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Pre-print version

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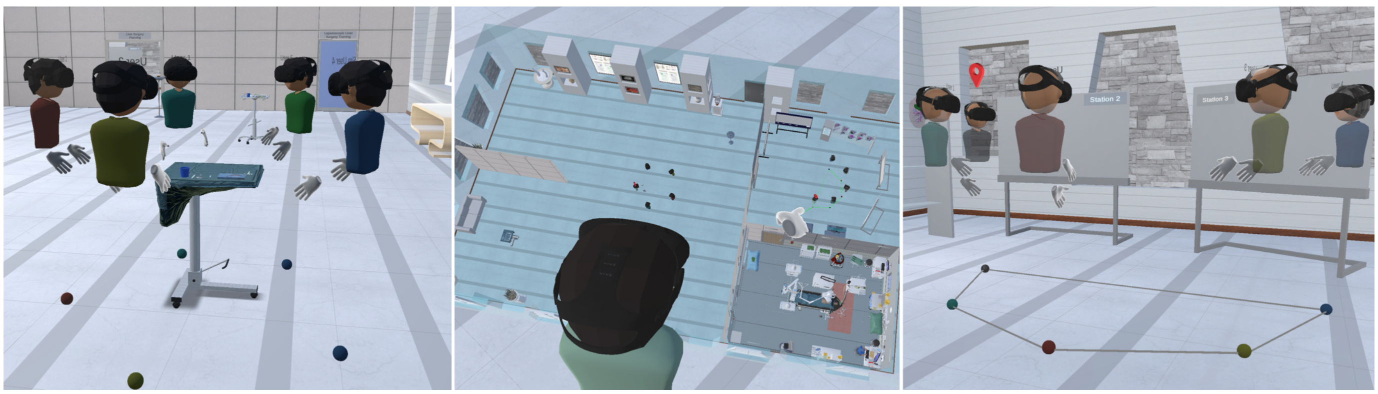

Fig. 1: Overview of the WiM-based group navigation for collaborative VR environments. *Left:* The group gathers in VR. *Center:* The guide chooses a group formation and uses the group WiM for navigation. *Right:* The group arrives at the destination.

***Abstract*—Group navigation is essential for arranging group members in a certain configuration, as it supports team communication and interaction in collaborative virtual reality (VR). We propose a group *World-in-Miniature* (*group WiM*) navigation technique that allows a guide to control and navigate a team within a miniature replica of the entire virtual environment. We evaluated the technique's usability, user performance, and discomfort considering both user roles: the group guide, who controls navigation and arrangement, and group members, who are the ones being navigated and arranged. In addition, we compared it with a state-of-the-art *group teleportation* technique in a user study ($n = 20$). No significant differences were observed in the placement error and for the interaction effect. Qualitative feedback on the perceived advantages and disadvantages of both techniques was collected and summarized. The participants highlighted that the group WiM provides an overview and full control for navigation in complex virtual environments, while group teleportation provides a good understanding of the spatial environment during the navigation.**

***Index Terms*—Collaborative virtual reality, group navigation, world-in-miniature, collaborative interactions**

I. Introduction

Collaborative virtual reality (VR) allows multiple users to simultaneously interact with objects and share experiences in a common virtual environment. In recent years, collaborative VR has emerged as an essential research topic and has been utilized to support communication and team training in various fields, such as in medical training and planning [1]–[3]. Several studies show that collaboration and team training in immersive VR provide a better environment for discussion and training when compared to a desktop-based solution [4], [5].

In the real world, an instructor or a guide often leads a group to different locations or rooms. The guide also often asks group members to stand in a configuration that is suitable for communication and interaction, e.g., a circular arrangement that allows everyone to get a good view of a presented object. Inspired by such situations, group navigation is also discussed for VR. Group navigation allows users to create a spatial arrangement, explore, and travel together at the same time [6], [7]. While many navigation techniques have been investigated for single-user VR, only a few techniques are concerned with navigation as a group [8]–[10]. The most common approach for navigation in collaborative VR environments is to allow each user to navigate individually using single-user techniques. A strong advantage of group navigation is *group formation*, which supports collaboration and team building and, in particular, helps to establish and assign roles for team training [11], [12].

In this work, we present a group navigation technique based on a *World-in-Miniature*, hereafter referred to as *group WiM* (see Fig. 1). A collaborative VR environment based on the real world example of medical training and planning was designed to assess the usability and comprehensibility of the proposed technique [13]. We enhanced a pilot study design [14], which had only one real user in each session, by supplementing user roles of group guide and members to perform together at the same time. A user study was conducted in comparison with the state-of-the-art technique, *group teleportation* [15]. The

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contributions are:

- Results of a user study ($n = 20$) providing insights on usability, discomfort, and user performance.
- Exploratory analysis of qualitative feedback to identify the perceived advantages, disadvantages, and potential research directions for group navigation.
- Development of a group WiM navigation technique for collaborative VR environments.

II. Related Work

Navigation in a virtual environment is one of the most common forms of interaction and is an essential element for providing an immersive experience [16]. A navigation technique is a combination of two components: a cognitive component *(wayfinding)* that allow the users to control and change their movements and viewpoints, and a motoric component *(travel)* [17], [18]. Various navigation techniques have been investigated, including redirected walking and virtual travel [8], [19]. In the following sections, we provide an overview of two main categories of navigation techniques: individual and group navigation.

A. Individual Navigation

Most recently developed VR headsets are equipped with tracking systems that allow users to navigate by physically walking within a tracking area. Navigation based on the physical movement of the user's body is beneficial for enabling a high degree of presence [20]–[22]. Redirected walking is widely used to navigate within limited tracking spaces [23], [24]. This navigation technique manipulates the physical path of the user's movements by introducing imperceptible rotations to the virtual environment [25]–[27].

Virtual travel techniques usually require less physical space and are adapted for travel even over long distances in the virtual environment [28]. There are two common types of virtual travel techniques: target-based (also known as teleportation) and steering-based approaches. Target-based virtual travel techniques allow the user to specify the target and instantaneously teleport the user to the specified target [29], [30]. The transition between the current location to the target location can be instant, smoothly animated, or multi-stepped interpolation [31]–[33]. However, it can be inconvenient for exploration and the spatial awareness of the user due to missing information along the route [34]. Steering-based travel techniques refer to continuous motion that requires the specification of direction and movement speed continuously [18]. They usually follow metaphors, e.g., driving and flying, where the travel can be controlled through controllers or by tracking the user's body posture, hand, or gaze [35], [36].

A WiM is a duplicate of the entire virtual environment in a scaled-down size [37], [38] and can be used to support travel. Navigation based on this miniature provides a third-person viewpoint in addition to the user's viewpoint within the virtual environment [39]–[41]. Thus, the user can interact, scale, and rotate the WiM to observe the environment from any angle. Furthermore, it allows users to quickly navigate to any point in the virtual environment without any restrictions concerning the line of sight or availability of physical space [39]. Changes on the WiM will be simultaneously applied to the original environment [42]. For example, users can move objects in a full-scale environment using the WiM. Berger et al. [43] compared three locomotion techniques, including continuous motion, teleportation, and WiM-based locomotion. Their results indicate that single-user navigation with WiM outperforms the other techniques regarding task completion time for longer distances. Moreover, it provides a good overview and causes the least motion sickness among other techniques. In addition, Elvezio et al. [44] demonstrated an interaction technique that allows the user to point at the WiM and perform navigation with an avatar. They also highlighted the benefits of using WiM and pre-orientation of the avatar to reduce effort and task completion time.

Other approaches, such as manipulation-based, portal, and mini-map techniques enable users to travel by object manipulation, marked point, virtual scene interaction, or direct manipulation of the user's viewpoint [45]–[50]. While many works suggest the strength of a stand-alone navigation technique, there are also advantages of technique combination, e.g., teleportation and WiM [51], [52].

