An Overview of Group Navigation in Multi-User Virtual Reality

Tim Weissker* Pauline Bimberg† Bernd Froehlich‡
Virtual Reality and Visualization Research, Bauhaus-Universität Weimar

ABSTRACT

Group navigation techniques can allow both collocated and distributed collaborators to explore a shared virtual environment together. In this paper, we review the different facets, the resulting challenges, and previous implementations of group navigation in the literature and derive four broad and non-exclusive topic areas for future research on the subject. Our overarching goal is to underline the importance of optimizing navigation processes for groups and to increase the awareness of group navigation techniques as a relevant solution approach in this regard.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Collaborative and social computing—Collaborative and social computing theory, concepts and paradigms—Social navigation; General and reference—Document types—Surveys and overviews

1 INTRODUCTION

The interactive exploration of virtual environments that cannot be overlooked from a single vantage point requires navigation, which is a combination of the motor component *travel* and the cognitive component *wayfinding* [9]. While previous research has investigated a large number of navigation techniques for individuals (see [2, 35] for overviews), the growing popularity of multi-user virtual reality systems raises the central research question of how common single-user navigation processes can be adapted or enhanced to support the requirements of groups exploring a shared virtual space together. The most straightforward solution to multi-user navigation in these systems is to equip each member of a group with individual navigation capabilities through established single-user techniques. However, this approach can lead to several undesired side effects like non-negligible coordination overheads, the risk of losing each other, and the unnecessary allocation of attentive resources for navigation by every member of the group.

Group navigation techniques aim to overcome these limitations. Similar to sharing a vehicle in the real world, they allow the group to stay together while only one person at a time is responsible for movement control. In this paper, we present an overview of the different facets, the resulting challenges, and previous implementations of group navigation techniques in different multi-user virtual reality systems. Our overarching goal is to underline the importance of optimizing navigation processes for groups and to increase the awareness of group navigation techniques as a relevant solution approach in this regard.

2 GROUP NAVIGATION TECHNIQUES IN THE LITERATURE

While the exact definition of the term *group* varies between publications, most of them emphasize some form of social relationship or interdependence between members, in which the actions and thoughts

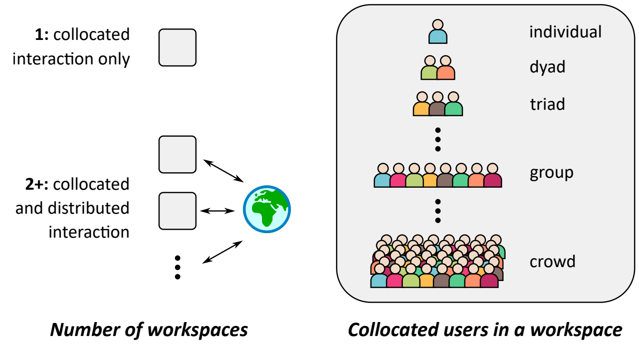

Figure 1: We classify group navigation techniques in virtual reality by the number of involved distributed workspaces (left) and the number of collocated users situated within each of theses spaces (right). *Figure adapted and reprinted with permission from [55].*

of one member can influence the others [20, chpt. 1]. Therefore, groups can be diverse with examples ranging from dyads working together over small groups exploring a museum to large crowds and audiences, where one member starting to clap might motivate the others to join. Based on Tuckman's model of small-group development [50,51], group navigation techniques involve processes in four different phases, visualized in Figure 2, which can be summarized as forming navigational groups (*Forming*), distributing navigational responsibilities (*Norming*), navigating together (*Performing*), and eventually splitting up again (*Adjourning*) [54]. In multi-user virtual reality, the members of a group can be either collocated in a single workspace or distributed across multiple workspaces:

Single Workspace Members of a group meet in the same physical location to experience the virtual environment. This is usually realized by equipping each member with a head-mounted display within a common tracking space (e.g. [31,42,56]) or by employing multi-user projection technology (e.g. [1, 12, 29]). As a result, all participating users can have an individual perspectively-correct view onto the virtual environment.

Multiple Workspaces Members of a group are in different locations and join the virtual environment using a network connection (e.g. [7, 21, 37, 54, 55]). The absence of a shared physical space typically requires additional communication mechanisms like an audio connection via the network.

