Getting There Together: Group Navigation in Distributed Virtual Environments

Tim Weissker, Pauline Bimberg, and Bernd Froehlich, *Member, IEEE*

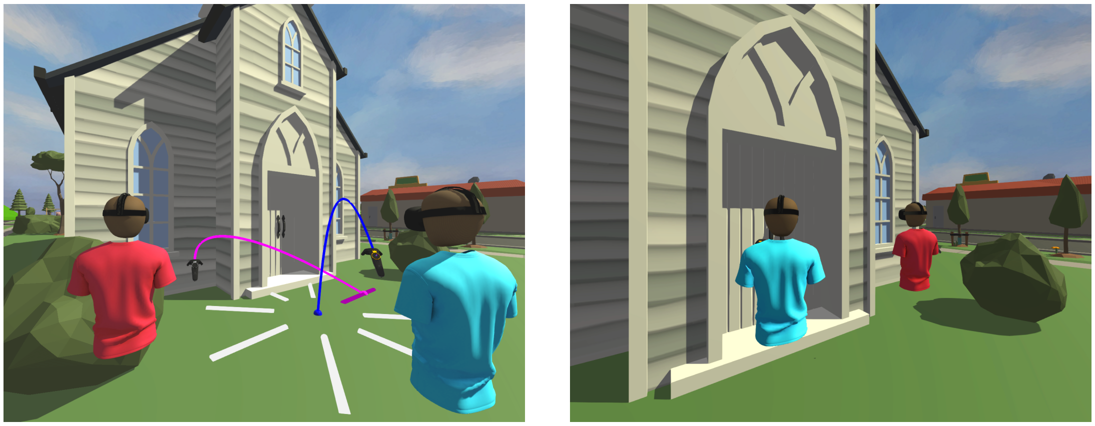

Fig. 1. Our two-user jumping technique for remote collaboration allows the navigator (blue) to adjust the translational offset of the passenger (red) when planning a jump (left image). As a result, the group adjusts their formation during the jump, and the participants arrive at the appropriate locations to observe and discuss points of interest together (right image).

Abstract—We analyzed the design space of group navigation tasks in distributed virtual environments and present a framework consisting of techniques to form groups, distribute responsibilities, navigate together, and eventually split up again. To improve joint navigation, our work focused on an extension of the *Multi-Ray Jumping* technique that allows adjusting the spatial formation of two distributed users as part of the target specification process. The results of a quantitative user study showed that these adjustments lead to significant improvements in joint two-user travel, which is evidenced by more efficient travel sequences and lower task loads imposed on the navigator and the passenger. In a qualitative expert review involving all four stages of group navigation, we confirmed the effective and efficient use of our technique in a more realistic use-case scenario and concluded that remote collaboration benefits from fluent transitions between individual and group navigation.

Index Terms—Virtual Reality, Collaborative Virtual Environments, Remote Collaboration, Group Navigation, Teleportation, Jumping.

1 Introduction

Distributed virtual reality systems allow multiple users around the globe to explore a shared virtual environment together. In these systems, participants are represented by avatars and can meet to perform collaborative actions as a group. However, staying together for a joint tour through the environment can be difficult because each user has to navigate individually without losing track of the other members. The attention to this task can distract from experiencing the actual tour – especially for novice users of virtual reality.

In this paper, we explore the design space of group navigation techniques in distributed virtual environments. Based on the Tuckman model of small-group development [49, 50], we derived a framework for group navigation that consists of techniques allowing users to form navigational groups (*Forming*), distribute navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*). Based on the observation that virtual group formations in the distributed case are more flexible than in collocated scenarios, we designed, implemented, and evaluated a two-user jumping technique based on *Multi-Ray Jumping* [52], which allows the navigator to change the group's formation as part of the target specification process. In a quantitative user study, we investigated the benefits of these formation adjustments for two-user travel. In a qualitative expert review, we evaluated all four stages of group navigation and the use of our technique in a more open scenario, which allowed participants to switch between individual and group navigation at any time.

Our focus on small-group development and interaction is motivated by the increasing popularity of social virtual reality systems, in which group navigation is an elementary form of interaction that is not yet supported. However, group navigation and particularly sequences of joint short-distance teleportation (jumping) can often result in involuntary changes of a group's formation. In particular, the combination of virtual translations by jumping and physical rotations to change direction lead to situations where, for example, a group in a side-by-side formation transitions to a queue formation at turns of 90°. While the previous formation can only be reestablished by physical walking in collocated setups, virtual formation adjustments during group jumping of distributed users can simplify this process. Our contributions are:

- a systematic analysis of the design space of group navigation techniques in distributed virtual reality, resulting in a group navigation framework consisting of techniques for group *Forming*, *Norming*, *Performing*, and *Adjourning*,
- the design and implementation of a two-user jumping technique based on *Multi-Ray Jumping*, which allows to prepare group formation adjustments during target specification,

- *The authors are with the Virtual Reality and Visualization Research Group at Bauhaus-Universität Weimar. E-Mail: {tim.weissker, clara.pauline.bimberg, bernd.froehlich}@uni-weimar.de.*

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

- statistical evidence that two-user *Multi-Ray Jumping* with virtual formation adjustments leads to significantly more efficient travel sequences while imposing significantly lower task loads on both navigator and passenger,
- the results of an expert review on two-user navigation, which confirm the effective and efficient use of our technique in a more open use-case scenario and show that fluent transitions between individual and group navigation with virtual formation adjustments can be beneficial for collaborative activities in distributed virtual reality.

