Shake*). Here, the state before the navigation of a visitor (marked with an arrow) is shown, once from the viewpoint of the guide (top row) and from the viewpoint of the visitor (bottom row). Note that the guide is coloured orange, while the visitors are coloured blue. Interactions can be seen in the accompanying video.

ABSTRACT

In collocated social virtual reality, the relative physical and virtual positions of users are often synchronised to reduce audio-visual inconsistencies and the risk of collisions between users. For virtual navigation previous work has proposed group navigation techniques that maintain spatial synchronisation. This, however, limits user autonomy and can be particularly frustrating when some users would prefer to remain at their current virtual position, as can be the case when users have differing goals, interests, or tasks within the virtual environment. In this paper, we introduce a two-phase confirmation-based group navigation concept for collocated scenarios which allows users to stay behind and catch up to the group based on individual confirmation. The confirmation to catch up can be triggered by the group's guide, the individual user or both. Ghost avatars, which visualise the physical locations of other users, are used to avoid physical collisions in situations where part of the group has already virtually navigated to a new location. We evaluate the three confirmation-based techniques in a user study (N = 24) in the context of a guided tour in a virtual museum and compare it to a baseline group navigation technique. Our findings show that users prefer having the autonomy to decide when to follow their group. Despite increased complexity, the proposed techniques achieved comparable levels of co-presence, spatial orientation, and understanding of others' positions in both the virtual and physical environments as the baseline, effectively balancing user autonomy, navigation understanding and social experience.

Index Terms: Group Navigation, Social Virtual Reality, Spatial Desynchronisation, Guided Tours, Virtual Museums.

1 INTRODUCTION

Augmented reality (AR) and virtual reality (VR) technologies are increasingly being used in public settings such as museums, art installations and participatory projects [11, 20, 38]. Multi-user applications, where users explore an immersive virtual environment (IVE) together, can provide rich immersive and social experiences in these contexts. As the available physical space in public settings can be limited, collocated experiences where users jointly use the available space lend themselves as they maximise the physical space that each user can use. In such experiences, the relative alignment of users' physical and virtual positions reduces the risk of physical user collisions as well as audio-visual inconsistencies [52]. When the virtual space exceeds the physical space, virtual navigation techniques are needed to explore the virtual world [23]. While individual virtual navigation provides a high degree of user autonomy, it can cause spatial desynchronisation of the virtual and physical user positions [47], potentially causing collisions and restricting freedom of movement, which is undesirable in public contexts. Existing techniques for collocated group navigation address this problem by ensuring spatial synchronisation through simultaneous navigation of all users. This, however, limits user autonomy and can cause frustration when some users want to remain at their current virtual position, highlighting the need for group navigation techniques that strike a balance between providing user autonomy

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and minimising the risk of collisions.

To address this need, we propose the concept of a two-phase confirmation-based navigation process, to give collocated users more autonomy in group navigation. In this process, the navigating user (navigator) selects the next navigation target and is teleported to it, while the other users (passengers) remain at their current virtual position and follow the navigator only after a confirmation phase. This confirmation can be initiated by the navigator, each passenger individually or jointly by both. To address the spatial desynchronisation that occurs when some passengers have not yet followed the navigator, ghost avatars are employed to indicate the relative physical locations of other users, ensuring safe physical user navigation. We designed and evaluated three novel navigation techniques in a triad user study (N = 24) using a guided virtual museum tour and a common group navigation technique as a baseline.

Our research is motivated by a collaboration with a local museum interested in using collocated social VR for the guided exploration of a virtual museum space. Given the limited physical space available for the public installation and the need to explore a large IVE, a suitable group navigation technique was desired that would be easy to use for novices, prevent collisions, support user autonomy to cater for the different interests and goals of visitors, and allow for a high degree of social presence. To provide a similar experience to a real museum visit, a guide should be able to navigate a group of visitors through the museum, while visitors should be able to do both, follow the guide and explore exhibits on their own, at least for a little while, before catching up to the guide.

Our research aimed at addressing the navigation challenges in this context and resulted in the following main contributions:

- A novel concept for two-phase confirmation-based group navigation providing different degrees of autonomy to users.
- Ghost avatars are an effective means to prevent collisions and mitigate spatial desynchronisation for collocated group navigation techniques.
- Results from a triad user study (N=24) showing that the proposed two-step techniques provided similar levels of visitor orientation, understanding of navigation and social presence despite increased complexity.
- Recommendations for different group settings based on our results and qualitative analysis through interviews (N=24).

In summary, our concepts and techniques provide users with more autonomy in group navigation and provided good usability, user experience, navigation understanding and high co-presence. Our study showed that even with the increased complexity of our concepts, users understanding of physical and virtual positions was strong with all techniques and prevented collisions.

2 Related Work

In social IVEs, effective navigation techniques are integral to ensure seamless (social) interactions, especially when users share both the physical and virtual space. For this reason, we present related work on collocated VR, social presence and group navigation.

2.1 Collocated Virtual Reality

Our work focuses on a collocated shared VR setup, where all users occupy the same physical space and can see each other in the IVE [29]. It has been shown that in collocated VR physical locomotion behaviour reflects that of the real world [31, 34]. While asymmetric collocated VR, where users interact with different interfaces, has been explored [27], our focus is on symmetric collocated shared VR. In such environments, spatial desynchronisation can occur when users' physical and virtual positions do not align [23, 13]. This misalignment can lead to confusion if users' voices do not originate from their virtual position and can increase the risk of collisions between users.

To address collision risks, various techniques have been proposed, including displaying ghost avatars to represent users' physical locations [30], playing warning sounds [30], using bounding boxes around users when in close proximity [35], and overlaying real-world camera images with the virtual environment [35]. Among these, displaying ghost avatars and real images of users was preferred, as it provides clear positional cues and an indication of their future actions [30, 35].

