Group Navigation for Guided Tours in Distributed Virtual Environments

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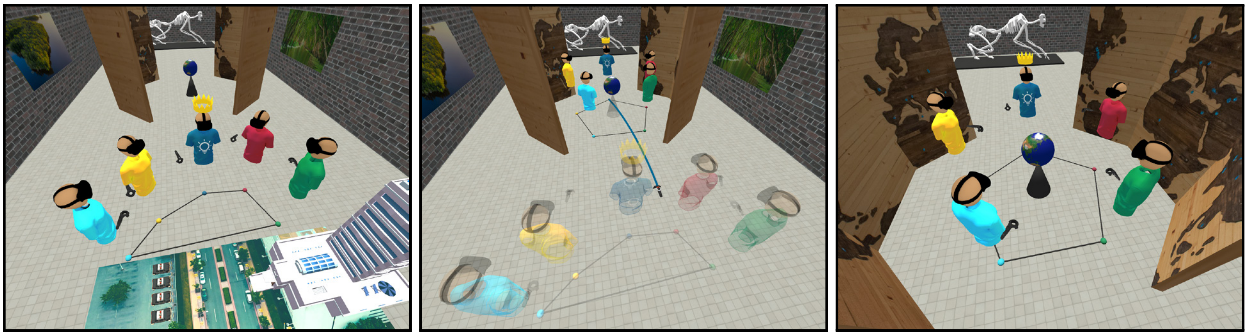

Fig. 1. *Left:* Five distributed users discuss with each other in a virtual museum. The group's spatial extent is visualized on the floor by the convex hull of the projected head positions. *Center:* The guide of the group plans a jump to another exhibit and rearranges the group to a circle formation for improved joint observation. *Right:* After the jump, the group ends up in the specified formation.

Abstract—Group navigation can be an invaluable tool for performing guided tours in distributed virtual environments. Related work suggests that group navigation techniques should be comprehensible for both the guide and the attendees, assist the group in avoiding collisions with obstacles, and allow the creation of meaningful spatial arrangements with respect to objects of interest. To meet these requirements, we developed a group navigation technique based on short-distance teleportation (jumping) and evaluated its usability, comprehensibility, and scalability in an initial user study. After navigating with groups of up to 10 users through a virtual museum, participants indicated that our technique is easy to learn for guides, comprehensible also for attendees, non-nauseating for both roles, and therefore well-suited for performing guided tours.

Index Terms—Virtual Reality, Collaborative Virtual Environments, Group Navigation, Guided Tour, Teleportation, Jumping

1 Introduction

The ongoing global health crisis has moved most social gatherings to online spaces. While conventional conferencing tools provide a 2D video stream of each participant, social virtual reality systems enable users to meet and interact with each other in a 3D environment using head-mounted displays and controllers. However, navigation through these environments is usually performed on a per-user basis only [35, 45], which leads to additional coordination efforts when planning to get to a new destination together. This overhead is especially pronounced in guided tour scenarios, where there is often a strong asymmetric distribution of knowledge between the guide and the attendees [5]. As a result, individual navigation responsibilities might distract attendees from the actual content of the tour, and the overall pace of the tour is slowed down by the required coordination efforts.

To overcome these drawbacks, prior research motivated the use of group navigation techniques in distributed virtual environments [60]. However, it is a responsible task for a guide to take over the navigation for the whole group, which requires a high degree of awareness of the current and future configurations of the group to avoid inconvenient positions and collisions. Attendees, as well, must be able to understand and predict what will happen to them and the group as a whole. While previous work introduced predictable, easy to learn, and non-nauseating group navigation for distributed dyads [60], group sizes for guided tours are often larger and these quality factors more difficult to achieve.

Therefore, this paper addresses the central research question of how effective group navigation can be realized in larger distributed group settings. We started by consulting related literature on group navigation to derive requirements for performing guided group tours in distributed virtual environments. Based on the common travel metaphor of short-distance teleportation (jumping) in social VR systems [35, 62], we developed solutions for each of the formulated requirements to design the first group navigation technique for more than two distributed users. In an initial usability study, proficient users of virtual reality systems evaluated the conduction of and participation in guided group tours using a virtual indoor exhibition as the scenario. Our research led to the following contributions:

- the derivation and formulation of requirements regarding group navigation techniques for guided tours in social VR,
- the design and implementation of a group jumping technique for multiple distributed users addressing the proposed requirements for performing guided group tours,
- the results of an initial usability study on group navigation with groups of five to ten (partially simulated) participants, which indicate the effectiveness, comprehensibility, learnability, and acceptance of our technique in the context of museum tours, and
- qualitative feedback on individual feature variations of our technique motivating potential future research directions.

In summary, our results encourage the integration of group navigation techniques for guided tours into social virtual reality systems.

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Manuscript received 9 Sept. 2020; revised 15 Dec. 2020; accepted 8 Jan. 2021. Date of publication 22 Mar. 2021; date of current version 7 Apr. 2021. Digital Object Identifier no. 10.1109/TVCG.2021.3067756

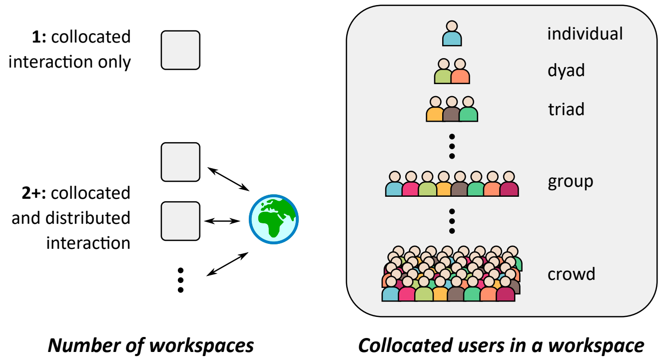

Fig. 2. We classify group interactions in virtual reality by the number of involved distributed workspaces (left) and the number of collocated users within each of these spaces (right). This paper focuses on group navigation techniques for distributed groups with one person per workspace.

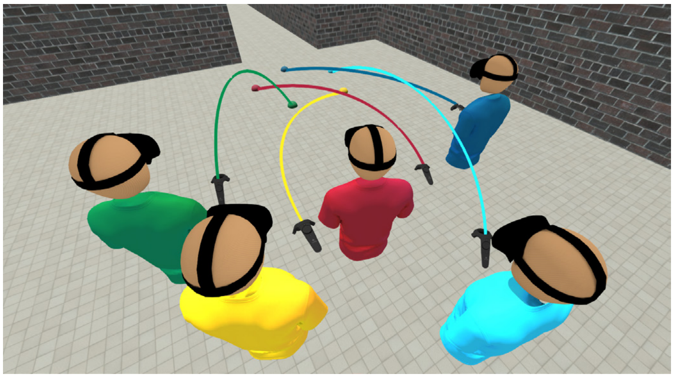

Fig. 3. In prior work for dyads, displaying one target ray per user was deemed helpful and comprehensible for joint navigation [60,61]. However, for larger groups, tracing one target ray per user can be confusing, especially if the formation of the group changes during the jump.

2 Related Work

Although collaborative virtual reality systems have been in use for quite some time, the design and development of techniques for navigating entire groups have not attracted much attention in prior research. In particular, commercial social VR systems almost exclusively rely on individual navigation capabilities. In contrast, approaches to group navigation have only been used in research prototypes so far.