Our analyses encourage the integration of group navigation techniques into social virtual reality systems and provide guidance for their design in all four phases of the group navigation process.

2 Related Work

Classic single-user virtual reality systems immerse an individual into the virtual environment without giving additional users the option to participate. Towards collaborative experiences, related work suggested solutions for asymmetric setups in which the immersed user is guided through the virtual environment by one or multiple collaborators using 2D interfaces [2, 9, 39, 40]. Symmetric setups, on the other hand, provide immersive display hardware for all involved users, allowing collocated (e.g [1, 30, 45, 46]) and distributed users (e.g. [3, 10, 33]) to explore a *collaborative virtual environment* (CVE) together. These environments should enable their users to "share information through interaction with each other and through individual and collaborative interaction with data representations" [12]. A popular application area of CVEs using head-mounted displays are chatrooms (e.g. *SteamVR Home*[1], *VRChat*[2], *Rec Room*[3]), also referred to as *virtual reality social networks* [41], for which users can design their own avatars and virtual worlds to meet and interact with other people around the globe. In this paper, we investigate joint navigation techniques for distributed users participating in such collaborative virtual environments or virtual reality social networks.

Navigation is the most prevalent form of user interaction [7] and inevitable to apprehend spaces of environmental and geographical scale [38]. It is subdivided into the motor component *travel* and the cognitive component *wayfinding* [7]. Darken and Peterson described the navigation process as the formulation of a goal (including a strategy to reach it) followed by a continuous loop of perception, assessment, and motion, which can potentially lead to redefinitions of the strategy or the goal as a whole [15]. In common virtual reality setups, users can travel by physical walking within a restricted tracking area and use virtual travel techniques to cover larger distances [19, 44]. Steering, a versatile option for virtual travel, introduces a sensory conflict between the visual and the vestibular systems of the user, which can easily lead to simulator sickness [31]. This effect is especially critical in head-mounted displays (HMDs) as opposed to other display media [48], but it can be mitigated by dynamic field-of-view modifications during travel [18]. Travel by teleportation, on the other hand, reduces sensory mismatches and was shown to result in lower simulator sickness than basic steering techniques [11, 43, 53]. In particular, short-range teleportation with egocentric target specification (jumping) has become a popular technique for single-user travel in HMD environments [53], and several implementation variants of jumping showed promising results regarding spatial awareness, presence, and user experience [5, 8, 26, 43, 53]. Generally, jumping techniques consist of a method for *target specification*, the display of *pre-travel information*, a *transition* mode, and optional *post-travel feedback* [53]. A suggested adaptation of jumping for multiple collocated users mediates the target positions of all involved users as additional pre-travel information to achieve a more comprehensible group jumping technique [52]. In the resulting *Multi-Ray Jumping* technique for two users, both users see an additional target ray from the passenger's controller pointing to the corresponding target position. In this paper, we investigate how this strategy for comprehensible group jumping can be adapted for the use by distributed participants.

Collaborative work in real-world settings builds on transitions between shared and individual activities, flexible and multiple viewpoints, sharing context, awareness of others, and negotiation and communication between the collaborating parties [12]. While it is helpful to constantly represent a group of collocated users as a single navigational entity to avoid spatial desynchronization between the real and the virtual world [52], group relationships between distributed users can be more flexible. As a result, individual activities as well as flexible viewpoints can be realized by separate navigation capabilities for each user while navigational groups for sharing context and shared activities may be dynamically formed and adjourned on a semantic rather than a physical level. Real-world observations revealed that small groups coming together to solve a specific problem undergo a sequence of developmental phases during their life cycles. Tuckman and Jensen summarized these phases as *Forming* (testing and orientation), *Storming* (conflict and polarization), *Norming* (development of cohesiveness), *Performing* (task solving) and *Adjourning* (termination of group work) [49, 50]. Within this process, the presence and extent of the phases may vary depending on the task, group size, and group life time. Dodds and Ruddle provided implementations of group *Forming* and *Performing* in a desktop CVE designed for architectural reviews. However, subsequent group navigation in their system is restricted to automated individual navigation within the group rather than navigation of the group as a whole [16, 17].

Examples of distributed users navigating together as a unit are rare. For the CVE *MASSIVE-2*, Benford et al. suggested the abstraction of multiple users into *crowds*, "which allows them to be treated as a whole in some circumstances [...] but as individuals in other circumstances". In the context of joint navigation, they suggest *mobile crowds* on shared group vehicles that are controlled on behalf of their members [4]. This concept is implemented in the immersive group-to-group telepresence system by Beck et al., where two distributed parties of collocated users can be explicitly coupled in face-to-face or side-by-side formations for joint steering through the virtual environment [3]. In this paper, we contribute a framework for group navigation and new ideas that allow individual users and/or groups of collocated users to join together for subsequent group navigation in distributed virtual environments.

3 A Framework for Group Navigation in CVEs

Tuckman's model of small-group development has become a general and widespread framework to discuss group processes in various disciplines [6]. On an abstract level, it highlights that groups need to come together (*Forming*), distribute responsibilities after resolving potential conflicts (*Storming/Norming*), work together (*Performing*), and eventually split up again (*Adjourning*). Based on these insights, we propose a four-tier framework for the design space of joint navigation in collaborative virtual environments (see Figure 2). We suggest that CVEs implementing joint navigation need to specify rules and mechanisms for all four phases, which will be detailed in the following.