2.2 Social Presence

In multi-user VR social presence or co-presence, which Biocca et al. define as the feeling of being part of a social interaction with others [4, 2], influences user experiences. Studies show that social presence is enhanced by both verbal and non-verbal communication [8, 16] as well as by the embodiment of the user in the virtual world [42, 24, 15]. While co-presence can be similar between collocated and distributed users, it is generally higher for collocated users [31], with physical walking increasing social presence in collocated scenarios compared to steering navigation [50]. Workspace awareness in IVEs can be seen as the basis for perceiving who and where other people are located [17]. Especially when the virtual and physical positions of collocated users do not match it is crucial that users are aware of their workspace to avoid physical collisions. Schott et al. have shown that mini-maps and navigation paths can contribute equally to increasing this awareness [37].

2.3 Group Navigation

Group navigation in VR involves moving users as a unit through virtual spaces. Weissker et al. structure group navigation into four phases: (1) forming, the initial group formation; (2) norming, defining who can influence navigation and when; (3) performing, executing the navigation; and (4) adjourning, dissolving the group [43, 44]. In these phases, communication within the group and mutual awareness are factors influencing navigation understanding. The use of pre- and post-travel feedback has been proposed to improve spatial orientation during teleportation navigation [49]. Using one ray per user for navigation preview during group navigation has been shown to improve both spatial orientation and understanding of the phases of group navigation [48]. While steering has been used for group navigation in VR [21], it poses a higher risk of motion sickness than teleportation-based navigation [10, 22, 33]. To optimize viewpoints during group navigation, techniques allowing the navigator to control the group's configuration at the target location have been proposed [46].

In contrast to previous work on group navigation, we propose a two-phase navigation process designed for safe use in collocated experiences that gives group members more freedom to explore without having to leave and rejoin the group.

3 Collocated Group Navigation Techniques

Here, we introduce the group navigation concept on which we base the design of our navigation techniques. We discuss properties all techniques share and subsequently introduce our techniques.

3.1 Two-Phase Confirmation-based Group Navigation

Existing group navigation techniques commonly navigate all users at once [43, 21, 44], which can force navigation on users when they would prefer to stay at their current place. For this reason, we propose a two-phase group navigation process. First, the navigator selects the next navigation target and is teleported there. Then, the other passengers follow the navigator based on a confirmation process. The latter can either require confirmation from the individual passenger, the navigator or mutual by both. This concept is motivated from the context of guided tours in real museum, where the guide leads the way and visitors are able to follow, when they seem fit or when the guide asks them to gather.

Figure 2: Ghost avatar of a visitor for a highlighted ROI, indicating how the visitor will be teleported.

3.2 Group Navigation Setup

In our approach users are located in a shared physical tracking space and their relative positions to each other are maintained in the virtual world. Similar to a guided tour in the real world, our navigation is based on regions-of-interest (ROI). ROIs are predefined, and have the same dimensions in width and depth as the available physical tracking space. They serve as fixed navigation destinations for group navigation in which physical navigation can be used. We consider the phases of forming, norming and adjourning [44] to be implicit. The group is formed by entering the tracking space and starting the application. All users are considered as a group for the entire time. Adjourning takes place when the users leave the application and the tracking space. For norming, the guide, who has planned the tour in advance, is implicitly regarded as the navigator of the group. The passenger's ability to decide when to follow the navigator varies depending on the respective confirmation mechanism (see **Section 3.5**). For navigation, the navigator can activate a pointing ray on either hand. We chose this method for its flexibility in selecting ROIs, as opposed to using a predefined list. Unlike map or world-in-miniature (WIM) approaches [39], the ray reduces the risk of spatial disorientation by limiting navigation to vista space. The navigator selects the next ROI by pointing the ray and confirms the selection by pressing a button on the corresponding controller, which then teleports them to the chosen location. Teleportation adjusts both the position and rotation to align users with the exhibit based on the predefined forward directions of the ROIs. We have opted for teleportation instead of continuous steering, as it has been shown to have a reduced risk of simulator sickness [9].

3.3 Pre- and Post-Travel Information

Informing passengers during group navigation about their future positions using pre-travel information has been shown to decrease cognitive load and spatial confusion [47]. When unaware of such changes, users may struggle to anticipate when and where they will be navigated or (after navigation) where they came from. To address this, we developed visual and haptic feedback for both pre- and post-travel phases. Pre-travel information consists of five key components: (1) the next ROI is highlighted with a blue area and rising particles, (2) a ghost avatar shows the user's future location on the ROI (see **Figure 2**), (3) a curved teleport ray for passengers, inspired by Weissker et al. [48], extends from the user's right hand to the next ROI, (4) haptic feedback is provided through vibrations in the right controller to draw attention towards the directional ray, and (5) a label on the right hand displays the message "You will be teleported soon" to clearly indicate the upcoming action. Post-travel feedback, based on Freiwald et al. [14], uses a particle trail following a curve from the user's previous position to chest height at their new location over a duration of 3 seconds to help users to understand both their navigation, as well as the navigation of others.

3.4 Spatial Desynchronisation and Collision Mitigation

During the two-phase navigation process, users may be located at different virtual ROIs, resulting in a mismatch between their relative physical and virtual positions. To minimise the risk of physical collisions and reduced social presence caused by this spatial desynchronisation, we adapt ghost avatars proposed by prior work [23, 36]. Ghost avatars replicate the avatars of users who are located at a different ROI at their actual physical location. They are semi-transparent, and coloured to distinguish them from real avatars. Ghost avatars for visitors are displayed blue, while the guide avatar is orange for easy identification. They mirror the user's movements, supporting users in maintaining spatial awareness and avoiding accidental collisions. Since the ghost avatars always provide a visual representation of the physical position of all users, we have decided to forego spatial audio chat to counter spatial desynchronisation and instead use communication exclusively in the real world.

3.5 Navigation Techniques

Here, we describe the baseline group navigation technique used in the evaluation, as well as our novel concepts based on the two-phase navigation approach. The three techniques developed differ in terms of who has the authority to decide when the users follow the navigator.While VR allows for manifold ways of navigating users, our techniques were kept relatively simple so they are easy to learn to cater for novice users [7].

3.5.1 Instantaneous (Baseline)

Our baseline technique *Instantaneous (IN)* corresponds to a group navigation technique frequently employed in collocated navigation [43, 44], where all visitors follow the guide immediately and there is only one navigation phase. As soon as the guide teleports to a new ROI, all visitors are automatically teleported as well. While individual virtual navigation is also commonly used in VR and can provide a high degree of autonomy, we did decide against it as a baseline as it can result in spatial desynchronisation in collocated scenarios, potentially causing collisions between users [5].