2.1 Individual Navigation in Virtual Reality

Navigation through virtual environments requires cognitive *wayfinding* processes and a *travel* technique allowing the user to execute movements to a new location [8]. Physical walking within the available workspace is deemed the most natural form of travel that can lead to high amounts of presence [58]. For multiple users sharing the same workspace, strategies for collision-avoiding redirected walking were suggested [2, 21, 43]. Virtual travel techniques, on the other hand, usually require less space and are therefore often adopted for covering larger distances in the virtual environment. However, anecdotal evidence suggests that many users even prefer virtual travel for small viewpoint adjustments that could be easily covered by physical walking otherwise [36, 60]. Two common metaphors for virtual travel are steering- and target-based approaches. Steering requires the continuous specification of the desired direction and speed of motion similar to driving a vehicle in the real world. In virtual environments, however, the resulting conflict between the visual and vestibular systems is often deemed a plausible cause of simulator sickness [18,39,49]. The severity of sickness symptoms can be reduced by displaying rest frames [11] or by reducing the user's field-of-view during travel and hence minimizing the amount of visual flow in the periphery [25, 44]. Target-based approaches, on the other hand, often avoid visual flow completely by teleporting the user instantaneously to the specified target. In particular, short-distance teleportation in vista space (often referred to as *jumping*) has become a prominent travel metaphor in applications for head-mounted displays [35, 62], and several studies confirmed that jumping can significantly reduce simulator sickness compared to steering [14, 16, 24, 32, 47, 62]. For this paper, we therefore decided to focus our research on the virtual jumping metaphor for groups of multiple users. It is important to note, however, that some researchers also use the term *jumping* to denote physical upward movements of the user for locomotion [31, 56, 63], which is beyond the scope of this paper.

2.2 Group Navigation in Multi-User Virtual Reality

A group consists of two or more individuals who are linked by their membership in a way that the actions and thoughts of one member can influence the others [26, chpt. 1]. As a result, group sizes are diverse and can range from dyads working together over small groups exploring a museum to large crowds and audiences, where one member starting to clap or chant might motivate the others to join. Multi-user virtual reality systems can enable both physically collocated and spatially distributed users to meet and form groups with each other in a shared virtual environment. As a result, group interactions in VR can be classified by the number of involved distributed workspaces and the number of collocated users situated within each of these spaces (see Figure 2). Motivated by the current pandemic circumstances and the available commercial social VR platforms [45], we focused our research on systems that support one immersed individual per workspace and therefore fully rely on distributed rather than collocated collaboration.

Most of such systems either provide independent virtual navigation on a per-user basis (see [1, 23, 27, 41, 53] for projection-based systems and [30,42,54,55,59] for head-mounted displays). While recent studies showed that individually navigating dyads could outperform individuals in the acquisition of survey knowledge [10], others lamented that individual navigation can lead to difficulties staying together, finding each other, or understanding spatial references [59, 60]. This strongly motivates the use of group navigation techniques for distributed setups, but the design, realization, and evaluation of such techniques has received only little attention in prior research. In a review of commercial social virtual reality applications, Kolesnichenko et al. reported about mechanisms that allowed users to form groups in order to switch between different virtual environments together [35]. For group navigation within the same virtual environment, Weissker et al. introduced a framework stating that group navigation techniques in distributed virtual reality should allow users to form navigational groups (*Forming*), distribute navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*) [60]. For the *Performing* phase, the authors suggested a two-user jumping technique, in which an operating navigator could take a nearby passenger along when executing a jump. For this purpose, when the navigator specified their target position using the conventional parabolic pick ray, the offset target position of the accompanying passenger was previewed by an additional secondary target ray starting from the passenger's controller. The comprehensibility of this approach was already evaluated positively in previous work for two collocated users, but the spatial synchronization between user positions in the physical and virtual space (implemented for improving mutual awareness in collocated setups) required dyads to perform frequent walking to adjust their spatial formation in certain situations, e.g. after turning at corners, to fit through spatial constrictions, or to investigate objects from different perspectives [61]. As a result, the follow-up work for two distributed users additionally allowed the navigator to adjust the spatial formation of the dyad virtually, i.e. without requiring physical walking. In particular, when planning a jump, the navigator could specify the passenger's new target position relative to their own one using the touchpad of the controller. This enhancement enabled navigators to perform travel sequences more efficiently, and the accompanying two target rays were deemed a helpful visualization by both navigators and passengers [60].

Nevertheless, two central aspects of the proposed technique design limit its scalability to groups of more than two users. First, displaying an individual visual ray to communicate each participant's target position can easily seem chaotic and difficult to decode. As visualized in Figure 3, this is especially true when the spatial formation of the group is planned to change during the jump. Second, the specification of virtual formation adjustments using the approach from prior work becomes increasingly challenging with larger groups since the navigator would have to manually specify new target positions for each individual passenger when planning a jump. In this paper, we present the design, implementation, and evaluation of a distributed group navigation technique that addresses these limitations to make group travel feasible and understandable for group sizes beyond dyads.

3 Requirement Analysis on Group Navigation Techniques for Guided Tours in Social VR

Guided tours are shaped by interactive exchanges between the guide and the individual attendees rather than by pre-defined sequences of movements and explanations [5]. As a result, a central task of the guide is to engage with the attendees to adjust the pace and content with respect to their interests and capabilities. In current commercial social VR systems, the main forms of exchange include audio communication using built-in headsets in the head-mounted displays as well as a basic set of gestures and expressions that can be generated with a user's avatar [35, 45]. In this section, we investigate how group navigation techniques can and should build upon these means of communication to allow a guide to perform a tour effectively and efficiently while giving attendees enough freedom for individual engagement.

3.1 Advantages of Group over Individual Navigation

Prior work motivated that successful remote collaboration benefits from fluent transitions between individual and group navigation [60]. Similarly, a guided tour might consist of loose phases where attendees explore on their own and close phases where the attendees strictly follow the narrative of the guide. We believe that group navigation can be especially beneficial for the latter type and argue that *Forming* and *Adjourning* navigational groups should be lightweight to support easy transitions between the two types of phases. For the close phases, we identify two central advantages of group over individual navigation:

Reduction of Input Redundancy for Travel When the guide moves towards the next object of interest, all attendees equipped with only individual navigation capabilities have to perform similar travel inputs to follow. This unavoidably leads to waiting times until all attendees have arrived and assembled with respect to the object/area of interest and shifts attentive resources from the content of the tour to the operation of the travel technique. Group navigation techniques allow the guide to move the group as a single entity and therefore assist the group in staying together. As the guide takes care of all travel inputs, attendees can also concentrate more on the subject of the tour. This advantage is especially pronounced for novice users of virtual reality systems, who would not need to learn the operation of a travel technique before being able to attend the tour.

Reduction of Navigational Accords for Wayfinding While the guide is knowledgeable about the environment they are presenting, attendees are often completely unfamiliar with its content and spatial layout. As a result, wayfinding to a new destination as a group with individual navigation requires either a pre-travel briefing, where the guide explains the next destination and how to get there, or asking attendees to blindly follow the guide on the go. While both of these options can be tedious and risk attendees losing the group, group navigation techniques keep the group together and allow to comfortably guide attendees towards the next destination.