3.1 Forming - Group Creation and Joining Mechanisms

As a first step, multiple users coming together in the virtual environment need to be able to join together for subsequent group navigation. In Tuckman's model, group forming is described as orientation towards the task, testing of boundaries of interpersonal and task behaviors, and the establishment of dependency relationships between group members [49]. While the first two of these processes can be achieved by the means of verbal and gestural communication provided by modern distributed CVEs (audio links and avatar representations), users need additional mechanisms to notify the system to switch from individual to group navigation for them. For this purpose, Dodds and Ruddle distinguished between implicit and explicit group forming based on proximity and selection, respectively [16]. We generalize this idea and suggest that group forming implementations can vary between several degrees of explicitness and user involvement. Without any claim to

[1] https://steamcommunity.com/steamvr
[2] https://www.vrchat.net/
[3] https://www.againstgrav.com/rec-room

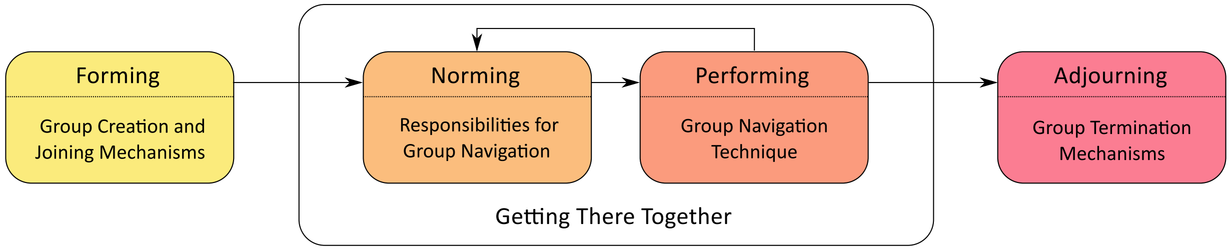

Fig. 2. The realization of joint navigation in collaborative virtual environments requires support for four different stages of group work following Tuckman's model of small-group development [49, 50]. In our framework, we suggest that users need to organize themselves in navigational groups (*Forming*), distribute navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*). Depending on the progress of the *Performing* stage, the assigned responsibilities might need to be redistributed.

completeness, we illustrate some exemplary design options from the most implicit to the most explicit in the following:

Circumstantial Based on heuristics like proximity [16] or spatial user arrangements like F-formations [14, 37], the system can decide to form user groups automatically.

Environmental Navigational groups can be formed by entering dedicated objects in the virtual environment such as vehicles [4].

Singular Confirmation The explicit selection and confirmation of a single user is needed to create a new group of surrounding users or to join an existing navigational group [16].

Mutual Confirmation A single user creates a group creation or joining request, which has to be confirmed by some or all of the other users to take effect.

Groups of physically collocated users (e.g. [3]) participating in remote collaboration may require a fully static navigational group assignment for the whole duration of participation [52]. In this case, forming is done in the real world by entering the shared physical space of the VR system. Moreover, groups can also be statically assigned for experimental study purposes (see Section 5).

3.2 Norming - Responsibilities for Group Navigation

Group navigation techniques can support different modalities for the distribution of responsibilities among participating users. This is related to the *Norming* phase in Tuckman's model, in which conflicts of interest during potential *Storming* need to be resolved. Similar to crowd-controlled desktop interfaces that aggregate multiple user inputs to a single stream for the application (e.g. [32, 34–36]), group navigation techniques in CVEs must specify (1) who of the group can give travel inputs at a given time and (2) to which degree the other users can support or intervene with the provided inputs. Some exemplary implementations include:

Equality All users of a group can provide travel inputs simultaneously, which are combined by the system on an equal basis (also referred to as *Mob* or *Anarchy* in the desktop context [32, 34]).

Weighting All users of a group can provide travel inputs simultaneously, but the inputs of different users have different influences on the overall result [32, 35]. The weights can be explicitly defined (e.g. for expert users) or implicitly derived by the system (e.g. based on previous contributions to the task).

Navigator Travel controls are restricted to a single user at a time, who is referred to as the *navigator* of the group while the other users are called *passengers* [52]. While this control scheme can be realized by the physical access to a shared input device in collocated setups [3, 29], it requires coordination in distributed CVEs. Controls might be readily available once none of the other members claims them, passed around based on time schedules [36] or explicit requests, or statically assigned to a single guide of the group.

System-Driven Travel inputs are automatically provided by the system based on pre-defined or automatically generated paths similar to system-guided travel for single users [21]. In this case, all users are passengers.

In the latter two cases, implementations can also allow passengers to provide feedback for the navigator or the system. Such mechanisms can be *confirmatory*, where choices have to be supported by the passengers, or *contradictory*, where passengers can block choices or even vote for transferring travel controls to a different entity. Depending on the application scenario, different rules for group navigation may be suitable to complete a task.

3.3 Performing - Group Navigation

The *Performing* phase is the core part of group work, in which the actual group navigation process is carried out. In accordance with Darken's and Peterson's model of the navigation process for single users [15], we suggest that navigation techniques for multiple users should support group *communication*, foster group *awareness*, and allow group *travel* in order to reach a target effectively and efficiently.