B. Group Navigation

Users collaborating in VR often have common interests. However, when navigation is performed by individuals, difficulties can arise, such as unnecessary allocation for navigation by each member and a risk of losing each other [6]. Buck et al. [53] investigated navigation in pairs in a shared virtual environment. Their results indicate that navigating as a group outperforms individuals in the acquisition of survey knowledge. Liu et al. [12] compared social VR platforms using a guided group walk-through method. Spatial navigation problems were found when individuals are free to move, e.g., overlapping of avatars when approaching others. Kolesnichenko et al. [54] presented design approaches to characterize avatars and allow users to form groups using commercial social VR platforms.

Navigation in co-located physical space often leads to spatial desynchronization [55]. For example, the voice of co-located users in the real world comes from different directions, while other users expect it to be based on the virtual position of the avatars. Moreover, voice synchronization between the real world and virtual environment can be delayed, and collisions between users can occur. Other studies [56], [57] also reported difficulties with individual navigation regarding staying together, understanding spatial references, and sharing experiences. Group navigation techniques should be assessed as to how co-located or remote users can travel as a single entity in a similar way to a virtual vehicle [15].

Group navigation aims to allow the group to stay together while only one user, a guide, is responsible for the creation, formation, and control of travel. Weissker and Froehlich [15] proposed a group navigation technique based on teleportation for guided tours. Four main requirements were described for the group navigation technique: comprehensibility, obstacle

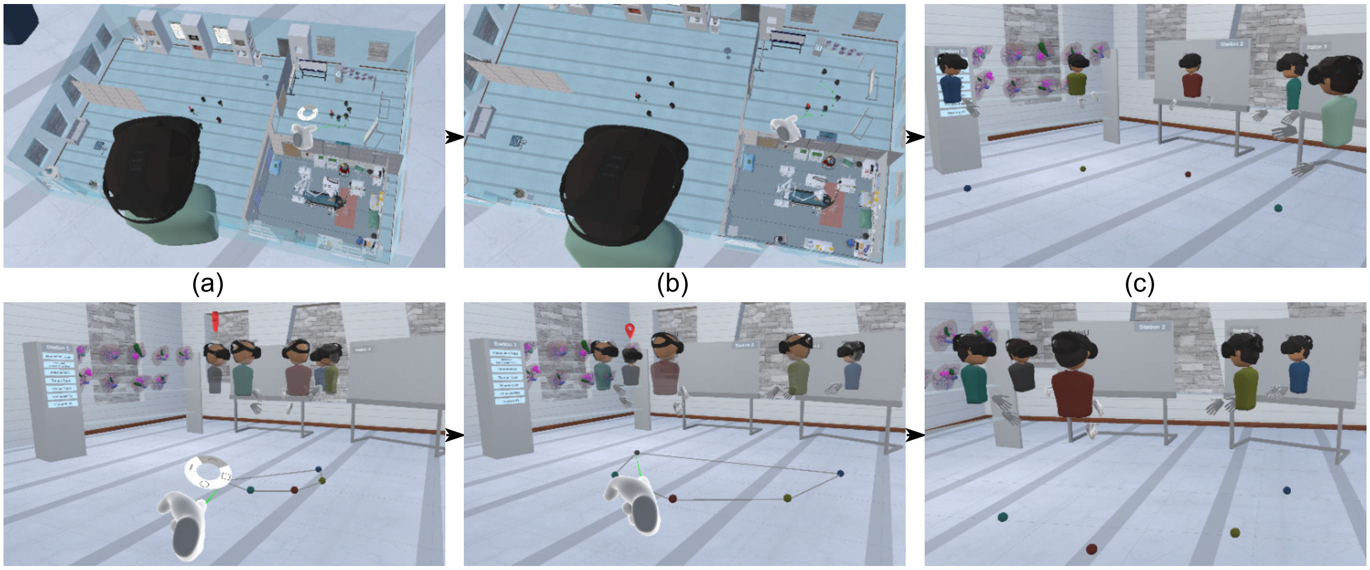


Fig. 2: Group navigation techniques based on WiM (top) and teleportation (bottom). (a) The guide uses the controller's touchpad to choose a group formation and specify the destination. (b) After pressing down on the touchpad, a group formation is chosen, e.g., a half-circle formation. The guide can adjust the spatial extent of group arrangement by radial swipes on the touchpad. Moreover, using the roll angle of the controller allows the guide to rotate the group arrangement. (c) The navigation is executed by pressing the trigger button, and the group will be transported to the destination.

avoidance, view optimization, and formation adjustments. Their proposed technique also allows users to choose pre-defined formations for navigation.

III. Design of a Group WiM Navigation Technique

A WiM represents the entire environment, including mimicked objects and avatar representations, that perform as a proxy to the original environment. The group WiM aims to allow the guide full control for navigational support. In the following sections, we provide more insights into the design and development process.

A. Group Representation and Preview Avatars

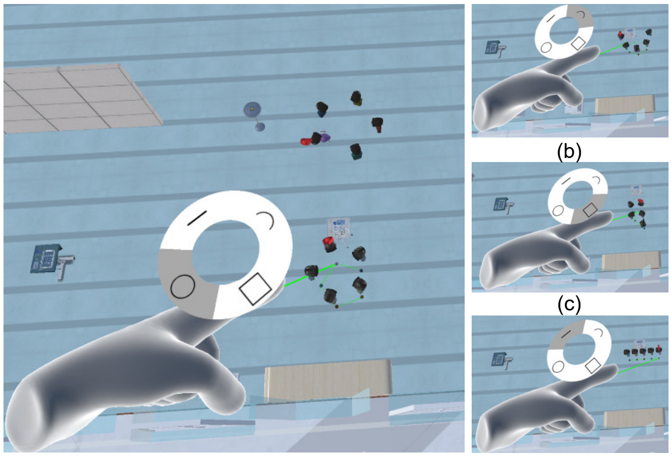
Each user is represented by an avatar with a virtual head wearing a head-mounted display, a virtual body with randomized color, and virtual hands. As the avatar's body and head are floating, a small sphere with the same color as the user's shirt is attached below the body to represent the current position on the floor. Moreover, a name tag is highlighted and a chat icon appears over the virtual head when the user engages in voice communication. Preview avatars of the group are highlighted with semi-transparent colors of their shirts during the navigation procedure. Additionally, a convex-hull line is displayed according to the positions of the users and group formations. In addition to the name tag, the user can identify their preview avatar during the travel operation with a location icon that appears on top of the virtual head.

B. Group Navigation

In the initial stage, the group gathers in the virtual environment. One user has the role of a guide, and the other users are assigned as group members. Therefore, the guide can enable the WiM and explore an overview of the entire environment with the members. This can be performed by pressing the menu button on the controller. Once the WiM is enabled, the guide can interact with this miniature by, for instance, grabbing and scaling using the controller's grip buttons. The group navigation procedure starts with the target and group arrangement specification, spatial extent adjustment, and group travel. Fig. 2 provides an overview of the procedure. The workflow for group WiM is described in the following.

1) Target and Group Arrangement Specification: To specify the target destination, the guide touches the controller's touchpad. Ray casting is used to determine the destination point on the WiM from the virtual hand's index finger. Furthermore, while touching the controller's touchpad, a radial menu appears on the touchpad to show the options for the group arrangement (see Fig. 3). There are four pre-defined formation types, similar to those proposed by Weissker and Froehlich [15], i.e., circle, half-circle, grid, and line (queue) formations. The guide can choose one of them by pressing down on the touchpad. In addition to the avatars that represent the users in the WiM, there are also preview avatars and a convex-hull line representation that represent the group when the guide chooses a group formation.