3.2 Requirements for Group Navigation Techniques

While the general quality factors for virtual travel like sickness-prevention, ease of learning, spatial awareness, and presence [7] also apply to group navigation, additional requirements specific to multi-user navigation can be derived based on prior work on collocated and distributed group work. Especially, the handling of the navigation controls for the whole group by the guide must be used responsibly. It is therefore a key requirement for the guide to conduct group navigation at an appropriate pace and to moderate the tour appropriately such that the group can understand what is happening and what to expect. To support this goal, the group navigation technique itself should provide *comprehensible* feedback mechanisms to improve mutual awareness and make the navigation process predictable:

Comprehensibility Performing techniques should "foster the awareness of ongoing navigation activities and facilitate the predictability of their consequences for the navigator [guide] and all passengers [attendees]" [61]. In particular, this means that each attendee should be able to understand and predict the navigational actions that the guide is applying to them and the group as a whole. The guide, on the other hand, should have an understanding of the future spatial formation of the group and how to predict and prevent undesired arrangements.

Furthermore, additional mechanisms are required to support the adjustment of undesired group formations:

Obstacle Avoidance Performing techniques should provide mechanisms that assist with avoiding collisions with objects in the virtual environment during travel [37]. In particular, the group should be able to fit through narrow aisles and confined spaces without any user being navigated out of bounds.

View Optimization When arriving at a certain object or area of interest, Performing techniques should provide mechanisms that support placing the group in a meaningful spatial arrangement for the joint observation and discussion of the respective content [37, 51, 60].

While these adjustments could be realized by individual user movements every time they are required, it is usually more comfortable and efficient to adjust the group's spatial arrangement virtually [37, 60]. In collocated setups, these individual virtual viewpoint adjustments per user would lead to spatial desynchronization and therefore disrupt the joint perception of a spatially consistent workspace [12, 37, 40]. In the scenario of distributed users, on the other side, group formations in the virtual environment are not bound to a physical counterpart and can therefore be adjusted more easily to meet certain criteria. As a result, we propose the following approach to *Obstacle Avoidance* and *View Optimization* in distributed virtual environments:

Virtual Formation Adjustments Performing techniques should allow the system and/or the users to adjust a group's spatial arrangement without requiring individual movements in order to meet the requirements of *Obstacle Avoidance* and *View Optimization* (cf. [3, 60]).

While there might be a large variety of group formations that are beneficial for *Obstacle Avoidance* and *View Optimization* in a given situation, observations from the real world indicate that people tend to assume certain characteristic formations when walking, observing, and discussing together [17, 34]. In his seminal work on spacing and orientation in co-present interaction, social anthropologist Adam Kendon identified so called functional formations (*F-Formations*) that help members of a group to organize their interactions and attentive resources in a meaningful way [34]. *Circle* formations, for example, create a shared transactional space for the exchange about a common theme. Current VR systems for distributed users motivate the creation of these formations as conversational anchors by placing campfires or round tables with exhibits into the virtual environment [45]. Two people often tend to be *vis-à-vis* or *L-shaped* [34]. If members of a group would like to focus their attention more on watching something in the distance rather than mutual interactions, they establish a *side-by-side* formation. A *horseshoe* formation offers a good compromise between observing something in the distance and talking about it within the group. When implementing *Virtual Formation Adjustments* for group navigation, we believe that it is helpful to support the creation of these or related F-Formations to conform to the requirement of *View Optimization*.

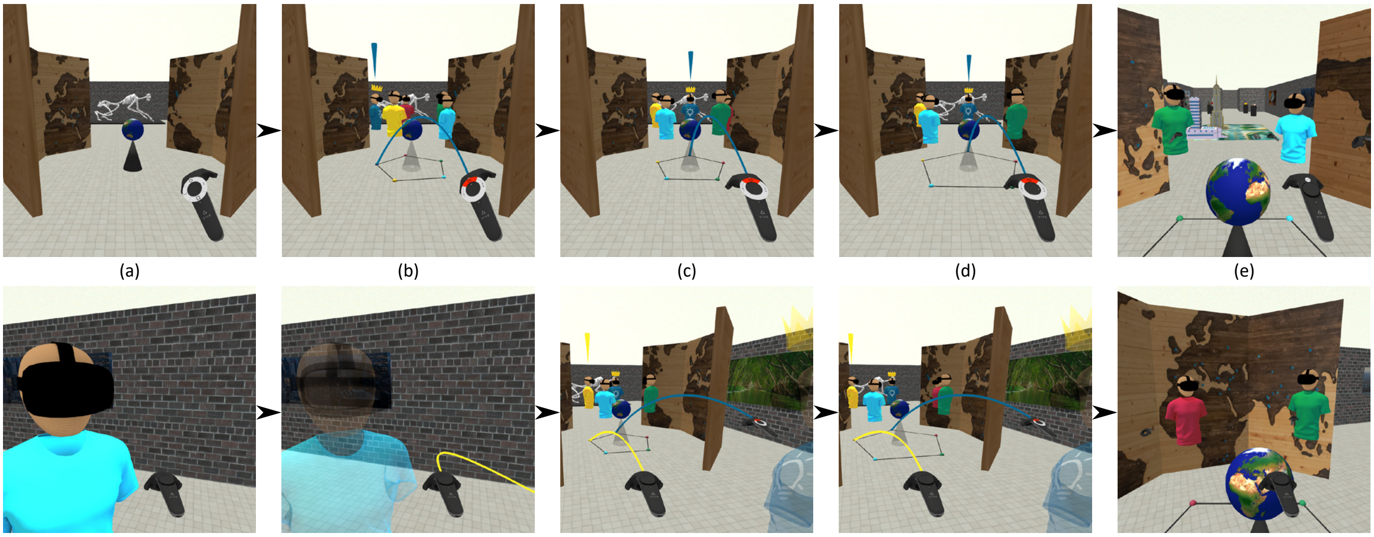

Fig. 4. Interaction sequence for executing the *formation-changing* jump in Figure 1 from the guide's (top row) and the yellow attendee's (bottom row) point of view. (a) The guide opens the radial menu around the controller's touchpad to select a formation. The attendee may be interacting with another group member and therefore not looking in the same direction as the guide. (b) The guide selects a circle formation by pressing and holding the touchpad button in the respective segment. Preview avatars allow the guide to predict how the group will be arranged after the jump. A secondary target ray only visible to attendees as well as the faded main avatars direct attendees' focus of attention towards the preview avatars. (c) The roll angle of the guide's controller allows rotation of the previewed group formation around its centroid. Attendees will always know where they will jump to when tracing their personal target ray. (d) Radial swipes on the touchpad of the guide's controller specify the spatial extent of the group. (e) When the guide has ensured that everyone is ready and releases the touchpad button, the group will be teleported as indicated by the preview avatars.

On the other hand, there are several approaches to supporting the requirement of *Obstacle Avoidance* with *Virtual Formation Adjustments*. In a few cases, it might be sufficient to only rotate the group in its current formation to create a collision-free user placement in the virtual environment. Other situations, however, might require increasing or decreasing the group's spatial extent to distribute users around a larger object of interest or to fit through narrow passages. The most extreme reduction of a group's spatial extent is to virtually overlay the positions of all users during travel, which requires hiding the avatars of the other users and impairs mutual awareness and interactions [45, 61]. Thus, we argue that *Virtual Formation Adjustments* for group navigation should allow reducing the group's spatial extent while still ensuring that appropriate distances between all users are kept [29]. A tradeoff between these two conflicting goals could be achieved, for example, by rearranging users in a compact *grid* formation (similar to a bus in the real world) or even a *queue* formation for very narrow spaces. When increasing the group's spatial extent, on the other side, it should be assured that users do not lose track of the other group members and the guide as they get more dispersed across the environment. As a result, we argue that solutions to *Obstacle Avoidance* can come in many different forms, which require group navigation techniques to offer strategies for rotating, scaling, or completely rearranging the group.