While many systems in the literature focus solely on either collocated or distributed group interaction, more advanced setups allow the collaboration of both collocated and distributed group members (e.g. [7]). As a result, group navigation in multi-user virtual reality can be classified by the number of involved distributed workspaces and the number of collocated users situated within each of these spaces (see Figure 1). In the following, we will apply this classification and terminology to categorize group navigation techniques presented so far and derive potentials for future research. An overview of the discussed publications with respect to their group composition and the realized mechanisms for *Forming*, *Norming*, *Performing*, and *Adjourning* is given in Table 1.

*e-mail: tim.weissker@uni-weimar.de
†e-mail: clara.pauline.bimberg@uni-weimar.de
‡e-mail: bernd.froehlich@uni-weimar.de

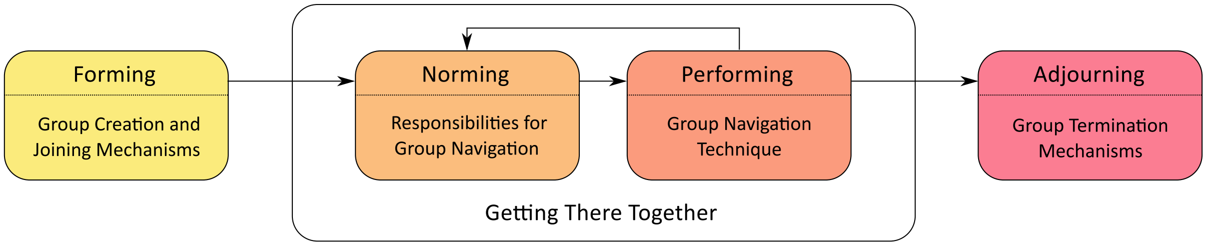

Figure 2: Similar to being in a vehicle in the real world, group navigation techniques allow groups to stay together while only one person at a time is responsible for movement control. They involve processes for creating navigational groups (Forming), distributing navigational responsibilities (Norming), navigating together (Performing), and splitting up again (Adjourning). Depending on the progress of the *Performing* stage, the assigned responsibilities might need to be redistributed. *Figure adapted and reprinted with permission from [54].*

Publication	Group Composition	Forming	Norming	Performing	Adjourning
Salzmann and Froehlich 2008 [43]	two collocated users (HMD)	physical	user in driver's seat is navigator	steering	physical
Salzmann et al. 2009 [44]	two collocated users (projection-based)	physical	user claiming input device is navigator	steering	physical
Kulik et al. 2011 [29]	a group of up to six collocated users (projection-based)	physical	user claiming input device is navigator	steering with virtual collision avoidance	physical
Weissker et al. 2019 [56]	two collocated users (HMD)	physical	fixed user is navigator	Multi-Ray Jumping	physical
Weissker et al. 2020 [54]	two distributed individuals (HMD)	holding controllers together	first user to activate target ray is navigator	Multi-Ray Jumping with formation adjustments	button
Weissker and Froehlich 2021 [55]	a group of up to ten distributed individuals (HMD)	not discussed	user with most expertise is navigator	Multi-Ray Jumping with preview avatars and formation adj.	not discussed
Party Portals in AltspaceVR[1], cf. Kolesnichenko et al. 2019 [28]	a group of distributed individuals (HMD)	selection of portal	portal creator initiates transition	scene transition	automatically after transition
Beck et al. 2013 [7]	two distributed groups of up to six collocated users each (projection-based)	button for linking distributed groups	input combination of both groups' navigators	steering and virtual group rearrangements	button for disconnecting distributed groups

Table 1: An overview of the discussed publications on group navigation techniques for collocated dyads and groups (Section 2.1), distributed individuals (Section 2.2), and distributed dyads and groups (Section 2.3).

2.1 Navigation of Collocated Dyads and Groups

Since collocated users are tracked within their common physical workspace, everybody can walk around in order to adjust their viewpoint onto the virtual content. In many systems in which the size of the virtual environment is similar to the physical workspace, this is the most prevalent method of navigation (see [1, 3, 4] for projection-based systems and [11, 13, 41, 42, 45] for head-mounted displays). If virtual navigation capabilities are provided on a per-user basis, the spatial user arrangement in the real world diverges from the arrangement of the avatars in the virtual environment, which can lead to a range of complications. For collocated users of head-mounted displays, for example, spoken words will be heard as coming from a different direction than one would expect based on the visual position of the virtual avatar. Moreover, the unawareness of another user's real-world position can easily lead to collisions during walking. Lacoche et al. coined the term *spatial desynchronization* for these situations and suggested additional visual mediators like ghost avatars and floor-projected heat maps to increase mutual awareness [31]. Other researchers focused on the almost imperceptible redirection of users during walking to prevent collisions [5, 17, 34, 36] or relied on users remaining mostly stationary in the physical space [10]. In multi-user projection systems, spatial desynchronization is especially disruptive since seeing the real-world bodies of other users in front of the shared projection screen(s) generates the wrong expectation that they can understand physical pointing gestures to refer to objects in the virtual environment. Nevertheless, Chen et al. argued that individual navigation in a two-user CAVE can be beneficial for loosely coupled collaboration tasks and proposed a variation of the human joystick metaphor to safely share the joint workspace while being in different locations virtually [12].