2) Group Arrangement Adjustment: When a formation is chosen, the guide can further adjust the spatial extent and rotation of the group arrangement (see Fig. 2b). Spatial extent adjustment is performed with radial swipes on the controller's touchpad [58]. The preview avatars and convex-hull line are scaled up and down based on swipes with a clockwise and



(a) (b) (c) (d)

Fig. 3: Group arrangement with four pre-defined formations can be chosen during target specification: (a) circle, (b) half-circle, (c) grid, and (d) line (queue).

(a) (b)

Fig. 4: Obstacle avoidance and additional mini-map for group members. (a) During the technique procedure, if the preview convex-hull line collides with obstacles, it will be highlighted in red and will prevent the travel. (b) A group member can enable a mini-map on a virtual tablet for an overview of the environment and the target destination.

counter clockwise direction. The guide can rotate the group by rotating their controller in the roll angle's direction.

The view directions of preview avatars are refined such that they are looking into the centroid. This is beneficial, especially for discussion after arriving at the destination. In this way, users do not need to rotate and find other users. However, we changed the view directions of preview avatars for the line formation so that users are standing in a queue, as proposed by Weissker and Froehlich [15].

a) Obstacle Avoidance: A *mesh collider* was attached to the preview convex-hull line and the mesh geometries in the virtual environment. As shown in Fig. 4a, if the guide moves the group such that it collides with the wall, the convex-hull line will be highlighted in red color and the travel will be prevented.

b) Notifications: In addition to the WiM representation, the group members will be notified via a controller's vibration once the guide chooses a group formation. Furthermore, the group members can use a mini-map on a virtual tablet if they press the controller's trigger button (see Fig. 4b). Our idea of using a mini-map would further support the understanding of navigational procedures and spatial arrangement. In this case, a virtual camera is placed above the WiM to generate a render texture for the mini-map.

3) Group Travel: During the procedure, the guide can release the thumb on the controller's touchpad. This allows for the exploration of the preview group arrangement in detail and adjustments to be made if needed. If the guide is satisfied with the current arrangement, the travel can be executed by pressing the controller's trigger button. This can also be applied when the guide is touching the touchpad, in case they want to travel instantly. However, if the guide is not satisfied with the current arrangement, this can be aborted without travel by pressing one of the controller's grip buttons.

IV. Evaluation

A user study was conducted to evaluate the proposed technique in a comparison with a reference group teleportation (see Fig. 2). The implementation of the group teleportation was based on Weissker and Froehlich [15]. Two real users were asked to pair as a group in one session, and additional three simulated users were added to provide a more realistic group size of five. Our key research questions are the following:

- RQ1 To which extent is group WiM more comprehensible compared to group teleportation in collaborative VR environments?
- RQ2 To which extent do group navigation techniques induce different degrees of discomfort for the guide and group members?
- RQ3 What are the perceived advantages and disadvantages of each group navigation technique?

A. Setup

A collaborative VR environment was developed with six navigational destinations and different formation patterns (see Fig. 5). To avoid bias due to learning effects, the starting location, the size of formation patterns, and position for start/stop buttons were randomized. Moreover, the order of group navigation was counterbalanced. The navigational directions also alternated between clockwise and counter clockwise directions. Once the first technique is initiated with clockwise navigational direction, the second technique begins in the reverse. Additionally, a small table with a yellow button to start and stop the task was randomized between 20 cm and 50 cm around the target position, indicated with dark-red color (see Fig. 7).

The *Unity* game engine (version 2019.4.34f1) was used for system development. A corresponding server was set up to provide services, including load-balancing and *Photon networking*, for a shared network session and data synchro-

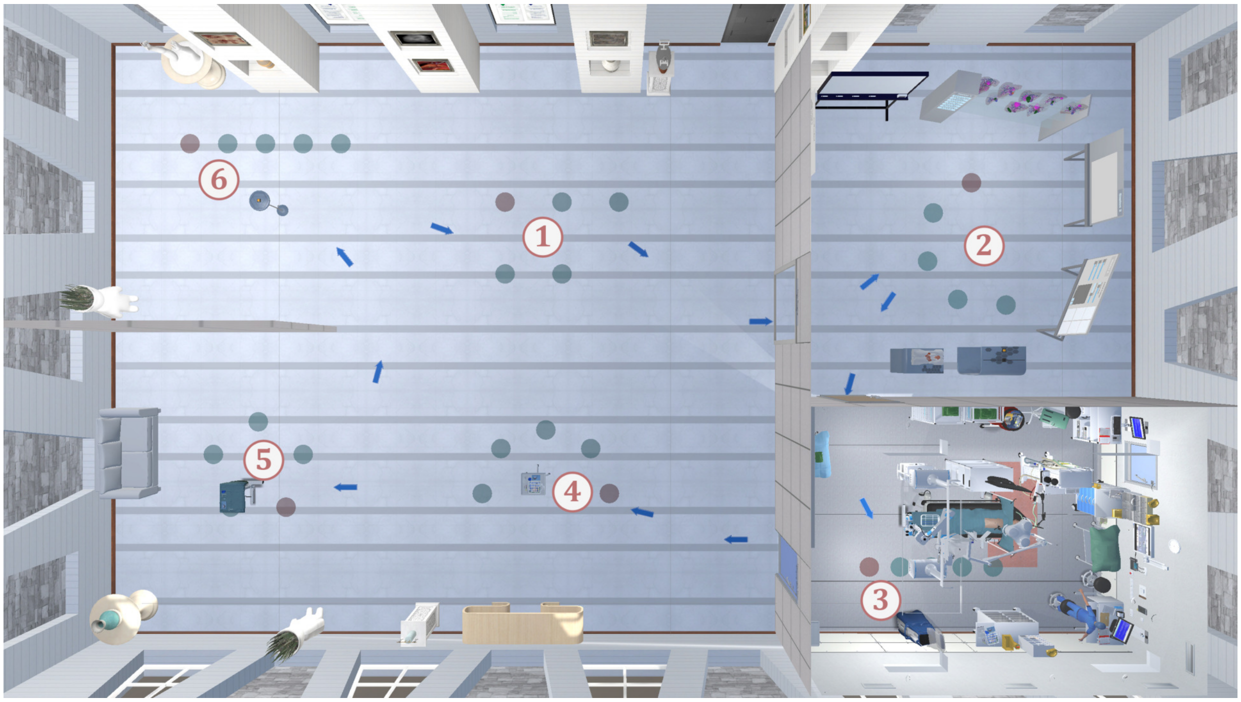


Fig. 5: Top view of a complex collaborative virtual environment targeted for medical training and planning used in the experimental study. In this case, the starting locations, navigational directions, start/stop buttons, and size of formation patterns were randomized.

nization. The server was running *Windows Server 2019*, on an Intel Xeon @2.49 GHz processor, with 16 GB RAM.

B. Independent Variables

The study was planned as a within-subject design with a two-factor test. The two factors were defined by independent variables: *navigation technique* and *difficulty*. The variable *navigation technique* consisted of two techniques: group WiM and group teleportation. *Difficulty* refers to the levels of difficulty of navigational path for reaching the target destinations. It has three levels: *easy*, *medium*, and *hard*. The easy level refers to the navigational path of the target destination that appears in front of user's line of sight, e.g., the path from the fourth to the fifth and the sixth to the first destination. The medium level refers to the path that has an obstacle and where the user must take a detour, e.g., the path from the first to the second and the fifth to the sixth destination. The hard level indicates the path that has a blocked obstacle, i.e., a closed door in between, which requires user interactions, e.g., the path from the second to the third and the third to the fourth destination.