4 A Group Jumping Technique for Guided Tours

The formulated requirements for realizing group navigation in the context of guided group tours can be implemented in various ways. In this section, we present and justify one way of addressing these requirements using jumping as the core travel metaphor. As a development platform, we used a proprietary virtual reality software system for rapid prototyping to create a shared networked virtual environment, which served as a basis for the developments presented in this paper. This system allowed distributed users to join with an *HTC Vive Pro* head-mounted display, to be represented as a basic avatar, and to communicate with other users using the built-in headsets of the display in a classic non-spatial audio channel. We identified this as a basic feature set that is supported by all commercial social VR systems reviewed in the surveys of [35, 45] and aimed at building our group jumping technique for guided tours on this common ground. This makes our technique independent from additional awareness mechanisms like spatial audio, animated high-fidelity avatars, and voice indicators that can be seen in some more advanced systems.

4.1 Group Representation

Avatars in our system consist of a virtual head with a head-mounted display, a shirt, and controller geometries (see Figures 1 and 4). We found this abstract representation suitable to support mutual awareness by providing more visual saliency than the representation of devices alone while not evoking uncanny feelings as known from imperfectly behaving avatars [52]. We suggest additional visualizations for the guide to improve recognizability, e.g. an icon on their shirt and/or crown above their head as illustrated in Figure 1. Since feet are usually not tracked in common head-mounted display setups, we project each user's head position onto the floor and display a sphere in the color of the user's shirt to improve depth perception. For members of a group, we also continuously display the convex hull of these points as an indication of the group's current spatial extent in the virtual space (similar to the concept of *group graphs* presented in related work [19, 20]), which can be used to judge the necessity of measures for *Obstacle Avoidance* and *View Optimization* during group travel.

4.2 Group Travel

Many commercial single-user applications for the *HTC Vive* family established the use of the controller's round touchpad button for jumping. It is customary to press and hold this button to activate target specification, select the target using a parabolic pick ray, and release the button for confirmation. We aimed at building upon this workflow to allow the guide to initiate, plan, and execute jumps for the whole group. An exemplary interaction sequence for executing a group jump is shown in Figure 4 and will be explained in the following.

4.2.1 Initiating Formation-Preserving and -Changing Jumps

Following our previous requirement analysis on group navigation, the guide may need to rotate the group, change its spatial extent, or rearrange participants completely to achieve *Obstacle Avoidance* and *View Optimization*. To address all of these possibilities, our technique distinguishes between the two modes of *formation-preserving* and

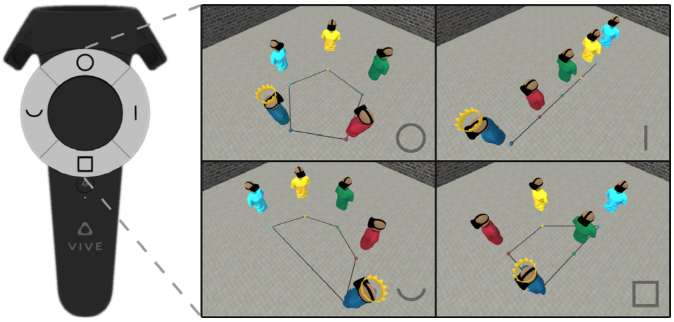

Fig. 5. In our implementation, the guide can choose between four pre-defined group formations to initiate target specification for a formation-changing jump: circle, queue, horseshoe, and grid.

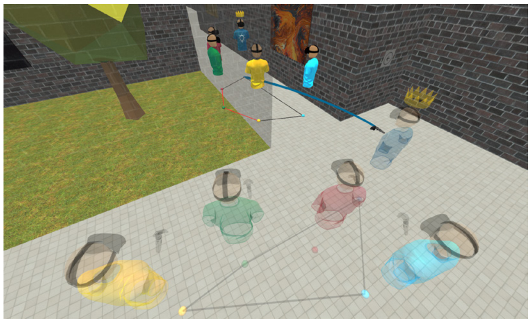

Fig. 6. If the preview avatars are occluded for participants, we suggest fading the corresponding scene geometries. If the previewed convex hull intersects with obstacles, the respective edges are colored in red.

formation-changing jumping, which have to be toggled before pressing the touchpad down for target specification. Formation-preserving jumping is the default and allows relocating the group in its current formation with potential adjustments only to its rotation and spatial extent. Formation-changing jumps, on the other hand, allow rearranging the group to a pre-defined formation and have to be toggled explicitly. To do so, the guide can open a radial menu around the touchpad by pressing the controller's menu button. The touchpad is then visually subdivided into four regions that correspond to different group formations when pressed down (see Figure 4a and 5). As group discussions are often focused on a particular object or region of interest, we decided to provide the *circle* and *horseshoe* formations for supporting joint observations. To achieve collision-free group placements when traversing narrow aisles, we offer *grid* and *queue* formations for space reduction. Once the guide decided on a formation-preserving or a specific formation-changing jump, they start the target specification process by pressing the touchpad down. Afterwards, the mechanisms shown in the following sections are identical for both types of jumps.

4.2.2 Target Specification and Comprehensibility Mechanisms

As explained in Section 2.2, the use of additional target rays to mediate user destinations seems to be restricted to dyads. For larger groups, we therefore decided to show secondary target rays only to their respective users and to mediate the group context by preview avatars (see also [22, 46, 64]) visible for all group members.

When the guide presses the touchpad down, the current avatars of the group become semi-transparent to avoid occlusions and to indicate their transitional state (see Figure 4b). The conventional parabolic pick ray starting from the guide's controller is used to determine an intersection point with the scene, but unlike in single-user jumping, we propose that this position is used as the new centroid of the group's convex hull instead of the guide's personal target position. The centroid is a more relevant point for the group as a whole and a more suitable anchor for rotations or changes in spatial extent. Preview avatars and a preview convex hull are then displayed around the specified centroid and allow to predict the group's spatial arrangement at the target as visualized in Figure 1 (center). Nevertheless, we believe that a visual target ray from the guide's controller to the group's new centroid might be a conflicting cue to the guide's off-centroid preview avatar. As a result, we suggest hiding the parabolic pick ray in favor of a curved feedback ray going to the actual target position of the guide in the preview. In Figure 4b-d, the centroid of the group is located below the globe while the guide's visual ray always goes to their target position. As suggested in previous work on two-user jumping, attendees can see an additional curved ray from their controller to their personal target position [61]. As these rays always emanate in the direction given by the respective controllers, attendee awareness is also raised if a jump is planned outside their field of view (see Figure 4b).