3.5.2 Guide Confirmation

In the *Guide Confirmation (GC)* navigation technique, the guide has the ability to decide when visitors should follow him to the next ROI. Here, the guide controls the confirmation, allowing him to decide how much preparation time is required at the new ROI and how much time the visitors have at the previous ROI. To coordinate the decision, visitors can be asked if they are ready before being teleported. As soon as the guide teleports to the next ROI, a confirmation object appears, which is represented by a blue sphere and a label (see **Figure 3a**). This object moves with the guide so that it remains in the guide's field of vision at chest height. To teleport the entire group of visitors to the next ROI, the guide must touch the confirmation object for a configurable dwell time. As soon as a hand intersects with the sphere, the pre-travel information is activated for the visitors. After the dwell time has expired, all visitors are teleported to the guide at the same time. If the guide removes his hand from the object before the dwell time expires, the teleportation is aborted. The guide receives feedback about the dwell time via a loading bar in the label of the confirmation object and the vibration of the intersecting controller.

3.5.3 User Confirmation

The *User Confirmation (UC)* technique allows visitors to individually decide when to follow the guide to the current ROI. In this technique, the confirmation is based entirely on each visitor's individual decision, giving them the autonomy to determine how much time they wish to spend at a ROI. Similar to the guide in the *GC* technique, each visitor receives their own confirmation object, which

(a) *Guide Confirmation* (External perspective on guide)

(b) *User Confirmation* (Visitor perspective)

(c) *Hand Shake* (Visitor perspective)

Figure 3: Navigation Techniques

follows the visitor to remain at chest height in their field of vision (see **Figure 3b**). Visitors can initiate teleportation independently by touching the sphere for a configurable dwell time. Touching the sphere activates the pre-travel information and the dwell time is indicated by a loading bar and a vibration of the touching controller. Removing the hand from the sphere before the dwell time has elapsed cancels the teleportation. Otherwise, the visitor is teleported individually to the next ROI.

3.5.4 Hand Shake

The *Hand Shake (HS)* technique, inspired by work on group navigation for distributed users [45], requires mutual confirmation between the guide and a visitor through a virtual handshake. In our approach, however, the handshake gesture is not used to form and maintain a navigation group, but to follow the guide to their ROI and requires passengers to physically approach and touch the hand of the navigator. This interaction is inspired by the social context of the gesture and because it has been shown that haptic interactions can increase social presence in VR [12]. Here both parties are involved in the decision-making process, and the approach is intended to foster social presence based on increased social interaction [8, 16]. From the perspective of guide and visitor respectively, the mutual handshake confirmation is enacted with the other's ghost avatar (see **Figure 3c**). When the handshake begins, the pre-travel information is activated for the visitor. For this technique the teleportation ray for passengers is not activated to prevent confusion caused by an activated ray when shaking hands. As with the confirmation object interactions, the *HS* has a dwell time that allows the teleportation to be aborted or confirmed. The dwell time is again represented by a vibration of the respective controllers involved. If confirmed, the visitor is teleported individually to the guide's ROI.

4 Evaluation

This section presents the evaluation of our group navigation techniques for guided virtual tours. We outline the motivation behind our study design, describe the study procedure, and introduce the hypotheses that guided our analysis. Participants of our study were guided through a virtual museum in short tours using the different techniques. A mix of questionnaires, quantitative measurements and a semi-structured group interview were used for evaluation. As the study was conducted at a university without an established ethics committee, no ethical approval was sought.

4.1 Experimental Setup

The study was conducted in a quiet and enclosed room. Four Meta Quest 3 HMDs were used in each session (one for the study conductor, three for participants). These were operated stand alone and were therefore not connected to a separate computer. The application was developed with Unity3D [40] with Unity Netcode as the networking basis [41], and our open-source framework vrsys-core for the multi-user setup. We provide the implementation of our techniques also as open-source to support replication [53]. The application renders at the native HMD resolution and with a refresh rate of 90 Hz. During the study, three participants and the person conducting the study were located in a shared 3m x 3m physical tracking space . The size of the tracking space was transferred to the ROIs in the virtual museum so that they had the same dimensions. A 3D model (named *"Art Gallery Vol.10"*) from the Unity Asset Store was used as the virtual museum. The virtual exhibit included stock images, as well as generic 3D models of busts and statues, some of which were based on real examples. We deliberately opted to use a generic museum rather than a real one, in order to minimise the influence of prominent building features or existing (orientation) knowledge about the museum that participants might have from previous visits.

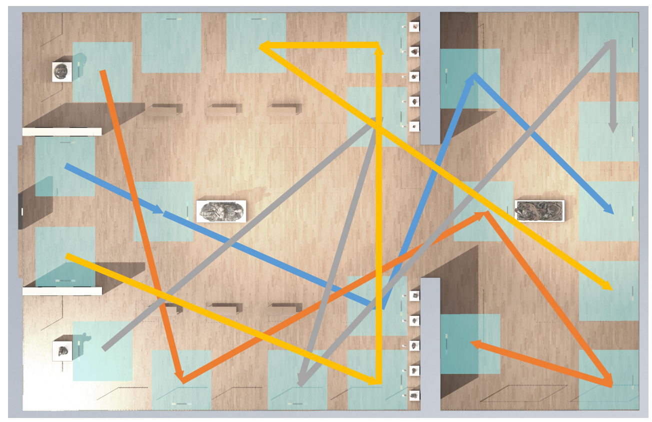


Figure 4: Four ROI sequences used as tours during the study.

4.2 Tasks and Conditions

In our study, participants took a guided tour in a virtual museum together with a study conductor. The participants were in the role of the visitors while the study conductor took in the role of the guide. The group performed a different tour in the virtual museum for each condition - *IN*, *GC*, *UC*, and *HS*. A total of 5 ROIs were visited during a tour, i.e. 4 jumps were made per tour. There were one or two exhibits to see at each ROI. A total of 4 tours were predefined, with each tour consisting of different ROIs (see **Figure 4**). The tours all started at the same side of the museum, worked their way to the other side and consisted of a mix of shorter and longer jumps.