C. Dependent Variables

During each navigational task, we measured data which were defined as dependent variables, including *task completion time* and *placement error*. The *task completion time* was recorded when users pressed down the button to start at their current location until arrival at the destination, where they pressed down the nearby button to stop the task. The navigational task was also designed to place the group as close to the targets' center as possible. Based on this placement, the *placement error* is calculated according to the average center distance of projected spheres on the floor (see Fig. 7). In addition to the variables for statistical analysis, we recorded *number of jumps* that we analyzed descriptively. The number of jumps describes how many times the user navigates the group to the target destination until it meets their satisfaction by pressing down the stop button.

Two additional dependent variables were measured from the questionnaires: *usability* and *discomfort scores*. The system usability scale (SUS) questionnaire was used to evaluate the usability [59]. Only the group guides answered the usability questionnaire because they were conducting the interactions we aimed to assess. The questionnaire consists of ten questions with a five-point Likert-scale ranged from *strongly disagree* to *strongly agree*. The evaluation for this usability scale was converted to a range between 0–100% (0–50%: not acceptable, 51–67%: poor, 68%: okay, 69–80%: good, 81–100%: excellent) [60].

To evaluate the discomfort, a standardized simulator sickness questionnaire (SSQ) was used [61]. This questionnaire has 16 items with a four-point scale. Each item represents a possible symptom from none to severe condition. Because the order of the techniques was counterbalanced, and the possible symptoms could be influenced by the first technique, we decided to use the SSQ questionnaire only before (pre-SSQ) and after (post-SSQ) evaluating the first method. Thus,

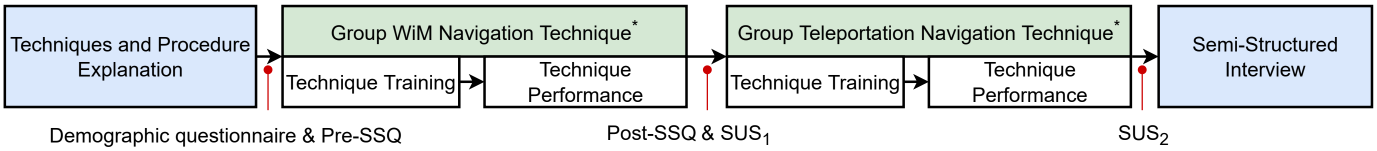


Fig. 6: Procedure of the user study. The order of the group navigation techniques (marked with *) was counterbalanced. During both technique performance steps, participants were asked to switch the user roles between the guide and group members. Thus, they both took turns at being guides and group members for both techniques. The discomfort was evaluated with the simulator sickness questionnaire (SSQ), and it was used only before (pre-SSQ) and after (post-SSQ) evaluating the first technique. The usability was assessed with the system usability scale questionnaire (SUS).

the analysis of discomfort was measured as a between-subject design. For *discomfort scores*, both user roles answered these questionnaires.

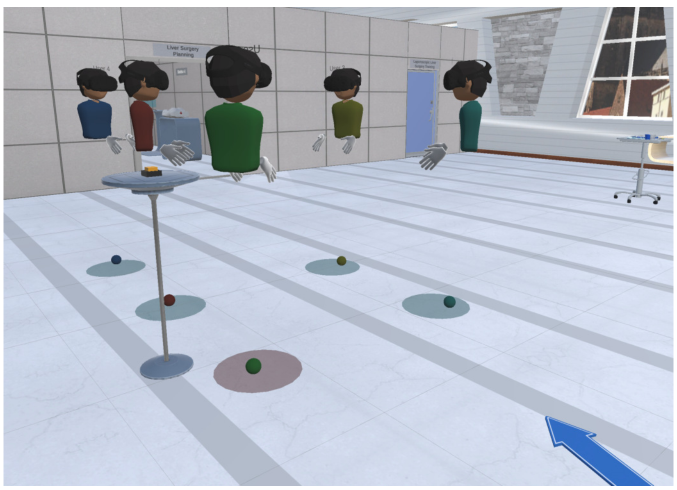


Fig. 7: The tasks include group placement in specific formation patterns and spatial arrangements. The positions of the guide and members are projected with the small spheres shown on the floor, which were used to calculate placement error.

D. Study Procedure

An overview of the study procedure is shown in Fig. 6. First, we introduced the study objective, group navigation techniques, and study procedure. The participants gave their consent in a signing form. They were also asked to answer the demographic and discomfort questionnaires (Pre-SSQ). Afterwards, the participants were introduced to the first navigation technique. The order of the techniques was counterbalanced. The procedure started with training in a different virtual environment. In this environment, the participants were introduced to simulated users and asked to try all the features, interactions, and navigation possibilities. The simulated users are predefined group members with basic animations to supplement the group size. The interactions included the group navigation procedure and interactions with the start/stop buttons.

1) Tasks: After the training, the participants were asked to join the collaborative VR environment (see Fig. 5). There were six navigational tasks. Once the start button was pressed down, the formation pattern and navigational arrows appeared. One participant was asked to perform as the guide. Thus, the task was to create a group formation and assign the group to each target destination according to its formation pattern and spatial arrangement. They could travel several times to reach the destination. After placing the group into the formation pattern and traveling to the destination, the users' task was to find and press the yellow button on the small table nearby. This would stop the current task. Once they pressed down this button, the task for the next target destination could be initiated.

After participants completed all navigational tasks, they were asked to take the VR headsets off and answer the mid-questionnaires, including discomfort (Post-SSQ) and usability questionnaires. At this point, the participants were asked to switch user roles and perform the tasks again, so they took turns at being the guide and group members in each technique performance.

Afterwards, the second group navigation technique was introduced. This followed the same procedure with the technique training and actual performance, and following the last technique phase, users were asked to answer only the usability questionnaire.

2) Semi-structured Interview: We conducted the semi-structured interview after the exploration and performance of the two group navigation techniques. The interviewer made notes of all relevant comments from the participants. The following questions were asked during the interview:

- What is your overall impression?
- What are the perceived advantages and disadvantages for group WiM and group teleportation techniques?
- Do you have any questions or comments?

E. Data Analysis

As described in *Tasks* (Sec. IV-D1), the participants were asked to complete six navigational tasks with three levels of *difficulty*. The tasks of each *difficulty* were conducted twice by each participant, thus, we calculated the mean value for navigational tasks with identical experimental conditions before any other tests. Four trials were removed for further analyses because of placement errors higher than one meter. Such large inaccuracies indicated user input errors and were, thus, considered outliers. Because of accumulated data of identical conditions for each participant, no data gaps resulted from this removal. RStudio with R was used for statistical computing. Data analysis was conducted using an analysis of variance (ANOVA) for two dependent variables: *task completion time* and *placement error*, paired t-tests for *usability*, and descriptive analysis for the additional variables, including *number of jumps* and *discomfort*. The *discomfort* was evaluated by calculating the differences between the pre- and post-SSQ questionnaire results for all scales for both guides and group members, as suggested by Bimberg et al. [62].

For qualitative participant feedback, the comments were collated into a common database and the redundancies were removed. Three main categories were defined: group teleportation, group WiM, and general feedback. Additionally, three subcategories were identified based on the semi-structured interview: perceived advantages, disadvantages, and suggestions to further improve the technique's usability. One author (*VC*) was responsible to cluster the information into the relevant categories.

V. Results

In the following sections, we describe the characteristics of the participants and results measured in the user study, including user performance and questionnaire data, as well as the qualitative participant's feedback. The total average time of the study was $105.6\,\text{min}$ ($SD = 19.69$), while the average time for the first training took $11.32\,\text{min}$ ($SD = 6.23$) and $5.76\,\text{min}$ ($SD = 1.69$) for the second technique.