While group communication and awareness are essential throughout all stages of group work, their role for *Performing* is providing means for the joint formulation of a common goal/strategy and the perception and assessment of the group's progress. Since formulating a strategy is closely linked to assigning user roles during *Norming*, changes of the strategy during travel may require a dynamic redistribution of user responsibilities. In addition to the already provided general functionalities by the CVE, an example for enhancing group communication is the aggregation and abstraction [4, 22], attenuation [16, 17], or cancellation [22] of speech coming from users that are not part of the group. Concerning group awareness, additional visualizations can help to locate other members more easily [16, 17] or to understand each other's technical limitations like tracking boundaries, fields of view, or network latencies [20].

Group travel relates to the specification of a technique that maps user inputs to group displacements in the virtual environment. In this regard, prior work in collocated setups investigated collision-avoiding group steering techniques [29] and different conceptual approaches to two-user jumping [52]. The formulated requirement of *comprehensible group jumping* states that techniques should "foster the awareness of ongoing navigation activities and facilitate the predictability of their consequences" for all participating users [52]. Examples for distributed users traveling together include the two-group steering technique by Beck et al. [3] and the concept of mobile crowds presented by Benford et al. [4]. We argue that the requirement of comprehensible group jumping formulated for collocated setups can be adapted to comprehensible group navigation in distributed scenarios as well. This highlights a close connection between group travel and group awareness, where additional mediators presented during group travel can allow to predict the group's position and constellation in a future time step.

3.4 Adjourning - Group Termination Mechanisms

When the formulated goals for group navigation are achieved, users need mechanisms to notify the system to switch back from group to individual navigation. Since this is the inverse task of the *Forming* phase, a suitable choice of an adjourning implementation is often governed by its preceding forming mechanism. If a group was formed by circumstantial or environmental criteria, for example, it might be suitable to use the same criteria for adjourning as well. However, depending on the use case, mixtures of the presented mechanisms can also be helpful. A group might, for instance, require mutual confirmation to join but allow each member individually to decide to leave by singular confirmation.

3.5 Discussion

The presented four-tier framework of group navigation assumes that users need to spatially come together to form a group. While this is realized by physically entering a common tracking space in collocated setups, distributed users need to apply individual navigation inputs to approach the avatars of other collaborators. We argue that the spatial proximity of users in the virtual environment is essential for the joint observation and discussion of virtual content. As a result, our definition of a group differs from higher-level semantic group assignments like in the system by Dodds and Ruddle [16, 17], where collaborators can be dispersed across the whole environment. However, we note that systems for group navigation may provide additional tools to locate other users in the virtual environment more easily or to quickly re-join groups that were previously adjourned.

We underline that the four stages in our framework should not be treated independently from each other. For example, we illustrated that choices in the *Forming* stage can have an influence on the corresponding mechanism in the *Adjourning* stage. Moreover, the progress of *Performing* can often lead to reconsiderations of *Norming* decisions. Overall, we argue that the concrete choice of mechanisms for each of the stages is highly dependent on the use-case scenario.

Since related work up to this point has mostly covered group navigation for collocated users, we will set our focus on the *Performing* phase of distributed collaboration in the remainder of this paper. We will investigate how the lack of a shared physical interaction space allows for an adjustment of group formations during travel, which can be used to design more flexible and efficient group navigation techniques.

4 Adjusting Group Formations during Joint Travel

Group formations are "spatial-orientational arrangements sustained over time [...] through the cooperation of the participants" and can vary largely depending on the common activity [27]. Circular formations, for example, create a functional space for discussions while side-by-side formations allow to jointly focus on a feature of the (real or virtual) environment. As a result, collaborating groups fluently transition between different formations with respect to their current tasks and goals. However, group travel in virtual environments can change formations involuntarily. Users of head-mounted displays performing group jumping, for instance, may start side by side but change to a queue formation after turning at a corner [52]. The reason for this is the combination of virtual translations and physical rotations required for travel. To reestablish the previous side-by-side formation, users would need to physically walk in their tracking space or temporarily switch to individual navigation if possible. Physical walking is also required if a queue formation needs to be established on purpose, for example if the group must fit through narrow pathways. In small tracking spaces and seated setups, however, the available space might not be sufficient for realizing the required formation changes.

To avoid frequent formation changes by physical walking, we suggest enabling the navigator to virtually adjust group's formation as part of the group travel technique. This is not possible in collocated setups where the virtual group arrangement must be identical to the one in the shared physical interaction space [3, 29, 52]. In distributed setups, the lack of such a shared space allows for more flexibility in the placement of group members. In particular, distributed group travel techniques can support two aspects of formation adjustments. On the one hand, the spatial arrangement of the group can be manipulated by changing the relative position offsets between participants. On the other hand, the orientation of each individual participant can be adjusted by changing their viewing direction.

In the following, we present an exemplary implementation of virtual formation adjustments during group jumping of two distributed users with a navigator-passenger role distribution. Our technique enables the navigator to prepare various types of formation adjustments on the touchpad of a *HTC Vive* controller during target specification. Following the requirements of comprehensible group navigation, these adjustments are communicated to both users before they actually occur using the target rays of the *Multi-Ray Jumping* technique [52]. Since research on single-user jumping in virtual environments indicated negative effects of combined translational and rotational jumps on spatial awareness and user experience [8, 43], we decided to focus our research on the adjustment of translational offsets while keeping the users' viewing directions unchanged during the jump.

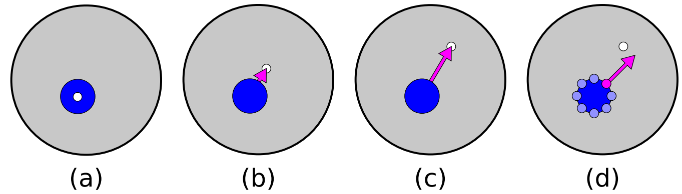

Fig. 3. Exemplary specification of a relative passenger placement vector on the round touchpad of the navigator. In each illustration, the white circle represents the current touch coordinates of the navigator. See Section 4.1 for additional explanations.