At each ROI, visitors were told something about the exhibits. A pre-recorded audio guide was used to minimize differences in the experience and ensure comparability. The audio guide recordings had an average length of 32.3 seconds. For exhibits that were based on an original, the knowledge presented corresponded to facts derived from the corresponding model. For all other objects and images, the knowledge was generated to match the artwork. The participants were informed about this before the study.

During the tour, the visitors had to complete two tasks. The first task served to investigate how well the participants were able to orient themselves in the room after a jump. To do this, 3 seconds after each jump they were prompted to estimate the direction they thought they had come from using a pointing ray. They were alerted to the task by a vibration of the right-hand controller and a label attached to it (see **Figure 5a**). They had 15 seconds from the start of the prompt, which was represented by a loading bar in the label. Users could activate the ray by holding down the grip button on the inside of the right-hand controller. Deactivating it by releasing the button confirmed the selection. The participants were able to adjust their selection as often as they wanted within the time available. The audio guide at the ROI was only started as soon as all visitors had estimated an orientation. This was visualised to the guide by a green sphere above the visitors' heads, only visible to the guide.

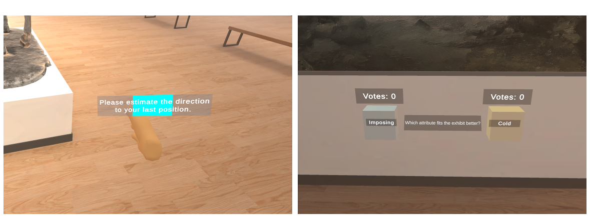
The second task was to motivate the visitors to engage with the exhibits and to move around the ROI in order to test the ghost avatars as collision avoidance technique. For this, a station was displayed at each ROI, directly in front of the exhibit(s), asking visitors to choose which adjective better described the particular exhibit, or if there were two objects, which adjective applied better to both. The adjectives were chosen in such a way that there was no objectively correct choice. Users could choose by touching the box containing the adjective with one hand (see **Figure 5b**). A count of how many visitors had chosen this option was also displayed above the boxes. This worked according to the either-or principle and only the last selection was counted. Users were free to choose when to select the adjectives for as long as they were at the ROI.

4.3 Participants

We conducted our study with 24 participants (15 male, 9 female, none diverse) recruited via university mailing list. Participants ranged in age from 22 to 54 (M = 27.96, SD = 6.41) and were university students and members. Two participants stated that they were expert VR users; twelve considered themselves to be more experienced users and ten stated that they had little to no experience with VR. The participation was compensated with 15€.

4.4 Procedure

The user study was a within-subject study and conducted on the basis of a Balanced Latin Square in order to avoid potential order effects. The order of the four predefined tours in the virtual museum remained the same for all groups. The order of the conditions was varied accordingly between the groups. After their arrival, the participants were first welcomed and informed about the study and the option of discontinuing the study at any time. They then signed a consent form and completed a demographic questionnaire. The participants then received an explanation of how to use and control the HMD and were given some safety instructions. After putting on the HMDs, all participants and the study conductor met in a virtual training room. In this room, before each tour with a new condition, the navigation technique and the study tasks were explained using three example ROIs and practised together. The guide started the tour once everyone had signalled that they were ready. One of the predefined tours was then carried out using the selected technique. In all techniques where the guide was involved in the confirmation process (including the baseline), the guide asked the visitors whether they were ready and informed them of an upcoming teleportation to the next ROI. After each tour, the participants completed a questionnaire in which they rated the technique in terms of usability, navigation understanding, comfort level and social presence. After all conditions were completed, the participants were asked to rank the techniques according to personal preference. Finally, a semi-structured group interview was conducted with all participants. The entire process took between 90 and 120 minutes.



(a) Orientation Estimation Prompt (b) Vote Station

Figure 5: Study task elements

4.5 Hypotheses

In preparation for the user study, we developed hypotheses based on the expectations arising from the related work, which served as the basis for the statistical analysis. With the orientation task during the study and the questionnaires, we wanted to find out whether the two-phase approaches enable equal spatial orientation and make the navigation as understandable as the baseline technique. All four conditions use the same pre- and post-travel feedback mechanisms - based on the results of previous work [48, 46] - and use a teleport for navigation. Therefore, we expect all conditions to provide similar levels of orientation and navigation understanding, and have therefore chosen undirected null hypotheses for these aspects.

H1. There is no significant difference in spatial orientation among the different conditions.

H2. There is no significant difference in users' understanding of navigation across the different conditions.

In the ranking of confirmation techniques, we expect participants to prefer the *UC* as it offers the greatest freedom in choosing the time of navigation. It also requires less coordination from participant and guide than *HS* and should therefore be easier to perform.

H3. *UC* is significantly preferred over the baseline technique and ranks highest.

In a group interview conducted at the end of the study (see **Section 4.6**), we asked which technique was perceived as the most social by the users. We expect *HS* to be mentioned most frequently, based on previous work suggesting that social interactions can increase social presence [8].

H4. The *HS* will result in a higher social presence compared to the other techniques.

4.6 Dependent Variables

During the orientation task, similar to previous work on investigating spatial awareness [32, 28], we record the angular mismatch between the original previous position and the indicated previous position in the ground plane, in our case the XZ plane. For investigation of (social) proxemic behaviour, the time spent by users within predefined, uniform 10 cm distance intervals from the guide was recorded to track user proximity during the interaction.