A. Participants

20 participants (14 male and 6 female) participated in the user study. They were between 21 and 33 years old (median = 26 years old). 16 of them had a background in computer science, two in mechanical engineering, and two in medical engineering. All participants had previous VR experience, 9 participants were reported as having little (used VR a few times only); 8 having much VR experience (used VR several times); and 3 consider themselves as experts. One of them was left-handed.

The participants were asked to pair as a group that consists of two real users in one session. In each technique performance, they were asked to switch user roles between the guide and group members. Each participant received a compensation of 30 EUR for their participation.

B. Statistical Results (RQ1)

The summary of the descriptive results for the dependent variables of user performance is listed in Table I. The results of the statistical analyses with ANOVAs are listed in Table II. Statistically significant effects were found regarding the task completion time for the *difficulty* factor ($p < 0.007$). We further analyzed the influence of difficulty on task completion time with pairwise t tests and the Bonferroni adjustment method for each technique. The results reveal that there was a significant difference between the easy and hard levels ($t = -2.80$, $df = 19$, $p < 0.034$) in the group teleportation (see Fig. 8) It could indicate that task completion time significantly increased with higher difficulty levels. However, we found no significant technique main effect and no significant interaction effect. For *placement error*, no significant differences were found. The results show a small difference between both techniques. It is also noteworthy that the group WiM accuracy stayed almost the same for each difficulty, while it decreased between difficulty levels for the group teleportation.

For *usability*, the SUS questionnaire results from all participants show an average score of 78.8 (SD = 15.80) for group teleportation and 80.40 (SD = 12.60) for group WiM. We further analyzed the usability results with paired t-tests. No significant differences were found between the techniques ($t = -0.49$, $df = 19$, $p = 0.627$). The SUS score for the proposed technique higher than 68 is above average, which indicates potential benefits in terms of usability.

C. Discomfort Scores (RQ2)

The discomfort scores were calculated with the pre- and post-SSQ questionnaires (see Fig. 9). The average total score for the group teleportation is $M = 5.24$ ($SD = 9.74$) for the guide and $M = 9.72$ ($SD = 14.40$) for group members. For group WiM, the average total score is $M = 8.23$ ($SD = 10.40$) for the guide and $M = 2.99$ ($SD = 14.80$) for group members. Both techniques induced discomfort symptoms. The average scores are lower for the guide's role in the group teleportation. For member's role, the average scores are lower in the group WiM.

D. Qualitative Participant Feedback (RQ3)

A total of 352 individual statements were received from all participants. In the following, we summarize the qualitative feedback in its relevant categories.

1) Group Navigation Techniques: The participants agreed that using group navigation is useful and beneficial for navigating users together, especially for training and educational purposes. They stated that both techniques were understandable with preview avatars and pre-defined formations.

a) Group Teleportation Technique: 16 participants stated that the group teleportation could provide presence and spatial understanding of the environment. This is because it was more direct and provides an impression of navigational paths during travel. The placement of the group could provide a good understanding of the target destination with preview avatars and could be performed directly. Five participants stated that the group teleportation requires multiple steps if the target is a large distance away or is blocked by obstacles. Moreover, seven participants noted the adjustment of the group arrangement as challenging. Because they had to concentrate and spend more time to place the group into the correct formation pattern and rotation. This was particularly true when the group was significantly far from, or too close to, the target destination. Six participants mentioned some discomfort symptoms, especially disorientation, while performing as the group members. This could be an issue with the automatic viewpoint changing. They emphasized that their viewpoints were somehow changed in a way that they were not expecting.

TABLE I: Summary of descriptive results for all dependent variables of user performance ($n = 20$).

Variable	Task Completion Time (s)	Placement Error (m)	Number of Jumps
Group Teleportation	52.10 (21.50) [2.78]	0.105 (0.034) [0.004]	2.38 (0.72) [0.09]
Easy	45.98 (19.93) [4.45]	0.107 (0.034) [0.008]	1.75 (0.50) [0.11]
Medium	53.19 (24.08) [5.38]	0.101 (0.032) [0.007]	2.47 (0.61) [0.13]
Hard	56.97 (19.84) [4.43]	0.108 (0.037) [0.008]	2.90 (0.52) [0.11]
Group WiM	47.40 (25.80) [3.33]	0.106 (0.033) [0.004]	1.02 (0.11) [0.01]
Easy	45.32 (29.15) [6.51]	0.105 (0.031) [0.007]	1.02 (0.11) [0.02]
Medium	47.74 (25.21) [5.63]	0.106 (0.036) [0.008]	1.02 (0.11) [0.02]
Hard	49.04 (23.87) [5.33]	0.107 (0.032) [0.007]	1.02 (0.11) [0.02]

All entities are in the format: mean value (standard deviation) [standard error].

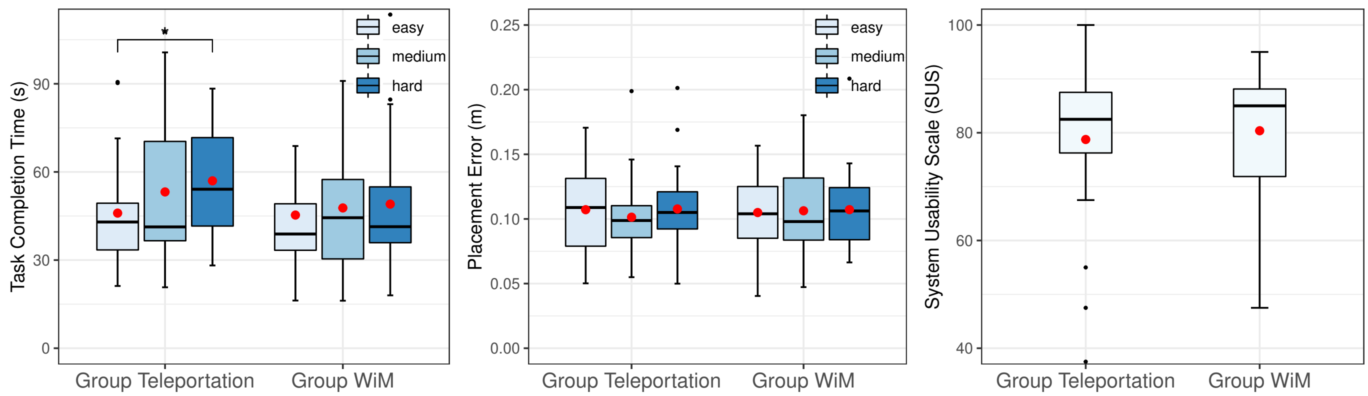


Fig. 8: Results for dependent variables: task completion time (left), placement error (middle), and usability (right). (*Red dots are mean values.*)

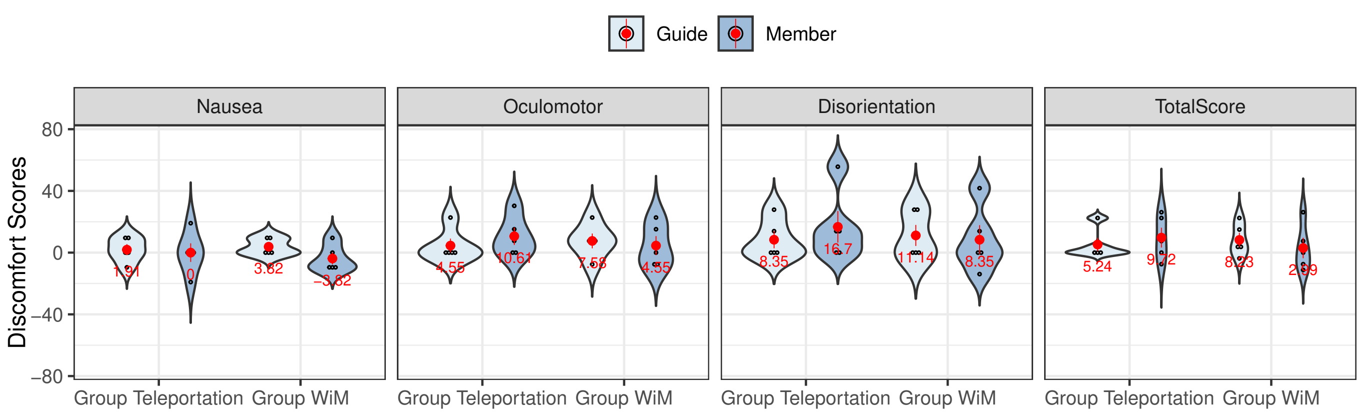


Fig. 9: Results of discomfort scores visualized in violin plots. Positive values indicate increased scores of a discomfort symptom comparing between the pre- and post-SSQ questionnaires (*red dots are the mean values*).