For rotating the group around its centroid, the guide can use the otherwise unemployed roll angle of their controller, which is amplified such that all potential rotations of the group can be achieved by comfortable wrist rotations (see transition from Figure 4b to c). Furthermore, the guide can perform radial swipes on the touchpad (similar to the Pie Slider technique [38]) to scale the previewed group formation around its centroid (see transition from Figure 4c to d). The minimum selectable size of the group in this process is computed ensuring that no user pair will ever jump into each other's intimate space, which is usually defined by an interpersonal distance of 0.45m [28, 29]. Scalings that violate this constraint are clamped and previewed at the smallest possible group size. If the guide is unsatisfied, target specification can be aborted without jump execution by pressing one of the grip buttons on the controller. These buttons require slightly more effort to reach and are therefore good candidates for destructive actions that should not be triggered by accident. If the guide, however, is satisfied with the shown preview, they can release the touchpad to execute the jump (see Figure 4e).

4.2.3 Interaction of Preview Avatars and the Environment

To achieve the requirement of *Comprehensibility* for all involved users during target specification, it is vital that everybody is able to see the provided preview avatars and rays to understand what will happen next. While we already discussed the semi-transparency of the current avatars in that regard, certain parts of the group preview at the new target might still be occluded by objects in the environment. Figure 6 shows an example of such a situation, where the preview avatars would be occluded by walls for the leftmost users if no countermeasures were taken. We therefore suggest making occluding scene objects translucent such that an obstruction-free view can be ensured for all participants.

With the requirement of *Obstacle Avoidance* in mind, we implemented a simple heuristic that constantly checks for collisions of the previewed convex hull with the scene's geometries. Colliding edges are highlighted in red and signal to the guide that improvements might be required. This computationally inexpensive approach allows the guide to already detect many cases in which users might be moved out of bounds, placed inside of obstacles, or separated from each other. In the situation of Figure 6, one user would be separated from the rest of the group by a wall if the jump is executed, which can be disturbing. More sophisticated obstacle avoidance techniques could consider, for example, users inside the convex hull, arbitrary floor geometries as well as lines of sight between users and objects of interest.

4.3 Discussion of Interaction Design

As guided tours usually are highly dynamic and dependent on the individual attendees, our described group navigation technique allows the specification of versatile group transitions for different situations. While our proposed solution is only one of many options on how the formulated requirements can be fulfilled by a group navigation technique, it builds upon prior research on two-user jumping and requires only one controller per user to operate. As a result, a potential second controller could be fully employed for more use-case specific features and interactions. Our formations for formation-changing jumps were chosen to match the characteristics of museum-type indoor environ-

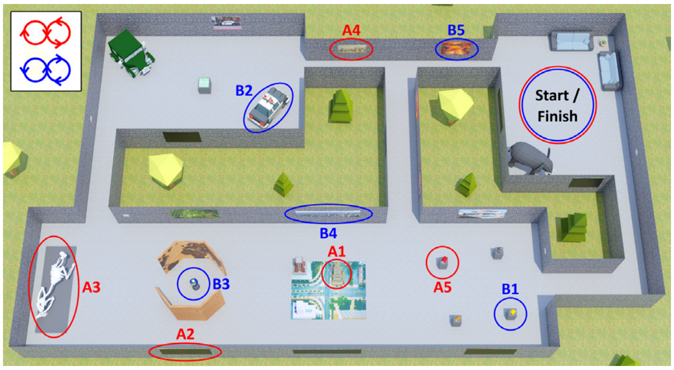

Fig. 7. Top view of the museum in our initial usability study. The guided tours to be conducted by participant A and B, respectively, both started in the welcome lounge (top right), followed a figure-eight pattern through the rooms, and covered five exhibits to be presented to the group.

ments and can be easily replaced or extended by other application- or environment-specific formations if required. All in all, the large navigational freedom of our technique might also make it more complex to learn and operate, which was an important subject of investigation in our initial usability study described in the next section.

Two aspects of our proposed technique give particular rise to debate. First, when performing a formation-changing jump, there is a multitude of ways to arrange users within the desired target formation. While our current solution always places users in a fixed order with the same interpersonal distance for neighbors, more sophisticated approaches could consider social ties and relationships between users, the surrounding objects, or information from the formation before the jump to derive more advanced placement suggestions. As we acknowledge that this might be a parameter to fine-tune for a specific composition of group members and virtual environment, we focused our initial usability study on a more general evaluation of our technique, in which one of our research questions (RQ2) asked if the provided preview avatars and target rays were sufficient for achieving *Comprehensibility* independent of particular placement heuristics for formation-changing jumps.

Second, jumping implementations in virtual reality can theoretically introduce changes to the users' positions and viewing directions. The most common variant, sometimes referred to as *partially concordant* jumping [13, 33], only shifts each user's viewpoint while keeping their global viewing directions unchanged. As a result, all changes in viewing direction must be generated by physical rotations. *Discordant* jumping, on the other hand, uses auxiliary mechanisms to specify a new viewing direction to be set in addition to the change in position. In our technique, the motivated formations for formation-changing jumps all come with an inherent idea of viewing directions for each individual user that seem to be suitable candidates for automatic view direction adjustments during jumping. *Circle* and *horseshoe* formations, for example, build on the importance of shared eyelines for conversations [34, 45] while users in the space-compressing *grid* and *queue* formations might benefit from looking into the same direction for traversing the scene (similar to a vehicle in the real world). When rotating the group in a formation-preserving jump, on the other hand, adjusting each user's viewing direction accordingly can improve visual consistency of the other users' avatars before and after the jump. As a result, automatic view direction adjustments seem to be advantageous for reducing the number of physical rotations required. However, related work on discordant jumping usually reports on negative effects regarding spatial orientation and user comfort [9, 13, 33, 47]. To improve our understanding of the advantages and disadvantages of automatic view direction adjustments using our technique, we decided to gather more user feedback on this subject in our initial usability study by formulating and evaluating a corresponding research question (RQ3).

5 Initial Usability Study on Guided Group Jumping

Since the ongoing global pandemic circumstances and the related safety measures of our university prevented us from carrying out a user study with a large participant sample, we decided on an initial usability study, more particularly a single-condition assessment test [50], of our technique with an emphasis on qualitative measures. This procedure allowed us to explore how well users can learn to perform realistic tasks with our technique and identify potential usability deficiencies. Based on the general workflow of usability testing, we started by formulating the following research questions:

RQ1 Is the operation of our group navigation technique learnable and suitable for moderating guided tours?

RQ2 Are the preview avatars and target rays comprehensible visualizations for predicting what will occur to oneself and the group?

RQ3 What are the perceived advantages and disadvantages of automatic view direction adjustments during group navigation?

RQ4 Does the prolonged use of our group navigation technique induce symptoms of discomfort?

RQ5 What are the differences when navigating a small group of five users compared to a larger group of ten users?

To answer these questions, we chose the scenario of tours through a virtual museum (see Figure 7) and recruited participants familiar with VR systems. To be compliant with prevailing heath regulations, we invited only two participants per session, who later formed a virtual group with the experimenter and additional simulated users to achieve more reasonable group sizes for guided tours.

5.1 Experimental Setup

We equipped three separate rooms with a workstation, an *HTC Vive Pro*, and corresponding controllers. Two ceiling-mounted base stations 2.0 were used as tracking references for an interaction space of 2.0m x 1.5m in each room. The workstations were connected to each other via a 10 GigE network connection and ran our proprietary distributed VR application. Each machine rendered user perspectives with a resolution of 1080x1200 pixels per eye and an update rate of 90Hz. All workstations were also connected to a *Mumble* server to allow for audio communications using the built-in headphones and microphones of the head-mounted displays. In comparison to a user study with remote participants, this setup allowed us to ensure maximal stability, minimal latency, and fully comparable hardware for all participants.