The questionnaire completed after each condition consisted of the System Usability Scale (SUS) [6], User Experience Questionnaire Short (UEQ-S) [25] as well as selected elements from the Networked Minds Social Presence Inventory (NMSPI) [3] and the RawTLX questionnaire [18]. For the NMSPI, we limited ourselves to four statements from the First Order Social Presence questionnaire, which participants were asked to rate on a Likert scale from 1 (Strongly disagree) to 5 (Strongly agree). Statements were chosen to assess participants' perceptions of mutual awareness and co-presence within the virtual museum, focusing on both individual and shared experiences of social presence. The statements were: (1) I often felt as if the others and I where in the museum together. (2) I was often aware of the others in the museum. (3) The others were often aware of me in the museum. (4) I often felt as if we were in different places rather than together in the same museum. The RawTLX is generally used to ask about parameters such as cognitive load when using interfaces. We extracted the questions on mental demand, temporal demand and frustration and mapped them onto a 5-point Likert scale. These were primarily intended to assess the quality of individual exploration. We used only elements of the NMSPI and RawTLX that were relevant to our research questions in order to keep the questionnaires from becoming longer than necessary. The final section of the questionnaire comprised custom questions designed to assess participant experiences in more detail. Participants were asked to rate their level of discomfort on a scale from 1 (very low) to 10 (very high). Additionally, 5-point Likert scales were used to measure, how well the participants were able to orient themselves in the virtual space, whether they understood where other users were physically or virtually located, whether they were able to concentrate on the audio guide, whether they were able to spend enough individual time at the exhibits, whether the individual phases of navigation were comprehensible and if they had the feeling that other user were often getting too close. Participants were also asked to indicate what they liked and disliked about the technique used.

After completing all the conditions, the participants ranked the techniques according to personal preference. The final semi-structured group interview focused on two key questions that each participant answered. First, they were asked which technique they preferred most and least, and why. Second, they discussed which technique they perceived as the most social and why.

5 Results

In the following, we present the results of our study without interpreting them. First, we discuss the results of the statistical analysis of the quantitatively collected data, followed by a summary of the qualitative questionnaire parts and interviews.

5.1 Quantitative Data

Each of the 24 participants went through each condition (*IN*, *GC*, *UC*, *HS*) once and completed 4 teleports within each condition. The questionnaires were completed once for each technique and the ranking once per study run. This results in 96 jump-related data points per technique (angle mismatch) as well as 24 data points per technique for questionnaires (see **Table 2**) and ranking. Based on our hypotheses, we performed statistical analyses to test the data sets for significance. First, all data sets were tested for normal distribution using the Kolmogorov-Smirnov test [26]. For normally distributed data sets, a repeated measures one-way ANOVA was performed first to check for significance ($p < 0.05$). If significance could be proven, post-hoc tests were carried out using T-tests to identify significance between the individual pairs of techniques. For non-normally distributed data sets, a Friedman test was first performed for general significance analysis across all conditions ($p < 0.05$). The possible post-hoc tests were performed using the Wilcoxon Singed Rank Test (WSRT) [51]. A Bonferroni correction was performed before all post-hoc tests ($p < 0.008$).

5.1.1 Orientation

No normal distribution could be determined for angle mismatch (see **Figure 6**) and the orientation question, asking if participants could understand from where they came. The angle mismatch data showed individual outliers with an angle mismatch value of -1. These can be attributed to errors in the calculation caused by not correctly registered position estimations. We decided to remove the outliers. To obtain an equal sample size between conditions, we removed randomly selected data points in the sets with more points. This resulted in a new sample size of N = 89 for the angle mismatch data. Friedman tests did not show significance for the angle mismatch ($\chi^2(3) = 0.398$, $p = 0.941$, $W = 0.013$) and for the score of the orientation question ("I knew where I came from", $\chi^2(3) = 2.438$, $p = 0.487$, $W = 0.305$). Thus, **H1** is supported.

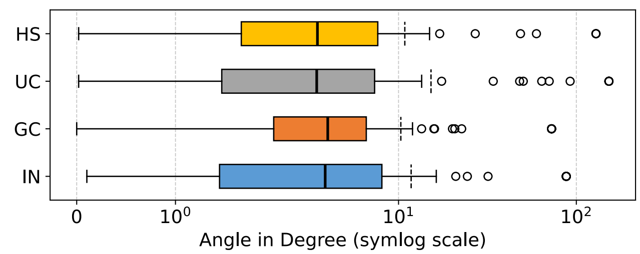


Figure 6: XZ angle mismatch results.

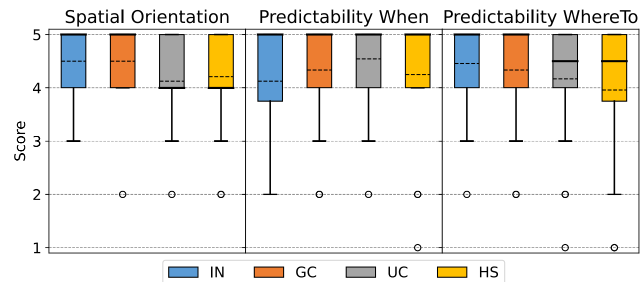


Figure 7: Navigation predictability and spatial orientation ("I knew where I came from")(5 = strongly agree, 1 = strongly disagree).

5.1.2 Understanding of Navigation

The questionnaire data related to navigation comprehension was not normally distributed (see **Figure 7**). A Friedman test showed that the choice of confirmation technique had no significant effect on understanding when (When: $\chi^2(3) = 1.513$, $p = 0.679$, $W = 0.189$) or where (WhereTo: $\chi^2(3) = 1.288$, $p = 0.732$, $W = 0.161$) teleportation occurs. This means we can support **H2**.

5.1.3 Technique Ranking

Figure 8 shows how often the techniques were assigned to the different ranks by the participants, after they had completed all conditions. The *UC* technique was ranked the most preferred technique, with 15 times rank 1. The *IN* technique was ranked most often at rank 2. The *GC* is distributed relatively evenly across all ranks with a slight accumulation at rank 3. The *HS* technique is the least preferred and is ranked primarily at ranks 3 and 4. With an average ranking of 1.67 *UC* had the highest average ranking (*IN*: 2.67, *GC*: 2.5, *HS*: 3.17). For the ranking the performed Friedman test revealed a significant influence of the technique ($p < 0.001$). The

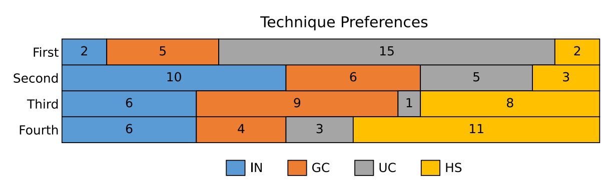


Figure 8: Technique preferences

WSRT post-hoc tests showed that *UC* achieved significantly higher rankings than *IN* ($p = 0.008$) and *HS* ($p = 0.001$). **H3** can therefore be accepted. Investigating concordance, the Kendall's W [19] indicates a lesser degree of unanimity ($W = 0.233$).