b) Group WiM Technique: 20 participants stated that the group WiM provides a good overview of the environment. 17 participants stated that navigation with this technique was intuitive and flexible, and that they could adjust the group arrangement easily, especially for the group guide. Additionally, this could provide the understanding of their current locations in the environment. Navigation was also faster in the complex navigational path. Seven participants did not have much discomfort while performing as the group members. They stated that they were concentrated on the WiM and might have already built a mental map before navigation. However, eleven participants stated that using the WiM requires more interactions, for example, interactions that enable more exploration, and could be one of the reasons that discomfort was induced for the guide.

There were also difficulties when users wanted to place the group in the precise formation pattern and needed to scale the WiM up. Five participants commented that the WiM might provide less understanding and realism of the spatial environment, as most of the time was spent on the WiM. Despite this,

TABLE II: Summary of statistical results for dependent variables of user performance data ($p < .05$).

Variable	df	F	p	Sig	η^2
Task Completion Time					
Technique	1	0.742	0.399		0.007
Difficulty	2	5.647	<0.007	*	0.023
Technique * Difficulty	2	1.090	0.346		0.007
Placement Error					
Technique	1	3.958	0.061		0.028
Difficulty	2	1.734	0.190		0.029
Technique * Difficulty	2	1.736	0.189		0.031

they were able to build a mental map of the environment. Two participants, the experienced VR users, suggested a scaling limitation for the WiM. It was noted that it might be confusing if the WiM is scaled up to such a degree that it reaches the same size as the original environment. Nonetheless, all participants agreed that this technique is essential in guiding and navigating users in the complex VR environment.

2) General Feedback: The participants were positive regarding the use of the group navigation technique. They had difficulties and some confusion at the training stage, causing the training time of the first technique to be quite long. After several instances of navigation, however, users stated that they could adapt to the concept and interactions. They expressed that it was difficult to place the group precisely inside the strict formation pattern with pre-defined circles, while in a real use-case, it actually might be unnecessary. The participants stated that both techniques have advantages, for instance, teleportation could provide a better spatial understanding of the navigation path. However, it could induce discomfort symptoms for group members. The WiM could provide an overview and arrange the group faster. Nonetheless, it might require more interactions. Five participants commented that a combination of both of them would be highly beneficial for the guide to control and navigate the group more effectively.

VI. Discussion

The proposed technique was evaluated in a comparative user study with a reference group teleportation. The user performance was measured for both user roles (*RQ1*). Significant effects were only found on the task completion time for the *difficulty* factor. However, no statistically significant effects were found on the technique main effect and placement error. The results show that the task completion time significantly increased with higher level of difficulty. The medium and hard levels required more jumps than the easy level in the group teleportation. This could indicate that the users navigated closer to the target destination and placed the group more precisely.

The discomfort results between pre- and post-SSQ questionnaires show that both techniques induced some discomfort symptoms (*RQ2*). Average scores of nausea symptom for the guide are higher than the group members in both techniques. Positive values indicate the increased discomfort by comparing the pre- and post-SSQ questionnaires. Some participants stated that they had to interact with the WiM to assign and adjust the group, while they could easily point to the floor in the group teleportation. When they performed as the group members with group teleportation, however, they noticed the disorientation after the group travel. For group WiM, they stated it was better. One reason might be they were focused on the WiM and already built a mental map before the navigation process. Partially because of the between-subject design chosen for collecting the SSQ data, the sample is too small to draw meaningful comparative conclusions. Investigating the induced discomfort of users in group navigation more closely would be an interesting follow-up project.

The qualitative feedback shows the potential benefits and limitations of both navigation techniques (*RQ3*). Preview avatars and the convex-hull line representation were helpful in indicating the group arrangement at the target destination. The group WiM could thus provide full control and a good overview of the environment, which would be beneficial for the guide and navigation in complex virtual environments and over longer distances. The group teleportation provides a good understanding of the spatial environment and navigational path. As suggested by Berger et al. [43], choosing the right VR navigation technique should depend on the scenario and use case. A combination of both techniques shows the additional potential for effective group navigation [51].

The evaluation results provide insights into the effect of the techniques. Despite being a collaborative VR design, users were not actually collaborating, thus, two real users were joined with three additional simulated users in each session in this study. The results show that only for the *difficulty* factor of the task completion time was a statistically significant effect found. However, it could be essential to study the techniques with the group scalability, for example, high numbers of real users, and real use cases.

Applying artificial intelligence (AI) with group navigation could be interesting and beneficial for future investigation. For example, predicting group members attention during navigation could enhance user experiences and improve efficiency for interaction tasks [63]. Further research on trajectory and obstacle prediction could be beneficial for group navigation [64], [65]. Using sketch-based interactions to suggest group arrangements with collision avoidance could improve the WiM-based navigation technique [66]. Furthermore, AI techniques could be useful to optimize and calculate optimal group forming patterns and spatial arrangements [67], [68]. Future studies should also investigate the group navigational procedure in detail and compare it to different techniques, e.g., redirected walking [20] and steering [69] techniques would be beneficial. For group WiM, a group arrangement specification was developed similar to Weissker and Froehlich [15]. Nonetheless, the group formation for WiM can be achieved by other approaches, e.g., manipulation-based approaches to arrange the group [39], [43].

VII. Conclusion

We have presented a WiM-based group navigation technique, *group WiM*, to support group arrangement and navigation in collaborative VR environments. The WiM performs as a proxy to the entire environment, and it provides full control for navigation. A comparative evaluation was conducted to investigate user performance, usability, and discomfort of our proposed technique compared to a reference group teleportation. The group WiM could be an effective navigation tool in the collaborative VR, and especially for the complex virtual environments. Further comparison and evaluation of group forming and navigation with different techniques and group scalability for real use cases could be essential for future research. Combination with AI to predict user attention and optimize spatial arrangements for group navigation could be interesting as well.

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REFERENCES

[1] R. Anthony J. de Belen, H. Nguyen, D. Filonik, D. Del Favero, and T. Bednarz, "A systematic review of the current state of collaborative mixed reality technologies: 2013–2018," *AIMS Electronics and Electrical Engineering*, vol. 3, no. 2, pp. 181–223, 2019.

[2] V. Chheang, V. Fischer, H. Buggenhagen, T. Huber, F. Huettl, W. Kneist, B. Preim, P. Saalfeld, and C. Hansen, "Toward interprofessional team training for surgeons and anesthesiologists using virtual reality," *International Journal of Computer Assisted Radiology and Surgery*, vol. 15, no. 12, pp. 2109–2118, 2020.

[3] R. Q. Mao, L. Lan, J. Kay, R. Lohre, O. R. Ayeni, D. P. Goel *et al.*, "Immersive virtual reality for surgical training: a systematic review," *Journal of Surgical Research*, vol. 268, pp. 40–58, 2021.