To avoid the problem of spatial desynchronization completely, group navigation techniques consider collocated users as a single entity that can only be moved as a whole by virtual navigation. Therefore, the shared workspace is often imagined as a virtual vehicle [29], conveyor [19], or magic carpet [38] that can be operated to move through the virtual environment. As a result, *Forming* and *Adjourning* are done in the real world by entering or exiting the physical space of the virtual reality system and putting the required hardware on or off. Regarding *Norming*, being on a shared vehicle usually leads to an asymmetric role distribution between the operating navigator and the passive passengers. The two-user seating buck system by Salzmann and Froehlich, for example, allowed the user in the driver's seat to steer a shared virtual car and therefore also the passenger through the environment [43]. Another system by Salzmann et al. allowed a dyad in front of a projection screen to switch between navigator and passenger roles for flying around a virtual object by passing a shared input device [44]. In the six-user projection system by Kulik et al., the shared input device was stationary within the physical workspace and could be claimed by each member of the group. During the *Performing* phase, the authors noted that the spatially consistent representation of the group can lead to uncomfortable situations when steering through doorways that are narrower than the physical workspace, where passengers collided with the adjacent virtual walls as a consequence. To address this problem, they proposed to automatically move users closer to each other in the virtual environment such that a collision-free path through the door could be guaranteed. After passing the door, users were moved back to a spatially consistent configuration. This approach was evaluated positively for providing comfortable user paths while the short moments of spatial desynchronization were not considered disrupting or nauseating [29]. In the realm of head-mounted displays, travel by steering is mostly avoided since it is often deemed a plausible cause of simulator sickness due to the resulting sensory conflict between the visual and the vestibular systems [14, 30, 40], which is especially detrimental in these setups as opposed to other display media [48]. For collocated group navigation with head-mounted displays, Weissker et al. therefore relied on teleportation-based movements for *Performing* and introduced the notion of *comprehensible group navigation*, which underlines the importance of mutual awareness and predictability of actions during the joint navigation process. To meet these quality criteria, they presented a short-distance teleportation technique for two-users called *Multi-Ray Jumping* that communicated the target position of the passenger by using a secondary target ray (see Figure 3). In two user studies, this additional mediation was confirmed to improve comprehensibility and reduce cognitive load without inducing higher simulator sickness for users in the passenger role [56].

2.2 Navigation of Distributed Individuals

Several research prototypes investigated the networked combination of single-user projection systems when collaborating users were geographically far apart or multi-user technology was not available (e.g. [21, 32, 46]). For head-mounted displays, recent technological advancements and affordable hardware have led to an increasing number of users having a personal virtual reality system, which also sparked commercial developments of networked multi-user applications for distributed individuals (see [28, 37] for an overview). Since the problem of spatial desynchronization is non-existent for purely distributed interaction, most systems provide independent virtual navigation on a per-user basis and only omit virtual navigation if the environment can be apprehended by physical locomotion only (see [3, 18, 21, 32, 46] for projection-based systems and [24, 33, 47, 49, 52] for head-mounted displays). Although the presence of others is purely virtual in these systems, it was shown that users still exhibit negative reactions to violations of their personal space, i.e., when the avatars of others approach them too closely [57]. As a result, several commercial systems implement some form of protective mechanism to increase user comfort by preventing users from entering the personal space of others or at least making intruding avatars transparent [37].