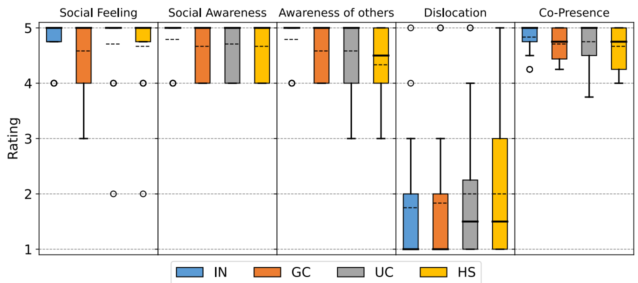


Figure 9: Co-presence questionnaire results. Note, that the co-presence score was computed using only 4 of 8 items of the NMSPI.

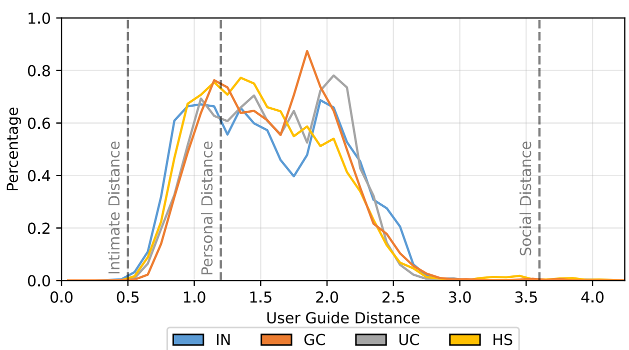


Figure 10: Average proxemic distance distribution between visitors and guide. Proxemic distances are marked as dashed lines.

5.1.4 Social Presence and Proxemic Distance

Investigating the proxemic distance distribution, between guide and visitors (see **Figure 10**), no influence of the technique on the distribution can be directly observed. Analysing the distributions, the means are relatively close to each other (*IN*: 1.56m, *GC*: 1.60m, *UC*: 1.60m, *HS*: 1.53m). Drawing 5,000 samples for each technique, based on the midpoints of the distance intervals weighted by their respective percentages, and applying the Shapiro-Wilk test for normality, shows that none of the distributions follow a normal distribution ($p < 0.05$ for all techniques).

The applied Friedman test showed no significant differences in the results for the question if other users often came too close ($p = 0.357$). The Kolmogorov-Smirnov test also did not show normal distribution for the computed social presence scores, based on the NMSPI questions. The performed Friedman test also indicated no significant influence of the used technique on the social presence scores ($\chi^2(3) = 2.588$, $p = 0.46$, $W = 0.323$). All techniques had relatively similar means (*IN*: 4.65, *GC*: 4.5, *UC*: 4.5, *HS*: 4.42).

During the group-interviews, 21 participants rated the *HS* technique as the one in which they had the most social and strongest group feeling. Three participants found the *IN* technique to be the most social. However, as no significance could be determined, the hypothesis **H4** is rejected.

5.1.5 System Usability and User Experience

The average SUS scores (see **Table 1**, **Figure 11**) for *IN*, *GC* and *UC* (all scores > 80.3) indicate an excellent usability of the techniques. The average SUS score of *HS* of 69.48 is on the lower end of a good usability [1]. The SUS and UEQ-S data collected were all normally distributed. The ANOVA showed significant influence of the condition for the SUS scores ($F = 3.79$, $p = 0.013$, $\eta^2 = 0.124$). The post-hoc T-tests showed that *IN* and *GC* had significant higher scores than *HS* (both $p < 0.008$). No significance was found for the other condition combinations (all $p > 0.008$). The performed ANOVAs identified no significance for the UEQ-S overall scores ($p = 0.211$, $\eta^2 = 0.05$), pragmatic scores ($p = 0.124$, $\eta^2 = 0.064$) and hedonic scores ($p = 0.14$, $\eta^2 = 0.061$).

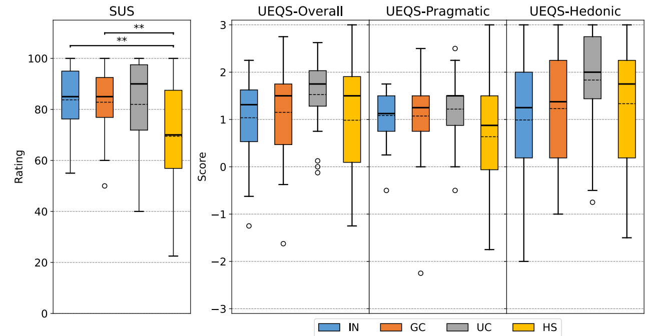


Figure 11: SUS and UEQ-S scores ($p < 0.01$ **, $p < 0.05$ *).

	Instantaneous		Guide Confirmation		User Confirmation		Hand Shake	
	M	σ	M	σ	M	σ	M	σ
SUS	83.75	13.55	82.81	13.38	81.98	19.7	69.48	19.86
UEQ-S Overall	1.04	0.9	1.15	0.98	1.53	0.76	0.98	1.19
UEQ-S Pragmatic	1.08	0.52	1.07	0.93	1.22	0.69	0.64	1.23
UEQ-S Hedonic	0.99	1.46	1.23	1.24	1.83	1.07	1.33	1.29

Table 1: SUS and UEQ-S means (M) and standard deviations (σ).

No significant influence of the technique on discomfort was found perfoming an ANOVA ($p = 0.896$, $\eta^2 = 0.006$). An increase in discomfort over the duration of the study was detected with a mean of 2.875 for the first, 3.250 for the second, 3.208 for the third and 3.625 for the last trial.

5.2 Qualitative Data

In the following, we present the participants' feedback on each navigation technique from the questionnaires and the interview.