[4] R. Liu, X. Wen, M. Jiang, G. Yang, C. Zhang, and X. Chen, "Multiuser collaborative illustration and visualization for volumetric scientific data," *Software: Practice and Experience*, vol. 51, no. 5, pp. 1080–1096, 2020.

[5] P. Wang, X. Bai, M. Billinghurst, S. Zhang, X. Zhang, S. Wang, W. He, Y. Yan, and H. Ji, "AR/MR Remote Collaboration on Physical Tasks: A Review," *Robotics and Computer-Integrated Manufacturing*, vol. 72, p. 102071, 2021.

[6] T. Weissker, P. Bimberg, and B. Froehlich, "An overview of group navigation in multi-user virtual reality," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2021, pp. 363–369.

[7] S. Beck, A. Kunert, A. Kulik, and B. Froehlich, "Immersive group-to-group telepresence," *IEEE transactions on visualization and computer graphics*, vol. 19, no. 4, pp. 616–625, 2013.

[8] M. Di Luca, H. Seifi, S. Egan, and M. Gonzalez-Franco, "Locomotion vault: the extra mile in analyzing vr locomotion techniques," in *Proc. of CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–10.

[9] Y. M. Kim, Y. Lee, I. Rhiu, and M. H. Yun, "Evaluation of locomotion methods in virtual reality navigation environments: An involuntary position shift and task performance," *International Journal of Human-Computer Studies*, vol. 155, p. 102691, 2021.

[10] C. Boletsis and J. E. Cedergren, "Vr locomotion in the new era of virtual reality: an empirical comparison of prevalent techniques," *Advances in Human-Computer Interaction*, vol. 2019, pp. 1–15, 2019.

[11] T. Weissker, P. Bimberg, and B. Froehlich, "Getting there together: Group navigation in distributed virtual environments," *IEEE transactions on visualization and computer graphics*, vol. 26, no. 5, pp. 1860–1870, 2020.

[12] Q. Liu and A. Steed, "Social virtual reality platform comparison and evaluation using a guided group walkthrough method," *Frontiers in Virtual Reality*, vol. 2, p. 668181, 2021.

[13] V. Chheang, D. Schott, P. Saalfeld, L. Vradelis, T. Huber, F. Huettl, H. Lang, B. Preim, and C. Hansen, "Towards virtual teaching hospitals for advanced surgical training," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2022, pp. 410–414.

[14] V. Chheang, F. Heinrich, F. Joeres, P. Saalfeld, B. Preim, and C. Hansen, "Group WiM: A group navigation technique for collaborative virtual reality environments," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2022, pp. 556–557.

[15] T. Weissker and B. Froehlich, "Group navigation for guided tours in distributed virtual environments," *IEEE Transactions on Visualization and Computer Graphics*, vol. 27, no. 5, pp. 2524–2534, 2021.

[16] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev, "An introduction to 3-d user interface design," *Presence*, vol. 10, no. 1, pp. 96–108, 2001.

[17] R. P. Darken and B. Peterson, "Spatial orientation, wayfinding, and representation," in *Handbook of virtual environments*. CRC Press, 2002, pp. 533–558.

[18] D. A. Bowman, D. Koller, and L. F. Hodges, "Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques," in *Proc. of IEEE International Symposium on Virtual Reality*, 1997, pp. 45–52.

[19] Y. Zhang, S.-T. Ho, N. Ladévèze, H. Nguyen, C. Fleury, and P. Bourdot, "In touch with everyday objects: Teleportation techniques in virtual environments supporting tangibility," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2021, pp. 278–283.

[20] D. Kim, J.-e. Shin, J. Lee, and W. Woo, "Adjusting relative translation gains according to space size in redirected walking for mixed reality mutual space generation," in *Proc. of IEEE Virtual Reality and 3D User Interfaces (VR)*, 2021, pp. 653–660.

[21] M. Rietzler, M. Deubzer, T. Dreja, and E. Rukzio, "Telewalk: Towards Free and Endless Walking in Room-Scale Virtual Reality," in *Proc. of ACM SIGCHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–9.

[22] G. Bruder, F. Steinicke, and K. H. Hinrichs, "Arch-explore: A natural user interface for immersive architectural walkthroughs," in *Proc. of IEEE Symposium on 3D User Interfaces*, 2009, pp. 75–82.

[23] N. C. Nilsson, T. Peck, G. Bruder, E. Hodgson, S. Serafin, M. Whitton, F. Steinicke, and E. S. Rosenberg, "15 years of research on redirected walking in immersive virtual environments," *IEEE computer graphics and applications*, vol. 38, no. 2, pp. 44–56, 2018.

[24] S. Razzaque, "Redirected walking," Ph.D. dissertation, University of North Carolina at Chapel Hill, 2005.

[25] M. Azmandian, T. Grechkin, and E. S. Rosenberg, "An evaluation of strategies for two-user redirected walking in shared physical spaces," in *Proc. of IEEE Virtual Reality (VR)*, 2017, pp. 91–98.

[26] D.-Y. Lee, Y.-H. Cho, D.-H. Min, and I.-K. Lee, "Optimal planning for redirected walking based on reinforcement learning in multi-user environment with irregularly shaped physical space," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2020, pp. 155–163.

[27] T. Dong, Y. Shen, T. Gao, and J. Fan, "Dynamic density-based redirected walking towards multi-user virtual environments," in *Proc. of IEEE Virtual Reality and 3D User Interfaces (VR)*, 2021, pp. 626–634.

[28] Y. Zhang, N. Ladevèze, H. Nguyen, C. Fleury, and P. Bourdot, "Virtual navigation considering user workspace: Automatic and manual positioning before teleportation," in *Proc. of ACM Symposium on Virtual Reality Software and Technology*, 2020, pp. 1–11.

[29] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, "Point & teleport locomotion technique for virtual reality," in *Proc. of annual symposium on computer-human interaction in play*, 2016, pp. 205–216.

[30] M. Funk, F. Müller, M. Fendrich, M. Shene, M. Kolvenbach, N. Dobbertin, S. Günther, and M. Mühlhäuser, "Assessing the accuracy of point & teleport locomotion with orientation indication for virtual reality using curved trajectories," in *Proc. of ACM SIGCHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–12.

[31] K. Rahimi, C. Banigan, and E. D. Ragan, "Scene transitions and teleportation in virtual reality and the implications for spatial awareness and

sickness," *IEEE transactions on visualization and computer graphics*, vol. 26, no. 6, pp. 2273–2287, 2018.

[32] M. Husung and E. Langbehn, "Of Portals and Orbs: An Evaluation of Scene Transition Techniques for Virtual Reality," in *Proc. of Mensch und Computer*, 2019, pp. 245–254.

[33] B. Bolte, F. Steinicke, and G. Bruder, "The jumper metaphor: an effective navigation technique for immersive display setups," in *Proc. of Virtual Reality International Conference*, vol. 1, 2011, pp. 1–7.

[34] C. G. Christou and P. Aristidou, "Steering versus teleport locomotion for head mounted displays," in *International conference on augmented reality, virtual reality and computer graphics*, 2017, pp. 431–446.

[35] B. Gao, Z. Mai, H. Tu, and H. B.-L. Duh, "Evaluation of Body-centric Locomotion with Different Transfer Functions in Virtual Reality," in *Proc. of IEEE Virtual Reality and 3D User Interfaces (VR)*, 2021, pp. 493–500.

[36] E. A. Suma, S. Babu, and L. F. Hodges, "Comparison of travel techniques in a complex, multi-level 3d environment," in *Proc. of IEEE Symposium on 3D User Interfaces*, 2007, pp. 147–153.