4.1 Implementation of Two-User Formation Adjustments

We recognize that not every two-user jump needs to apply changes to the current formation and therefore seamlessly integrated formation adjustments as an option into the target specification phase of the navigator. On an *HTC Vive* controller, it is established to operate jumping techniques with the thumb on the round touchpad button. Pressing this button activates a parabolic ray for the specification of a target, which is confirmed upon release. In case of *Multi-Ray Jumping*, a secondary target curve is shown to illustrate the passenger's target position as well. We propose to employ the currently unused touch coordinates during target specification to trigger and specify formation adjustments. In the moment of pressing the touchpad down, the system creates a circular zone around the touch point, in which the navigator can move their finger during target specification without triggering formation adjustments (Figure 3a). When moving the finger outside of this zone, the navigator can explicitly specify the position of the passenger relative to their own target position (Figures 3b and 3c). For this purpose, we suggest fixing a minimum and maximum passenger placement distance to avoid both avatar collisions and overly large user distances. To simplify placement, we suggest constraining the position of the passenger along four or eight directions around the navigator (visualized for eight directions in Figure 3d). Additional visualizations of these axes around the currently specified target point can mediate the available options for passenger placement, which is illustrated in Figure 1 (left) for the inputs shown in Figure 3d. In summary, our proposed realization of formation adjustments on the touchpad of the *HTC Vive* controller needs five parameters: the minimum distance of a swipe on the touchpad to activate formation adjustments (d_{s_min}), the distance of the passenger to which a minimal swipe is mapped (d_{p_min}), both of these values regarding the corresponding maximum distances (d_{s_max} and d_{p_max}), and the number of directions that are used for discretization (*num_dir*).

4.2 Discussion

We believe that our suggested addition of virtual formation adjustments to two-user jumping allows navigators to resolve problematic configurations arising from group travel more easily. Moreover, it enables navigators to guide the group through spatial constrictions and towards objects of interest for its joint observation and discussion. The potential adjustment of the group's formation places additional responsibilities on the navigator while the passenger does not need to contribute at all. We consider this helpful for performing guided tours through the virtual environment – especially when the passengers are novice users of virtual reality. Alternative approaches could aim for a more even division of work between the navigator and the passenger, but they would also introduce a coordination overhead in the usually rather short time frame of the target specification phase. In the following, we therefore decided to investigate how well navigators can handle the additional efforts of specifying formation adjustments with our technique, and how well the visual mediation provided by *Multi-Ray Jumping* conveys the intended actions to the passenger.

While it seems reasonable to employ the unused touch coordinates of the navigator's controller to specify formation adjustments, there are two issues with our implementation that need to be considered carefully. First, when the touchpad is pressed at a position close to its borders, certain formation adjustments may be impossible to specify. For these cases, we suggest an additional mechanism to abort target specification without executing a jump, allowing the user to reposition their finger on the touchpad for a new attempt. The trigger button on the opposite side of the controller seems a good candidate for this purpose since it can be easily operated in parallel to the touchpad. Second, the execution of touchpad gestures while keeping the touchpad pressed down at the same time may be difficult to handle. An alternative to our suggested *press-swipe-release* paradigm could be to activate target specification by *press-release*, allowing the navigator to *swipe* without pressing the button. However, this sequence requires a second *press-release* for confirmation, which interferes with the convention for specifying jumps without formation adjustments. Mixed variants of both paradigms are possible, but the different modes might be more difficult to learn and distinguish. In the remainder of this paper, we therefore focused on an evaluation of the usability and effects of virtual formation adjustments using the *press-swipe-release* paradigm.

5 Quantitative Evaluation of Formation Adjustments

We argued that the addition of virtual formation adjustments during jumping can simplify group navigation since formation changes can be initiated more directly than by physical walking. However, the specification of proper formation adjustments places additional responsibilities on the navigator and introduces a higher risk of passenger confusion, which could have negative impacts on the perceived task load for both collaborators. We therefore decided to investigate the influences of our implementation of two-user formation adjustments on navigation performance and user experience in more detail. For this purpose, we conducted a formal user study comparing our proposed implementation of *Multi-Ray Jumping* with formation adjustments to the baseline in which user formations cannot be adjusted virtually.

5.1 Experimental Setup

We equipped two separate rooms with a workstation, an HTC Vive Pro head-mounted display, and corresponding controllers each. Two ceiling-mounted base stations 2.0 were used as tracking references for a calibrated quadratic interaction space of 2.5m x 2.5m in each room. The workstations were connected to each other via a 10 GigE network connection and ran a distributed two-user VR application designed for the study. In particular, each machine rendered the shared virtual environment with a resolution of 1080x1200 pixels per eye and an update rate of 90Hz. Both workstations were connected to a *Mumble* server to allow for audio communications using the built-in headphones and microphones of the head-mounted displays. An additional separate desktop setup allowed the experimenter to control the user study and to talk to both participants in the instruction phase.

5.2 Conditions

Since the focus of our study was on investigating techniques for the *Performing* phase of joint navigation, we decided on a static navigational group assignment throughout the whole study. As a result, virtual *Forming* and *Adjourning* mechanisms were not necessary. Regarding *Norming*, we randomly assigned a static navigator role to one person of each team in the beginning of the study. This allowed us to study the effects of our techniques on both user roles in isolation while excluding potential confounders.