5.2 Experimental Procedure and Methods

Participants arrived in pairs at our laboratory and were briefed about the scope of the experiment. They were informed that they would be distributed to separate rooms and meet again virtually as part of a group with the experimenter and additional simulated users that should be treated as if they were real humans. We emphasized that both participants would take turns in being the guide for performing joint tours and that we would record all inputs for further analyses. Participants gave their written consent by signing a form before continuing. Once everybody was separated and put their head-mounted display on, participants and the experimenter had a short verbal chat in the welcome lounge of the virtual museum to ensure that participants could identify the avatars of the others and that the audio channel was working correctly. They were also introduced to the simulated users, whose head direction always automatically followed the current guide's viewpoint. Afterwards, the experiment followed the structure shown in Figure 8.

System and Technique Explanations First, the experimenter assumed the role of the guide in a group of five users (i.e. two additional simulated users) and showcased all features and navigational possibilities the system had to offer in an order similar to Section 4. Participants in the attendee role could observe the guide's controller and actions during jumping, understand the preview avatars and their personal target rays (RQ2), and ask questions if necessary. The experimenter also demonstrated the optional addition of automatic view direction adjustments and underlined that participants would be asked

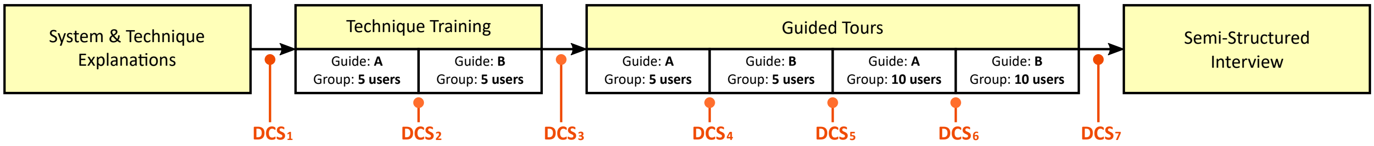

Fig. 8. Procedure diagram of our initial usability study (introduction and conclusion omitted for simplicity). After the initial technique explanations by the experimenter, Participants A and B took turns in training and performing guided tours for the rest of the group. At various points across the study, we asked participants for their current discomfort score (DCS) to be able to intervene if necessary.

to form an opinion about its utility later (RQ3). In this phase, we only measured the total duration to get an impression on how long an exhaustive presentation of all features including follow-up questions may take (RQ1).

Technique Training Afterwards, the guide's controls were passed on to the first participant to try all group navigation features of the technique on their own while the other participant could still observe as an attendee. The operating participant should replicate the same series of jumps as the experimenter in the previous phase to ensure that all features were understood and operated at least once. Particularly, the experimenter configured the system such that the participant could experience jumps with and without automatic view direction adjustments (RQ3). Next, the same process was repeated after passing controls to the second participant. We silently measured the duration of each participant's training to avoid pressure. Moreover, we asked participants to think aloud as they progressed and asked follow-up questions where appropriate (RQ1), a methodological mixture of a *concurrent think aloud* and *concurrent probing* protocol [4]. After both participants were done, we conducted a short interview in VR on their opinions regarding automatic view direction adjustments during jumping (RQ2) and asked them to decide whether they would like to perform the rest of the study with or without this optional addition. We asked for this decision early in the study to allow for a fallback option if participants felt uncomfortable about virtual rotations as reported in previous work [9, 13, 33, 47].

Guided Tours (5 users) The guide's controls were passed back to the first participant, who was tasked to conduct a guided tour for the whole group through the museum. Since both participants were unfamiliar with the environment prior to the study, we displayed the intended route, five exhibits of interest, and a one-sentence fact about each of these exhibits using orange arrows and highlights (see Figure 9). These helper visualizations were only visible for the guide while the other user in the attendee role had to rely on the guide's narration. In particular, the task of the guide was to move the group along the displayed route, ensuring that everyone could follow along, place the group with respect to the featured exhibits, and to communicate the additional facts to them. After completing the tour, the controls were passed to the second participant and the process repeated with a different tour layout. To be comparable, both tour layouts started and concluded in the welcome lounge and followed a figure-eight pattern through the rooms and aisles of the museum (cf. Figure 7). For both tours, the five exhibits of interest were chosen to include one of the large exhibits (A3/B2), one of the medium-sized exhibits (A1/B3), one of the small exhibits on a pillar (A5/B1), and two of the wall-mounted images (A2;A4/B4;B5). During the tours, the experimenter assumed the role of a silent attendee to observe how guides were performing in this task (RQ1). The system recorded all head and controller inputs for further analyses.

Guided Tours (10 users) After completing both tours, we added five additional simulated users and asked participants to repeat their tours using the previously described procedure. This allowed us to draw conclusions on the applicability of their acquired knowledge and training to a larger group (RQ5).

Semi-Structured Interview In a final interview, we questioned both participants about their experiences using our technique focusing particularly on the aspects formulated in our research questions. This methodology is commonly referred to as *retrospective probing* [4]. Finally, each user was asked individually to provide a numeric rating for

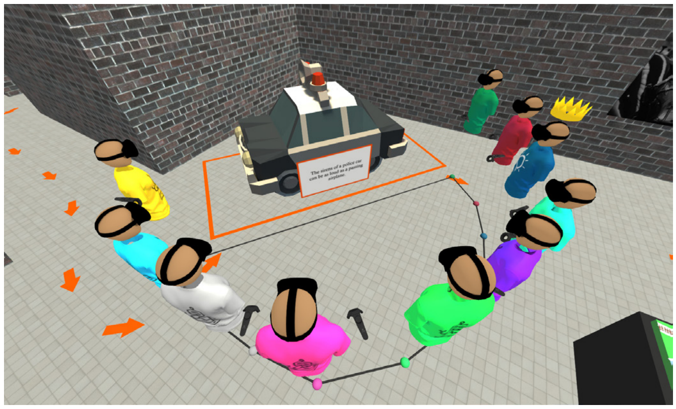

Fig. 9. A guide, two real attendees, and seven simulated attendees observe a virtual car as part of a guided tour in the 10-user condition of our usability study. The orange arrows, highlights, and additional information panels were visible to the guide but not the attendees to simulate the common asymmetric knowledge distribution in guided tours.

each feature of our technique on a scale from 0 (very disturbing) to 10 (very helpful), where 5 was labeled neither disturbing nor helpful.

To ensure the continuous wellbeing of our participants during the study (RQ4), we repeatedly asked each user of a team for their discomfort score (DCS) at the measurement points illustrated in Figure 8 using the question "On a scale of 0-10, 0 being how you felt coming in, 10 is that you want to stop, where are you now?" [25, 48]. This wording was previously deemed suitable for detecting the onsets of simulator sickness and considered more feasible to administer for repeated measurements compared to the commonly used SSQ [6, 48].

5.3 Participants

12 participants (2 females and 10 males) between 23 and 34 years of age ($M = 26.75$, $\sigma = 3.33$) participated in our study in pairs. They came from both academic and industrial contexts and claimed to have between one and seven years of prior experience with head-mounted displays ($M = 3.17$, $\sigma = 2.21$). They were hence able to provide valuable feedback, discussions, and suggestions regarding our developments.