5.2.1 Instantaneous

With regard to the *IN* technique, participants noted that they considered it straight forward and easy to understand, due to the fact that no interaction was required for confirmation (Comment occurrence (CO) = 12). It was also perceived as positive that the group was always together, which increased the group feeling (CO = 4). Participant 3.1 described it as "...pretty easy moving with the guide all together.". Participant 5.3 summarised it as "Fun, efficient and

	Instantaneous		Guide Confirmation		User Confirmation		Hand Shake	
	M	σ	M	σ	M	σ	M	σ
Enough time to listen	4.708	0.675	4.500	0.763	4.583	0.759	4.625	0.695
Enough time to look	3.875	1.092	3.958	1.171	4.041	1.019	3.958	0.888
Physical location understanding	4.250	0.968	4.125	1.012	3.958	0.978	3.875	1.129
Virtual location understanding	4.625	0.633	4.500	0.816	4.375	0.806	4.208	1.039
TLX Mental demand	1.750	0.829	1.666	0.897	1.958	1.098	1.833	0.799
TLX Temporal demand	2.375	0.992	2.333	1.027	2.125	1.053	2.333	1.027
TLX Frustration	1.375	0.563	1.625	0.753	1.708	0.840	1.791	0.911
Spatial navigation predictability	4.454	0.865	4.272	0.897	4.409	1.105	3.863	1.337
Temporal navigation predictability	4.125	1.129	4.333	0.942	4.541	0.815	4.250	1.089
Proxemic violation	2.291	1.135	2.500	1.443	2.583	1.114	2.791	1.322
Knew where I came from	4.500	0.577	4.500	0.707	4.125	0.832	4.208	0.911

Table 2: Means (M) and standard deviations (σ) of responses given to the custom single-item questions (5 = strongly agree and 1 = strongly disagree)
.

quick to learn.". Some participants found *IN* to be the most social (CO=3). The main reason they gave was that the group always stays together with this technique. The most often mentioned criticism was that there was not enough time to look at exhibits and there was a lack of control over the timing of the teleportation (CO = 9). Participant 3.2 said "I sometimes felt that I was pressured by the time since maybe the others were done looking at the paintings and ready to jump.". It was also noted that orientation after the jump was sometimes difficult (CO=2).

5.2.2 Guide Confirmation

GC was perceived as a user-friendly technique, as there were no operating mechanisms to learn (CO = 9). Furthermore, the opportunity to spend their own time exploring exhibits was appreciated (CO = 3). Participant 7.3 described it as "...very similar to how an actual museum guide would have guided visitors...". The extra time also seemed to be helpful in orienting oneself as to when and where to be teleported next (CO=4). The main criticism expressed was that they had no control over how long they can stay at a ROI and when the jump takes place (CO=8). Additionally, it was observed that users could experience disorientation if they were suddenly teleported while still investigating the exhibit (CO=3). Two of the participants also noted that it was sometimes difficult to keep track of all ghost avatars and their meaning (CO=2).

5.2.3 User Confirmation

The high degree of freedom of the *UC* was particularly appreciated. Participant 6.2 appreciated that he "...had control of when I wanted to move to the next location." Participant 6.3 liked the additional "...time to checkout the exhibitions on my own.". Confirmation using the sphere was described as easy to use and efficient (both CO=3). Participant 1.1 also noted "You could see where the guide and the others were going to jump beforehand.". One criticism was the behaviour of the confirmation sphere (CO=6), as it always tried to remain in the field of view of the respective user. This meant that the teleport was sometimes unintentionally cancelled when looking around, as reported by participant 2.2, for example. Users also reported disorientation because they focussed on the sphere before the teleport and not on the next position (CO=5).

5.2.4 Hand Shake

Participants commented positively on the interaction required between users in the *HS* technique, as this created a greater awareness of the other users (CO=7). The gesture of shaking hands was perceived as appropriate (CO=6). Users also positively noted the additional time at the ROI (CO=6), the ease of use of the technique (CO=5) and the degree of freedom to determine the time of teleportation (CO=4). Participant 1.1 reported "You had enough time to look at a work of art. Communicating with the guide and shaking hands to be teleported made you feel like you were really interacting with each other.". The majority of participants rated the *HS* technique as the most social (CO=21). Three reasons were given for this. Firstly, the hand shake as a gesture was perceived as the most social form of confirmation. Furthermore, it was reported that the physical touch also created a stronger feeling of actually being together in the same space. The third reason given was that the need for interaction between the participants increased the social feeling. This was due to performing a joint gesture, but also because coordination between the participants was necessary in order to agree who would perform the hand shake when and where. However, some participants also found the hand shake cumbersome (CO=7). The reasons mentioned were that it takes a lot of physical movement to get to the guide and users have to coordinate well to avoid running into each other (CO=8). Two participants noted that they as introverts found the physical contact during the *HS* uncomfortable.

6 Discussion

In this section, we discuss our results with regards to user experience, spatial awareness, and social presence. We address scalability and provide recommendations for future applications of the evaluated techniques.

6.1 User Experience

The SUS scores reveal that the *HS* technique was perceived as the least usable technique, while all other techniques received similar ratings (between 81.98 and 83.75) indicating an excellent usability. This is also reflected in the technique ranking, where *HS* was most often ranked as least preferred, while *UC* was most often ranked as most preferred. However, Kendall's W indicates a lesser degree of agreement among participants, suggesting the existence of different user preference typologies. The analysis of the UEQ-S shows this difference also only partially. While all techniques were rated similarly in terms of pragmatic quality, the hedonic quality varied, with *UC* receiving the highest mean rating, suggesting that users preferred the autonomy it provided. This is supported by the technique ranking, where *UC* had the highest average ranking, followed by *GC* and *IN*. While discomfort often increases over the experiment duration, and can influence participant feedback, there was only a slight increase in discomfort over the course of the experiment (0.8 on a 10-point scale).

All techniques provided users with sufficient time to explore ROIs and did not significantly impact mental demand, temporal demand, or frustration. While users liked that *IN* was uncomplicated and easy to understand, they criticised that there was not enough time to investigate on your own and a lack of control over the navigation timing. *GC* was criticised for the same reason, while also being considered user-friendly. The high autonomy of *UC* was appreciated by participants. The confirmation sphere was found to be easy to use, but its behaviour was criticised, indicating room for improvement. In addition, some users felt disoriented after navigation, because they focused on the sphere and not their next position while confirming. This is reflected in the slightly higher mental demand of the technique. The *HS* was found to provide a greater awareness of other users, and the gesture was deemed appropriate for the context. In addition, the autonomy and ease of use were rated positively. However, some users found the technique to be cumbersome as it required physical movement and coordination. This is reflected in the slightly higher frustration rating.