For *Performing*, the *Baseline* condition was a straightforward adaptation of *Multi-Ray Jumping* for two remote users without additional formation adjustment options. We overlaid the tracking spaces of both

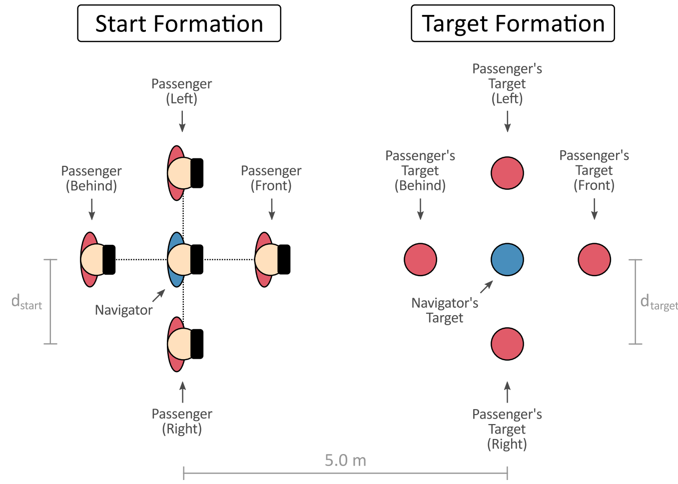

Fig. 4. For a task item, navigator and passenger started in one of four configurations with varying interpersonal distances. The task involved to jump and potentially adjust the group's formation at the target, either by physical walking (*Baseline* condition) or by specifying virtual formation adjustments during the jumping process (*Adjust* condition).

users in the virtual environment for this condition, and a jump did neither change the spatial arrangement nor the viewing orientations of the group. A secondary ray during target specification showed the passenger's offset target position in addition to the target indicated by the navigator. User avatars were made semi-transparent during target specification to ensure that both target rays were always visible. Afterwards, an instant transition without post-travel feedback was implemented to teleport both users to their targets.

The *Adjust* condition extended this baseline implementation by the options for virtual formation adjustments presented in Section 4.1. We decided on a passenger placement range between $d_{p\_min} = 0.46m$ and $d_{p\_max} = 3.70m$ as the boundaries of intimate space and social space, respectively [23]. On the touchpad, these distances were mapped onto swipes between $d_{s\_min} = 0.0025m$ and $d_{s\_max} = 0.02m$. A coarse discretization of $num\_dir = 4$ cardinal directions facilitated the creation of formations involving users standing next to, in front of, and behind each other. In both conditions, group awareness was enhanced by showing the boundaries of both tracking spaces to indicate the available walking areas.

5.3 Experimental Task

In order to investigate virtual formation adjustments on navigation performance and user experience, we decided to recreate typical situations during two-user jumping that require formation changes. Two frequently occurring formations in this regard are side-by-side and queue formations, which support the joint observation of a common focus point [27] or the joint navigation through narrow pathways [29], respectively. However, regularly structured environments like office floors or Manhattan-based city models often require physical turns of 90°, which changes a side-by-side formation to a queue formation and vice versa. Furthermore, turns of 180° change the order of users within a formation. As a result, we chose transitions within and between side-by-side and queue formations to compare both physical and virtual formation adjustments in our study.

As visualized in Figure 4, a single task item of our study asked the two participants standing in a side-by-side or queue formation to perform a short jump ($5m$ for the navigator) and potentially adjust the group's formation at the target. A task item is characterized by its start and target formation, each of which consists of a passenger direction to the *left*, to the *right*, in *front* of, or *behind* the navigator together with the corresponding interpersonal distance. The task item $[behind, 1m] \rightarrow [right, 1m]$, for example, describes the change of a queue to a side-by-side formation without changing the distance be-

right	→	*right*
left	→	*right*
right	→	*front*
right	→	*behind*
behind	→	*right*
front	→	*right*
behind	→	*front*
front	→	*behind*

×

$1m$	→	$1m$
$1m$	→	$2m$
$2m$	→	$1m$
$2m$	→	$2m$

Table 1. Eight chosen transitions of passenger directions combined with four transitions of interpersonal distances resulted in a total of 32 task items for each condition of our study.

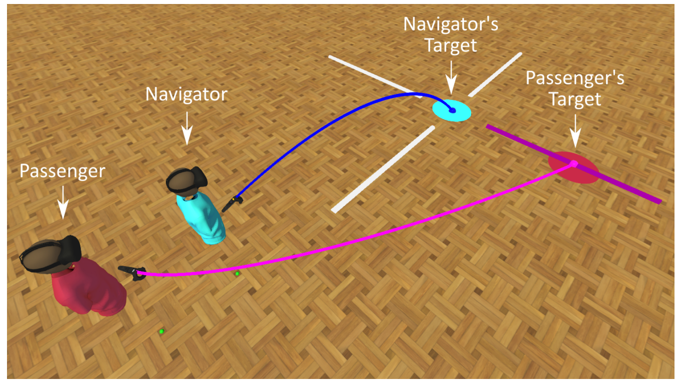

Fig. 5. Screenshot of two users completing the task item $[behind, 1m] \rightarrow [right, 2m]$ in the *Adjust* condition of our user study. The specification of virtual formation adjustments allows the navigator to directly place the passenger to the right of them during the jump.

tween both users. Our structure encompasses 16 possible transitions between passenger directions with arbitrary distances each. In order to reduce the directional transitions for our study, we decided to (1) reduce all transitions not involving formation changes to one representative and (2) merge start and target formations of the form $[left, d_i]$ and $[right, d_i]$ to one representative since passenger placements from and to either side of the navigator induce the same amount of physical effort and visual occlusion by avatars. Regarding interpersonal distances, we focused on a *small* distance of $1m$ and a *large* distance of $2m$. Our resulting 32 task items per condition are shown in Table 1. All task items were presented to the users in a continuous navigational sequence that asked them to perform physical rotations after completion of one task item in order to prepare the starting formation of the next task item. As a result, task randomization was constrained in a way that the start distance of a task item (d_{start}) always had to be identical to the target distance (d_{target}) of the previous one.