5.4 Results and Discussion

In the following sections, we summarize participant experiences as communicated when thinking aloud (technique training phase) and when probed in the semi-structured interview. We supplement our reports with quantitative logging data where applicable. When quoting participants, we use the team number for stating a consensual opinion shared by both team members (e.g. [T4] for the fourth team) and add the participant letter within a team if the opinion concerned only one member (e.g. [T4B] for member B of the fourth team).

5.4.1 Technique Operation (RQ1)

System and technique explanations took an average of 10:06min (σ = 0:55min) per team, followed by an average of 4:58min (σ = 1:23min) of technique training per participant. This form of introduction enabled all participants to successfully perform guided tours along the predefined routes and exhibits. Each of these tours had a mean duration of 4:05min (σ = 1:55min) and required guides to perform an average of 21.63 (σ = 3.92) group jumps, among which were 9.71 (σ = 5.76) formation-preserving and 11.92 (σ = 3.24) formation-changing jumps. As expected, *circle* and *horseshoe* formations were mainly used to place the group around the exhibits while *grid* and *queue* formations were mostly employed to move the group from exhibit to exhibit [T1-6]. Overall, our group navigation technique got very positive general feedback for being "straightforward" [T5], "fast to learn and good to use" [T6], "really informative and transparent" [T4] as well as "cool and helpful for museums" [T1]. Nevertheless, due to the large number of features, some participants mentioned to have taken training slowly as they observed themselves getting progressively better over time [T3, T6]. The most challenging part of our technique certainly was the specification of the group's new centroid together with the rotation and spatial extent of the group's formation in a single gesture. In that regard, participants appreciated that the guide's feedback ray always pointed at their target position instead of displaying the picking ray used to determine the group's new centroid [T1, T4, T5]. Furthermore, participants valued the "intuitive" nature of the controller's roll angle for specifying the group rotation [T4] and the addition of radial touchpad swipes for scaling to "complement [it] well" [T1] and "work nicely" [T2]. However, generating swipes on the touchpad while holding it down at the same time was deemed more challenging for larger swipe distances [T1]. A variation of our technique could therefore involve a press-release gesture for activating target specification such that all parameters can be specified without holding the touchpad down. Alternatively, the system could automatically derive and propose certain parameter values by considering the surrounding geometries.

5.4.2 Comprehensibility of Jumping Previews (RQ2)

The preview avatars consistently received positive ratings for both the guide and the attendee role. Across all teams, they were appreciated for communicating where the group would be located after a jump – of course only if the guide's pace allowed attendees enough time to see them [T5]. On average, the preview avatars were visible for only 2.67s (σ = 1.15s) per jump since the attendees were often already looking in the direction of the jump and therefore did not need much time to understand the planned jump. The see-through feature was also mostly valued, particularly for the attendee role [T1, T2, T4], with the exception of one team that worried about the correct perception of building proportions when walls are temporarily made semi-transparent [T5]. The previewed collisions of the new convex hull with the scene helped guides to optimize user placements or to understand when switching to a more appropriate formation mode was required [T1, T2, T4, T6]. The constantly updated visualization of the current avatars' convex hull, however, was a more controversial feature that individual participants described either useful for judging the next steps to perform [T1, T3A, T4, T5A, T6B] or slightly distracting [T2, T3B, T5B, T6A]. For the attendee role, the secondary target ray was mostly valued for guiding user attention to the preview avatars even when they were looking away [T2, T4, T5] while one team claimed that they were constantly looking in the direction of the preview avatars anyways [T6]. From this feedback in combination with our observations, we conclude that preview avatars seem to be a suitable means of achieving comprehensible group jumping that can benefit from additional awareness mechanisms when they are out of a user's field of view. The convex hull representation of the current avatars seems to be an optional addition.

5.4.3 Automatic View Direction Adjustments (RQ3)

After the technique training phase, only 2 out of 12 participants decided against automatic view direction adjustments for completing the guided tours [T3]. Consistent with reasons mentioned in previous work [9, 33, 47], they found automatic view direction adjustments to be "too disorienting" [T3A] and valued the increased individual freedom of physical rotations [T3B]. The remaining users, on the other hand, appreciated the increased efficiency of automatic view direction adjustments for jointly observing an object or direction of interest together [T1, T2, T4, T5, T6] while frequent physical rotations were even deemed "too exhausting" [T5]. Our preview avatars were explicitly mentioned for

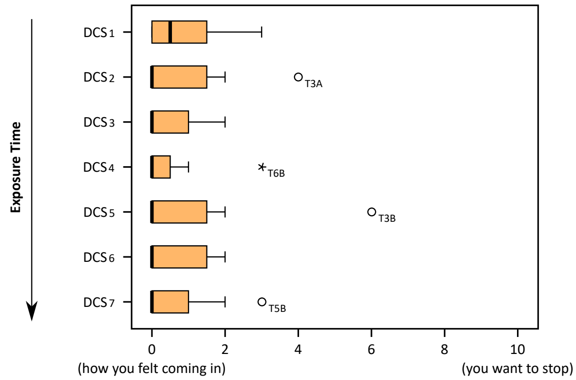

Fig. 10. Boxplots showing the distribution of discomfort scores (DCS) at the measurement points illustrated in Figure 8. $N = 12$ per boxplot. Circles and asterisks denote outliers and extreme values based on Tukey's fences with $k = 1.5$ for outliers and $k = 3.0$ for extreme values [57].

also conveying view direction changes comprehensibly [T1, T2, T4, T6]. Some participants even suggested view direction as another freely adjustable parameter during target specification instead of defaulting to the fixed directions for formation-changing jumps shown in Figure 4 (left) [T1, T2]. Based on related work, we were surprised about these positive reactions, which motivate more formal future research on the effects of preview avatars on spatial orientation and user comfort during automatic view direction adjustments.

5.4.4 Discomfort Scores (RQ4)

Except for uncomfortable heat developments due to the prolonged use of head-mounted displays [T1, T2, T5, T6], participants did not report any symptoms of simulator sickness or discomfort. This is underlined by the discomfort scores voiced during the course of the study as visualized in Figure 10, which had a median between 0 and 0.5 with standard deviations between 0.67 and 1.76 at all measurement points. We neither observed an increase of discomfort scores over time nor relationships between the discomfort score and the guide/attendee role assignment or gender. The unique maximum score of $DCS_5 = 6$ was given by a guide after accidentally stepping outside the calibrated area and colliding with a real-world obstacle. They declined the offer for a break and already felt better at the next measurement point ($DCS_6 = 2$). We therefore conclude that the discomfort introduced by operating and experiencing guided tours using our technique is negligible, which is consistent with previous comparisons of active and passive two-user jumping through virtual environments [60, 61].