While the autonomy provided by *HS* and *UC* was positively highlighted, this autonomy might result in situations where the navigator has to wait for users who remain at previous positions, potentially affecting the experience of other users. However, as our technique can be complemented with an explicit group gathering mechanism, we do not consider this a problem for guided tours.

6.2 Spatial Awareness

No significant differences were observed in the XZ angle mismatch or in questions related to spatial orientation and navigation predictability. This indicates that the pre- and post-travel feedback based on previous work [48, 14] also provided a high level of spatial awareness in our techniques, which made them suitable for group navigation. In addition, all techniques were rated to provide a good understanding of both the physical and virtual positions of users, with no significant differences between them. This suggests that the use of ghost avatars in our two-phase navigation process effectively enabled users to understand *both* their respective physical and virtual positions, extending on previous work using ghost avatars to inform about the physical positions of users [36, 23].

6.3 Social Presence

The analysis of co-presence questions did not reveal any significant differences between the techniques. However, qualitative feedback indicates that *HS* was perceived as the most social technique, despite being the least preferred in the technique ranking. As we suspected based on previous work [12], the HS was perceived as more social because of the gesture and the physical touch. This kind of forced social interaction, however, was uncomfortable for some participants (CO=2). This is also reflected in the fact that it also had the highest mean rating for proxemic violations, which is likely because users had to physically navigate to the guide and might have been closer to others than they were comfortable with. While the handshake interaction temporarily alters the group configuration, our results indicate that this did not significantly influence the overall spatial group configuration, which to some extent can be seen as an indicator of social proximity.

While we did not explicitly investigate the influence of ghost avatars on perceived social presence, our results on overall social presence suggest neither a positive nor a negative influence.

One factor that may have influenced the results in terms of perceived social presence is how well the participants of a study run knew each other. This was not addressed in the demographic questionnaire. It is, however, likely that some of the participants were familiar with each other, which is also often the case when being part of a guided tour.

6.4 Scalability

Scalability considerations are important when selecting a technique for group navigation. For collocated applications, available physical space limits the number of users which are supported.

Techniques like *IN* and *GC*, in which the guide has control over the navigation, scale well with the number of users. This is also the case for *UC*, where users can individually decide when to follow the guide. Here, however, explicit mechanisms for the guide to gather the group might be required, as the guide otherwise has to wait until other users follow on their own. In contrast, the *HS* technique can present scalability challenges, particularly with larger groups, due to the physical coordination required between participants and the guide.

A higher number of users may also increase the risk of collisions, especially when using the *HS* technique and its increased coordination effort. A solution could be to allow handshakes between visitors for navigation confirmation. As in previous work with two-user systems [23, 36], the ghost avatars in our study were found to be useful to recognizing the physical position of other users and avoiding collisions. However, participants also reported that it could become confusing, especially in situations with many active ghost avatars. We therefore consider it necessary to further investigate the use for larger groups with more than four users in future work. Here, it might be a solution to show ghost avatars only in the immediate vicinity of a user.

Scalability may also be affected by the number of ROIs over which users are distributed. In our study, all users are distributed over at most two different ROIs at the same time. Being distributed across more than two ROIs should be investigated by future work considering the impact on the understanding of physical and virtual positions, as well as on social presence.

6.5 Recommendations

For applications prioritising group cohesion and ease of use, *IN* and *GC* are suitable choices, as they simplify interactions without compromising social presence. For scenarios focused on individual autonomy, *UC* strikes a good balance, allowing users to explore at their own pace while maintaining good usability. We foresee that, with mechanisms to explicitly gather the group, e.g. by combining it with the *GC* technique, *UC* could also be a suitable choice for applications prioritising group cohesion. Techniques involving physical interaction, such as *HS*, should be avoided for larger groups or users who prefer less direct involvement. Here, reducing physical effort and improving coordination could further enhance scalability and user experience. The high social rating of *HS* suggests its potential for fostering social group exploration, which may be a desirable option in specific contexts with small group sizes and groups of friends or family members.

7 Conclusion and Future Work

In this paper, we introduce a two-phase confirmation-based group navigation concept for guided tours in collocated virtual environments, alongside three novel techniques based on this concept. The navigation process is structured such that the guide navigates first, and users follow through a confirmation process that requires input from the user, the guide, or mutually both. The proposed techniques provide varying degrees of autonomy in navigation and were compared to a baseline group navigation technique in a triad user study, where participants took part in a guided virtual museum tour. All techniques were found to foster good spatial awareness, be easy to understand, provide high co-presence and similar user experience.

Our results show that *UC*, where users follow the guide when they seem fit, was the technique ranked highest and preferred by users for providing them with time for exploration and navigation autonomy. While the *HS* technique, involving mutual confirmation through a handshake, was seen as the most social, its coordination demands were criticised, and some users disliked the required social interaction. The baseline technique (*IN*), where everyone navigates simultaneously, and *GC*, where the guide controls when users follow, provided strong group cohesion but were criticised for limiting user autonomy over exploration time and navigation timing.

An important perspective yet to be explored is that of the guide, who must balance providing visitors with autonomy while managing the tour within given time constraints. A solution could be a combination of the *GC* and *UC* technique, allowing users to control their pace while enabling the guide to gather the group when needed. The *HS* technique, while social, could be adapted to reduce the coordination effort required and improve scalability. One possible approach could be enabling users to shake hands not only with the guide but also with other users who have already followed the guide. We also see potential for this technique in free-roaming scenarios, where users could use the handshake to invite others to join them at their location, e.g. to share an interesting viewpoint.

To our knowledge, this is also the first time ghost avatars have been evaluated in a group navigation context with more than three collocated users. While they were effective means to prevent collisions and mitigate spatial desynchronisation, future research should investigate their impact on co-presence and interaction, particularly in social collaboration as well as their scalability for larger groups.

In summary, our work provides valuable insights into confirmation-based group navigation for guided tours in immersive social virtual environments, giving recommendations towards potential application scenarios and laying the basis for further exploration and refinement.

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