To study the operation of our travel techniques without any confounding external factors, we deliberately chose a very simplistic virtual environment for our study. It consisted of a large empty room with textured floor and ceiling, in which the next targets of both navigator and passenger were visualized as circular areas of diameter $0.5m$ on the floor. A task item was activated by a button press and considered complete once both users were standing within their assigned target areas. After completion, arrows were shown to guide participants to physically rotate to the next starting formation before activating the next task item with a button press. A screenshot of two users completing an exemplary task item in the *Adjust* condition is shown in Figure 5.

5.4 Procedure

Participants arrived at our lab in pairs, signed an informed consent form, and answered some general questions on their current health conditions. Participants reporting physical diseases or problems with color or stereo vision or were excluded from the experiment. Eligible teams were then randomly assigned to the navigator and passenger role and introduced to the hardware setup of the user study. All teams tested both the *Baseline* and *Adjust* condition in a within-subjects design, where both conditions were presented in counterbalanced order. Participants put on their head-mounted displays and received an explanation of the first travel technique. In a training session, they had the chance to practice the first technique and the task procedure in 13 unrecorded exemplary task items and ask questions if necessary. The following recorded phase involved the completion of all 32 task items motivated in the previous section in a semi-randomized order. Participants could talk to each other during both the training and the recorded study phase for coordination. Afterwards, we asked participants to fill in a Raw TLX questionnaire, a simplified variant of the NASA-TLX questionnaire [24, 25], to quantify the perceived task load. Furthermore, we added a custom questionnaire for task-specific feedback regarding the current condition. After a break of five minutes, this procedure was repeated for the second condition. In the end, participants filled in an additional concluding questionnaire on subjective technique preferences and demographics. The whole study took approximately 60 minutes to complete and was rewarded with an allowance of 10 Euros.

5.5 Dependent Variables and Hypotheses

A task item in our study was activated by a button press and considered complete when both users arrived within their assigned target areas. For each task item, we captured its duration (task completion time) and the physical walking distances of both the navigator and the passenger in their tracking spaces.

First of all, we were interested in finding out if the additional efforts of operating our interface for virtual formation adjustments would result in more efficient task completion:

H_1: The average task completion time in the *Adjust* condition will be smaller than in the *Baseline* condition.

Because formations can be adjusted virtually without physical locomotion, we hypothesized smaller walking distances for both user roles in the *Adjust* condition:

H_2: The average physical walking distances of both the navigator and the passenger will be smaller in the *Adjust* condition than in the *Baseline* condition.

Regarding the results of the Raw TLX questionnaire conducted after each study condition, we hypothesized a smaller score for the passenger role. However, we were uncertain if the additional responsibilities placed on the navigator would result in the same directional effect:

H_3: The task load score of the passenger will be smaller in the *Adjust* condition than in the *Baseline* condition. The task load score of the navigator will differ between both conditions.

Finally, without formulating concrete hypotheses, we asked navigator and passenger after each condition to rate how often spatial confusions occurred during jumping on a scale from 1 (never) to 7 (always). We also asked the navigator how well they understood the operation of the jumping technique from 1 (very poorly) to 7 (very well). In the end, both users stated their preferred travel technique of the user study. As the *Adjust* condition only allowed changes in the target point of the passenger without generating more or less motion flow than the *Baseline*, we did not expect differences in simulator sickness between both conditions and therefore excluded this measurement from our studies. However, the experimenter frequently ensured themselves of the participants' continued wellbeing in verbal conversations before, between, and after the trials of the study.

5.6 Participants

40 students and employees of our university from diverse fields (16 females and 24 males) between 20 and 38 years ($M = 26.13$, $\sigma = 3.82$) participated in our study in pairs. The sample consisted of four female-only, eight male-only and eight mixed dyads. Previous experiences with head-mounted displays varied, covering the full range of a scale

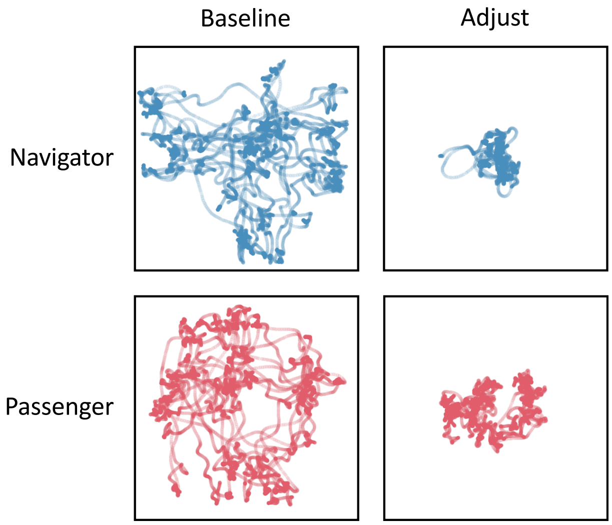

Fig. 6. Motion maps of an exemplary participant team, which indicate the tracked physical walking patterns of navigator and passenger throughout all task items in both the *Baseline* and the *Adjust* condition.