5.4.5 Scalability (RQ5)

Participants did not report on major problems of navigating the 10-user compared to the 5-user group with "no big differences" in technique operation [T4] and "surprisingly similar" interaction sequences [T5]. Nevertheless, users claimed that finding suitable group placements was more challenging in corridors and around exhibits [T1, T2, T3, T6]. For exhibits, this often resulted in smaller interpersonal distances than in the small group since all avatars had to be placed within the available space without occluding the view of others. However, planning user formations did not seem to take longer based on the recorded visibility durations, which were 2.89s (σ = 1.29s) and 2.46s (σ = 0.99s) per jump for the small and large group, respectively. For narrow spaces like corridors, guides claimed an increased preference of the *grid* over the *queue* formation in the larger group [T1, T4, T5, T6]. Indeed, the proportion of *grid* jumps compared to all formation-changing jumps went from 3.7% (σ = 6.1%) in the small to 27.4% (σ = 22.5%) in the large group. While all teams deemed a group size of 10 to be still manageable using our technique, they suggested that even larger groups could benefit from a more spacious virtual environment [T1-T6] and an adapted choice of formations for formation-changing jumps like a circle with multiple shifted rows or a "cinema seat" arrangement [T3,

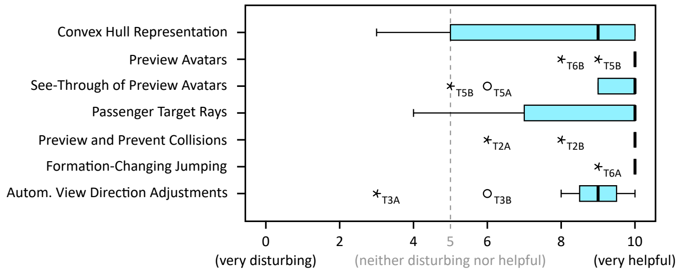

Fig. 11. Boxplots showing the distribution of responses to our concluding feature scoring questionnaire, where each feature was rated on a scale from 0 (very disturbing) to 10 (very helpful). $N = 12$ per boxplot. Circles and asterisks denote outliers and extreme values based on Tukey's fences with $k = 1.5$ for outliers and $k = 3.0$ for extreme values [57].

T4]. With these changes, even group sizes of up to 20-30 users were considered plausible for performing guided tours [T5]. Nevertheless, due to the large number of avatars, participants also raised the question if attendees really need to see each other during a tour or if merging at least sub-groups to a single viewpoint could also be a viable alternative [T2]. Based on related work on guided tours [5], however, we would suggest providing mechanisms for these cases that allow individual attendees to step out of the crowd to interact with the guide if necessary. If all attendees should be able to see and interact with each other at all times, we conclude that the complexity of group navigation increases with group size, where the requirements *Obstacle Avoidance* and *View Optimization* seem to be the key driving factors.

5.4.6 Individual Feature Ratings

At the end of our study, participants were asked to provide individual numeric ratings of certain aspects of our technique from 0 (very disturbing) to 10 (very helpful), which aimed at summarizing their voiced opinions in the semi-structured interview. As the overview of responses in Figure 11 shows, all features received very positive median scores between 9 and 10, which indicates a high level of acceptance for our group navigation technique across our participants.

5.4.7 Summary and Limitations

Our study results indicate that effective, comprehensible, and learnable group navigation techniques can be realized for guiding small groups through distributed virtual environments (RQ1, RQ2). Across all teams, we received particularly positive feedback regarding the use of preview avatars for role-independent *Comprehensibility* as well as collision previews and formation-changing jumps for *Obstacle Avoidance* and *View Optimization*. In particular, passive movement in the attendee role did not seem to lead to increased discomfort or confusion if the guide performed all actions with a reasonable pace (RQ4). This result underlines that the guide should watch their attendees for signs of distraction or confusion to adjust the pace of the tour if necessary. Moreover, the guide's narration can complement the visualizations of the group navigation technique if they are unsure about the attentiveness of particular attendees. The majority of users (10 out of 12) preferred automatic view direction adjustments during group jumping over physical rotations for their efficiency and underlined the preview avatars' comprehensibility also in this regard (RQ2, RQ3). Future more formal research is required to analyze the effects of view direction adjustments on spatial awareness and to investigate sources of discomfort for individuals. Overall, the discussions with the participants in our study gave us valuable insights on how certain aspects of our proposed jumping technique could be tweaked for specific use cases/user preferences and how it could be extended to guide even larger user groups, where the requirements *Obstacle Avoidance* and *View Optimization* seem to be the driving factors of complexity (RQ5).

While the results of our study are promising, we would like to emphasize that groups only consisted of three human group members with additional simulated users. This allowed participants to experience the navigation experiences in both the guide and the attendee role, but social ties and relationships one would usually observe between human group members were not present. As a result, future studies should investigate the influence of such interpersonal relationships on the group navigation process in more detail. In particular, it could be relevant to study how users should be placed and ordered within the target formation of a formation-changing jump, which target formations are particularly suitable for specific situations (also beyond the four we have chosen to match our scenario), and more sophisticated algorithms for predicting and preventing collisions in the virtual environment.

6 Conclusion and Future Work

Group navigation techniques allow getting to a destination together efficiently by reducing input redundancy for travel and navigational accords for wayfinding. In this paper, we identified the three central requirements *Comprehensibility*, *Obstacle Avoidance*, and *View Optimization* for group navigation and developed a corresponding technique using jumping as the core travel metaphor. Based on the positive results of our usability study, we conclude that our requirements are helpful for designing group navigation techniques for small groups of five to ten users and that our particular technique is an effective implementation that conforms to these requirements.

Future work might focus on the suitability of alternative travel metaphors for group navigation like steering, flying, or long-distance teleportation. This is especially motivated by related work that, despite the general acceptance of jumping for minimizing simulator sickness, observed small subsets of "telesick" users who seem to have more problems with jumping over its alternatives [15, 16]. While we believe that our requirements still apply to other metaphors, their implementations will certainly differ. Formation-changing transitions for steering, for example, should put a much stronger focus on optimizing the paths to be traversed by each user since prolonged visual flows as well as crossings with other user paths could easily introduce discomfort. For long-distance teleportation, as another example, additional views such as portals or worlds-in-miniature are required to be able to evaluate previews of the group at the destination.

Furthermore, the development of group navigation techniques for even larger groups such as school classes or virtual travel groups is an important next step. Our study already provides initial ideas on how to address the increased complexity of *Obstacle Avoidance* and *View Optimization* in managing such groups. In general, however, more formal studies are necessary to investigate suitable techniques for group navigation of only human users in more detail. Group navigation with even more users probably requires completely different approaches, which also have to consider the placement of users and their avatars very close to, on top of, or even intersecting each other.

While this paper only focused on distributed individuals, future work should also address the combination of collocated and distributed user groups for group navigation. The challenge here is to find appropriate solutions for group transitions that avoid spatial desynchronization for collocated participants while using the spatial flexibility of distributed entities for realizing *Obstacle Avoidance* and *View Optimization*.

In conclusion, research on group navigation is still at the beginning and therefore offers much potential for future investigations. We believe that group navigation is a valuable tool for social virtual environments and therefore plan to implement our results as plugins for commercially available platforms. We hope that this step will spark further discussions on effective group navigation in multi-user virtual reality and encourage researchers to investigate alternative mechanisms and scenarios for achieving *Comprehensibility*, *Obstacle Avoidance*, and *View Optimization*.

Acknowledgments

Our research received funding from the Thuringian Ministry for Economic Affairs, Science, and Digital Society under grant 5575/10-5 (*MetaReal*). We would like to thank the participants of our studies and the members of the Virtual Reality and Visualization Research Group at Bauhaus-Universität Weimar (`http://www.uni-weimar.de/vr`).

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