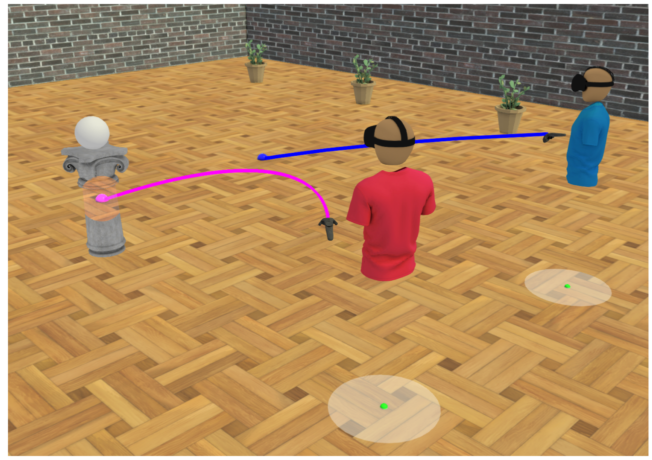

Figure 3: Multi-Ray Jumping allows two collocated users to avoid spatial desynchronization by maintaining the spatial user offset during teleportation. When the navigator (blue) specifies a target using the blue parabola, the magenta curve adjusts accordingly to show the correct offset target location of the passenger (red). *Figure adapted and reprinted with permission from [56].*

Recent research in larger virtual environments suggested that individually navigating users can have difficulties staying together, finding each other, or understanding spatial references [52, 54]. In that regard, the desktop-based system by Dodds and Ruddle offered additional group awareness mechanisms during individual navigation like visible connection lines between group members, direct teleportation to other group members, and sharing another person's viewpoint [15, 16]. Nevertheless, if group members should stay in close proximity to each other for exploring the same parts of the environment together, group navigation techniques can help to prevent members from having to give similar navigation inputs towards the same destination (input redundancy) and to reduce the need for coordinating where and how to get to the next destination (navigational accords) [55]. The concrete choice of how to implement *Forming* and *Adjourning* in distributed virtual environments is highly dependent on the use case and social relationships between participants. In a private classroom scenario, for example, the attendees of a tour might be inherently given while more open scenarios in public spaces would require giving explicit consent before joining a tour, for example, by moving to a meeting point within a certain time span, performing a coupling gesture, or simply pressing a dedicated button [7, 28, 54]. Similarly, a teacher might not want their students to leave the group before the end of the tour while this could be a desired feature when attendance is less strict. With respect to *Norming*, it seems reasonable to assign the main virtual group movement controls to the user with the most knowledge of the system and topic to be demonstrated. Nevertheless, this privilege might need to be passed on to a different guide when expertise is separated among multiple users. While this was mostly realized by changing the operator of a shared input device in collocated setups, distributed systems need to offer virtual mechanisms in this regard as well.

As an example for a limited form of group navigation with distributed individuals, the commercial system AltspaceVR[1] introduced the idea of *party portals* to transition from one virtual scene to another together. A party portal provided a preview of the target scene and allowed users to express their interest in joining by selecting the portal geometry. The transition was then initiated by the portal creator for all users at the same time. *Performing* group navigation within the same virtual scene for a longer period of time, however,

[1] https://altvr.com/

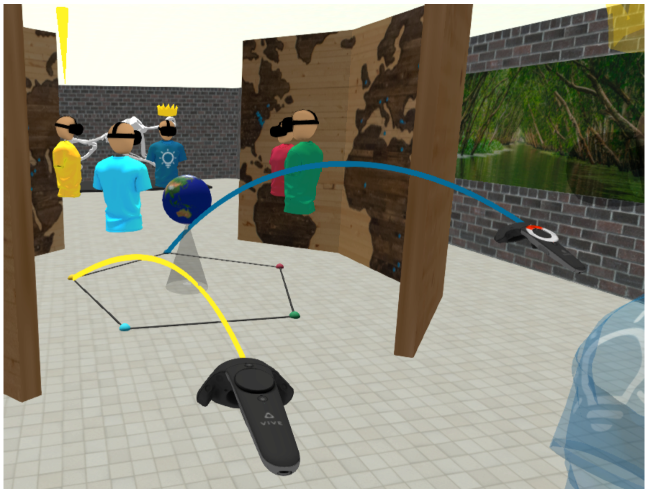

Figure 4: An extension of Multi-Ray Jumping for fully distributed groups of up to 10 users extends the feedback of the two target rays with preview avatars to communicate the group context. Since the issue of spatial desynchronization does not exist for distributed individuals, the navigator (right) can additionally rearrange the group to different spatial formations during teleportation (here: a circle for discussions). *Figure adapted and reprinted with permission from [55].*