[37] K. Danyluk, B. Ens, B. Jenny, and W. Willett, "A Design Space Exploration of Worlds in Miniature," in *Proc. of ACM SIGCHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–15.

[38] R. Stoakley, M. J. Conway, and R. Pausch, "Virtual reality on a WIM: interactive worlds in miniature," in *Proc. of ACM SIGCHI conference on Human factors in computing systems*, 1995, pp. 265–272.

[39] S. Truman and S. von Mammen, "An integrated design of world-in-miniature navigation in virtual reality," in *Proc. of International Conference on the Foundations of Digital Games*, 2020, pp. 1–9.

[40] P. Abtahi, M. Gonzalez-Franco, E. Ofek, and A. Steed, "I'm a giant: Walking in large virtual environments at high speed gains," in *Proc. of ACM SIGCHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–13.

[41] R. Pausch, T. Burnette, D. Brockway, and M. E. Weiblen, "Navigation and locomotion in virtual worlds via flight into hand-held miniatures," in *Proc. of ACM SIGGRAPH*, 1995, pp. 399–400.

[42] H. J. Kang, J.-h. Shin, and K. Ponto, "A comparative analysis of 3d user interaction: How to move virtual objects in mixed reality," in *Proc. of IEEE conference on virtual reality and 3D user interfaces (VR)*, 2020, pp. 275–284.

[43] L. Berger and K. Wolf, "Wim: fast locomotion in virtual reality with spatial orientation gain & without motion sickness," in *Proc. of International Conference on Mobile and Ubiquitous Multimedia*, 2018, pp. 19–24.

[44] C. Elvezio, M. Sukan, S. Feiner, and B. Tversky, "Travel in large-scale head-worn VR: Pre-oriented teleportation with WIMs and previews," in *Proc. of IEEE Virtual Reality (VR)*, 2017, pp. 475–476.

[45] M. Kraus, H. Schäfer, P. Meschenmoser, D. Schweitzer, D. A. Keim, M. Sedlmair, and J. Fuchs, "A Comparative Study of Orientation Support Tools in Virtual Reality Environments with Virtual Teleportation," in *Proc. of IEEE International Symposium on Mixed and Augmented Reality*, 2020, pp. 227–238.

[46] K. Zagata, J. Gulij, Ł. Halik, and B. Medyńska-Gulij, "Mini-map for gamers who walk and teleport in a virtual stronghold," *ISPRS International Journal of Geo-Information*, vol. 10, no. 2, p. 96, 2021.

[47] C. George, A. N. Tien, and H. Hussmann, "Seamless, Bi-directional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration," in *Proc. of IEEE International Symposium on Mixed and Augmented Reality*, 2020, pp. 412–424.

[48] I. Mahalil, A. M. Yusof, N. Ibrahim, E. M. M. Mahidin, and M. E. Rusli, "Virtual Reality Mini Map Presentation Techniques: Lessons and experience learned," in *Proc. of IEEE Conference on Graphics and Media*, 2019, pp. 26–31.

[49] S. Chen, F. Miranda, N. Ferreira, M. Lage, H. Doraiswamy, C. Brenner, C. Defanti, M. Koutsoubis, L. Wilson, K. Perlin *et al.*, "Urbanrama: Navigating cities in virtual reality," *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–14, 2021.

[50] S. Oberdörfer, M. Fischbach, and M. E. Latoschik, "Effects of VE Transition Techniques on Presence, Illusion of Virtual Body Ownership, Efficiency, and Naturalness," in *Proc. of the Symposium on Spatial User Interaction*, 2018, pp. 89–99.

[51] K. Danyluk and W. Willett, "Evaluating the Performance of Virtual Reality Navigation Techniques for Large Environments," in *Proc. of Computer Graphics International Conference*, 2019, pp. 203–215.

[52] P. Saalfeld, A. Schmeier, W. D'Hanis, H.-J. Rothkötter, and B. Preim, "Student and Teacher Meet in a Shared Virtual Reality: A one-on-one Tutoring System for Anatomy Education," in *Eurographics Workshop on Visual Computing for Biology and Medicine*, 2020, pp. 55–59.

[53] L. E. Buck, T. P. McNamara, and B. Bodenheimer, "Dyadic Acquisition of Survey Knowledge in a Shared Virtual Environment," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2020, pp. 579–587.

[54] A. Kolesnichenko, J. McVeigh-Schultz, and K. Isbister, "Understanding emerging design practices for avatar systems in the commercial social vr ecology," in *Proc. of Designing Interactive Systems Conference*, 2019, pp. 241–252.

[55] J. Lacoche, N. Pallamin, T. Boggini, and J. Royan, "Collaborators awareness for user cohabitation in co-located collaborative virtual environments," in *Proc. of ACM Symposium on Virtual Reality Software and Technology*, 2017, pp. 1–9.

[56] C. Y. Wang, M. Sakashita, U. Ehsan, J. Li, and A. S. Won, "Again, together: Socially reliving virtual reality experiences when separated," in *Proc. of ACM SIGCHI CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–12.

[57] T. Weissker, A. Kulik, and B. Froehlich, "Multi-ray jumping: comprehensible group navigation for collocated users in immersive virtual reality," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2019, pp. 136–144.

[58] A. Kulik, A. Kunert, C. Lux, and B. Fröhlich, "The pie slider: Combining advantages of the real and the virtual space," in *International Symposium on Smart Graphics*, 2009, pp. 93–104.

[59] J. Brooke, "SUS: A quick and dirty usability scale," *Usability evaluation in industry*, vol. 189, 1995.

[60] A. Bangor, P. Kortum, and J. Miller, "Determining what individual SUS scores mean: Adding an adjective rating scale," *Journal of usability studies*, vol. 4, no. 3, pp. 114–123, 2009.

[61] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *The international journal of aviation psychology*, vol. 3, no. 3, pp. 203–220, 1993.

[62] P. Bimberg, T. Weissker, and A. Kulik, "On the usage of the simulator sickness questionnaire for virtual reality research," in *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2020, pp. 464–467.

[63] X. Li, Y. Shan, W. Chen, Y. Wu, P. Hansen, and S. Perrault, "Predicting user visual attention in virtual reality with a deep learning model," *Virtual Reality*, vol. 25, no. 4, pp. 1123–1136, 2021.

[64] N. Bisagno, C. Saltori, B. Zhang, F. G. De Natale, and N. Conci, "Embedding group and obstacle information in lstm networks for human trajectory prediction in crowded scenes," *Computer Vision and Image Understanding*, vol. 203, p. 103126, 2021.

[65] R. A. Saeed, D. R. Recupero, and P. Remagnino, "Simulating people dynamics," in *Proc. of International Conference on Intelligent Environments (IE)*, 2021, pp. 1–8.

[66] A. Colas, W. van Toll, K. Zibrek, L. Hoyet, A.-H. Olivier, and J. Pettré, "Interaction fields: Intuitive sketch-based steering behaviors for crowd simulation," in *Computer Graphics Forum*, vol. 41, no. 2, 2022, pp. 521–534.

[67] G. Bremer, N. Stein, and M. Lappe, "Predicting future position from natural walking and eye movements with machine learning," in *Proc. of IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, 2021, pp. 19–28.

[68] D. Reiners, M. R. Davahli, W. Karwowski, and C. Cruz-Neira, "The combination of artificial intelligence and extended reality: A systematic review," *Frontiers in Virtual Reality*, p. 114, 2021.

[69] J. Clifton and S. Palmisano, "Effects of steering locomotion and teleporting on cybersickness and presence in hmd-based virtual reality," *Virtual Reality*, vol. 24, no. 3, pp. 453–468, 2020.