is more challenging. Based on earlier research on collocated group navigation, it can be derived that *Performing* techniques for distributed individuals should be comprehensible for both the navigator and passengers (*Comprehensibility*), assist the group in avoiding collisions with obstacles during joint travel (*Obstacle Avoidance*), and allow the creation of meaningful spatial arrangements to observe and discuss objects of interest together (*View Optimization*) while still conforming with personal space semantics [55]. To meet these requirements, variations and extensions of Multi-Ray Jumping for two [54] and up to ten [55] distributed users were developed. In addition to default mechanisms to relocate the group in its current spatial formation, these techniques also gave the navigator the ability to generate virtual formation adjustments, i.e., rearrangements of group members to a different spatial layout without requiring individual motion (see Figure 4 for an example for five distributed individuals). While this would immediately lead to spatial desynchronization in collocated setups, distributed individuals appreciated this feature as it allowed for more efficient travel sequences in order to meet the requirements of *Obstacle Avoidance* and *View Optimization* while the *Comprehensibility* was not compromised due to appropriate preview mechanisms. In the implementation for up to ten users, circle and horseshoe formations helped users to focus on a common area of interest (cf. [27]) while compact grid and queue formations were convenient for moving group members through narrow passages when getting to the next destination. To minimize discomfort, the system ensured that users were never placed inside the personal space of each other or inside obstacles in the virtual environment [55].

2.3 Navigation of Distributed Dyads and Groups

Virtual reality systems involving multiple distributed groups of collocated users are rare up to this point. An exception is the projection-based group-to-group telepresence system by Beck et al., which enabled two groups of up to six collocated users each to meet in the virtual environment using high-fidelity video avatars [7]. To avoid spatial desynchronization, individual user movements were restricted to walking in front of the respective projection screen while virtual steering could only be applied to each group as a whole. When both groups met in the virtual environment, they could decide to link themselves by coupling their navigation systems (*Forming*). As a result, the navigator of each local group could take the remote group along for joint explorations. If both local navigators provided inputs at the same time, they were simultaneously applied to the whole group (*Norming*). Additionally, navigators could also change the spatial arrangement of both groups to a side-by-side or face-to-face arrangement, which is similar to the idea of virtual formation adjustments for distributed individuals by Weissker et al. [54, 55]. However, to maintain spatial consistency among collocated users, virtual formation adjustments were applied on a workspace level rather than on individual users. As a result, for generating a side-by-side configuration, both virtual workspace representations could be overlaid, which still required the individual users in each room to perform physical walking to line up in a "true" side-by-side arrangement. A similar situation arose for the face-to-face configuration, where only the virtual workspace representations were placed and rotated to face each other in the virtual environment.

3 Discussion and Future Research Directions

Group navigation techniques assist users in staying together when exploring virtual environments by supporting *Forming*, *Norming*, *Performing*, and *Adjourning*. For collocated users, the shared workspace becomes an imagined virtual vehicle that moves the whole group together and therefore avoids spatial desynchronization at all times. For distributed users, group navigation techniques provide transitions between individual and joint navigation and might even allow changes of virtual user formations to increase efficiency and comfort when getting somewhere together. In any case, all variations of group navigation reduce input redundancy and the need for mutual coordination that is necessary with individual navigation. Nevertheless, the current state of development leaves many open research questions and a large design space to be explored by future work. We categorize these into four broad and non-exclusive topic areas:

Scalability Developing systematic and controlled evaluation protocols to be conducted with a large number of users per session is a challenging and laborious endeavour, which prevents the rapid acquisition of research insights. As a result, prior research mostly focused on small and therefore easily manageable group sizes. To get an initial impression on the challenges of navigating larger groups, the exploratory user study by Weissker and Froehlich [55] increased the number of participants to be navigated by adding up to seven simulated users to groups of three human participants. The results indicated that the main challenges for scalable group navigation seem to lie in assisting the group with *Obstacle Avoidance* and *View Optimization* while still conforming with personal space semantics. This means that the larger a group gets, the more challenging it is for the navigator to find suitable non-overlapping and collision-free user placements. While more spacious environments might help to reduce this problem to some extent, a large number of virtual avatars also leads to more turbulent scenes and occlusions among avatars, which might disturb the perception of the content of interest. In such cases, the group could be split into socially less-dependent sub-groups within which avatar visibility is restricted to members of the same sub-group and the navigator. This approach would allow the overlapping placement of different sub-groups without introducing additional visual disturbances, but it would also prevent all forms of social interactions between members of different sub-groups. As a result, systems following this approach should also provide options to switch between sub-groups or to become visible for everyone in order to initiate discussions. Nevertheless, allowing every user of a large group to perform actions at all times could become difficult to oversee and comprehend without any form of moderation. An additional challenge lies in finding a suitable aggregate visualization of the group for external observers [8], which allows them to get an understanding of the group activities even if the viewing positions of multiple users inside the group are overlapping.

Diversity Most of the related literature and user studies on group navigation focused on rather homogeneous scenarios regarding the physical collocation/distribution of collaborators, the use of certain types of VR hardware, and the individual capabilities of participants. While the combination of collocated and distributed users for joint navigation was initially approached by Beck et al. [7], the inherent challenges of avoiding spatial desynchronization for collocated participants while using the spatial flexibility of distributed entities for realizing *Obstacle Avoidance* and *View Optimization* (see Section 2.3) deserves further in-depth investigations. The combination of different hardware setups was also tackled only rudimentarily up to this point, mainly by desktop users providing verbal navigation assistance for an immersed individual [6, 39, 53]. Joint navigation of users with diverse immersive hardware, on the other hand, faces the challenge that some scenarios (like users in front of a single-screen projection system or seated users wearing head-mounted displays) require virtual rotation techniques to look around whereas other scenarios (like users surrounded by screens in a CAVE or standing users wearing head-mounted displays) enable users to perform full turns by physical rotations. The ability to rotate physically at any point in time might make it easier to maintain situational awareness, which could in turn lead to an improved *Comprehensibility* of the navigation process and therefore disadvantage other users without this ability. Finally, future studies on group navigation should also take place outside of laboratory environments to capture a more diverse audience with varying capabilities in order to validate the usability of the developed prototypes.

Social Factors While previous work confirmed initial benefits of group over individual navigation in both collocated and distributed scenarios, the underlying social factors and group processes during joint navigation are an important aspect for further investigation. Especially in distributed setups, where groups are formed only virtually, it is relevant to identify which aspects of application design are beneficial for social presence, mutual awareness, and the overall sense of belonging together during joint navigation. Based on these considerations, future evaluations could focus on the effects of individual and group navigation on more high-level goals like collaborative scene understanding, information gathering, or acquisition of spatial knowledge. The study by Buck et al. in head-mounted displays, for example, showed that dyads with individual steering capabilities could acquire better levels of survey knowledge when they were allowed to cooperate [10]. It would be interesting to see if similar results can be achieved with group navigation techniques as well and which cognitive strategies users employ to achieve the common goal. Moreover, the study of suitable group formations for specific situations within the group navigation process is still at the beginning. Particularly, the idea of virtual formation adjustments raises questions regarding more meaningful rearrangements of users considering social relationships, common (sub-)goals, and proxemic criteria like body orientations or spatial proximity (see [22, 23] for a complete overview of proxemic dimensions).

Alternatives to Group Navigation Navigation of the entire group is a responsible task for the navigator, which should be carried out with care. While previous studies did not indicate increases in simulator sickness during passive teleportation when the navigator performed all steps at an appropriate pace [55, 56], some passengers might not be satisfied with passing control over their viewpoints to another person. Therefore, the *Norming* phase of the group navigation framework offers potentials for adjustments, e.g., by allowing passengers to notify the navigator about disagreements or to block group navigation entirely when someone feels uncomfortable. In some cases, however, the strict coupling of users to a navigational entity might not be the desired solution. It is therefore crucial to study further how users with individual navigation capabilities can stay together as a group, understand how and where to go next, and prevent colliding with each other when being physically collocated. Apart from that, prior research indicated that certain collaborative tasks benefit from a division of work rather than staying together for the whole time. In collaborative search efforts, for example, it was shown that independently navigating dyads could locate more target objects than individuals alone [25, 26]. In the desktop collaborative virtual environment of Dodds and Ruddle [15, 16], group members inspected completely different parts of the scene as part of an architectural design review, but they needed to coordinate and potentially reconvene to continue at various points throughout the study. The proposed group visualizations and navigation aids for these situations provide interesting ideas towards supporting distributed group work with individual navigation, which however still require adaptations to and evaluations in immersive virtual reality.

4 Conclusion

We presented an overview of group navigation techniques for collocated and distributed multi-user virtual reality and explained the resulting challenges for their design and evaluation. From our observations, we concluded that research on group navigation in virtual reality is still at its beginning and derived four broad and non-exclusive topic areas for relevant future research. We hope that this paper will spark further discussions on the subject and inspire future research on effective methods for traversing virtual environments together.

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 members of the Virtual Reality and Visualization Research Group at Bauhaus-Universität Weimar (`http://www.uni-weimar.de/vr`).

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