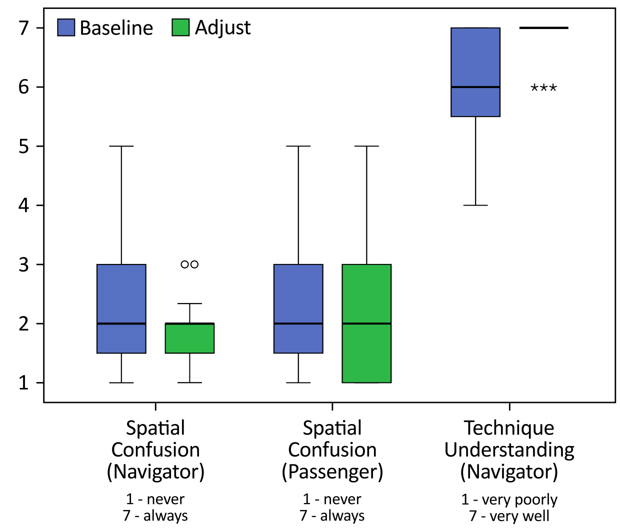

Fig. 7. Distributions of user responses rating the amount of spatial confusions during jumping (both user roles) and the understanding of technique operation (navigator only) after each condition on a discrete ordinal scale from 1 to 7.

from 1 (not experienced) to 7 (very experienced), $Mdn = 3$, $\sigma = 3.82$. Furthermore, team members mostly stated to know each other reasonably well on a scale from 1 (never met before) to 7 (best friends or romantic relationship), $Mdn = 5$, $\sigma = 1.55$.

5.7 Statistical Results

When analyzing data for normality, visual inspections of the normal QQ-plots were used in combination with Shapiro-Wilk Tests [47]. When data was non-normally distributed, we use a non-parametric test for the statistical comparison of both conditions. For each test, we computed the effect size r and applied the threshold values 0.1 (small), 0.3 (medium), and 0.5 (large) introduced by Cohen [13].

The average task completion time in the *Adjust* condition ($Mdn = 4.63s$, $\sigma = 2.24s$) was significantly smaller than in the *Baseline* condition ($Mdn = 8.44s$, $\sigma = 3.33s$), $W = 0$, $p < 0.001$, $r = 0.88$ (large effect). We therefore accept H_1.

The average physical walking distances of the navigators in the *Adjust* condition ($Mdn = 0.18m$, $\sigma = 0.18m$) were significantly smaller than in the *Baseline* condition ($Mdn = 1.49m$, $\sigma = 0.46m$), $W = 0$, $p < 0.001$, $r = 0.88$ (large effect). The same was true for a comparison of walking distances for the passenger role (*Adjust*: $Mdn = 0.25m$, $\sigma = 0.25m$; *Baseline*: $Mdn = 2.23m$, $\sigma = 0.43m$), $W = 0$, $p < 0.001$, $r = 0.88$ (large effect). This leads to an overall acceptance of H_2. A motion map of an exemplary participant team throughout all task items in both conditions is shown in Figure 6.

The task load scores of the navigators in the *Adjust* condition ($M = 19.42$, $\sigma = 10.11$) were significantly smaller than in the *Baseline* condition ($M = 32.79$, $\sigma = 18.95$), $t(19) = 3.94$, $p = 0.001$, $r = 0.67$ (large effect). The same was true for a comparison of task load scores for the passenger role (*Adjust*: $M = 16.37$, $\sigma = 12.40$; *Baseline*: $M = 36.00$, $\sigma = 15.55$), $t(19) = 6.91$, $p < 0.001$, $r = 0.85$ (large effect). We therefore also accept H_3.

Figure 7 shows the distributions of answers given to the questions on spatial confusion after jumping (both user roles) and understanding of technique operation (navigator only). In total, the *Adjust* condition was preferred by 13 of 20 navigators and 7 out of 20 passengers.

5.8 Discussion

Our controlled two-user study investigated pre-defined group jumping sequences between and within side-by-side and queue formations. The absence of salient landmarks and a secondary task in the virtual environment allowed us to study the effects of both jumping techniques in isolation without external confounders. As expected, our results showed that virtual formation adjustments during jumping reduce the necessity of physical walking largely, which is especially helpful for users in small tracking spaces and seated setups. Moreover, the additional effort required by the navigator for technique operation in the *Adjust* condition did not overshadow the benefits of reduced physical walking, which is indicated by significantly smaller task completion times and task load scores. The usability and comprehensibility of the *Adjust* technique were further confirmed by the responses regarding spatial confusion and understanding of technique operation (Figure 7). Navigators and passengers seemed to be always aware of each other's respective position after the jump. The observation of the jump planning process by the passenger and the actual planning of the jump by the navigator seem to foster a good spatial understanding of the future formation of the group for both.

Despite the positive results of the *Adjust* condition, only half of the participants favored it over the *Baseline*. While only one navigator stated problems with the *press-swipe-release* paradigm in this regard, the main reason mentioned by both user roles was the lack of teamwork and interesting things to do in the *Adjust* condition. Because of the simplicity of our study task, in which the system dictated the sequence of jumps to be executed, they found the cooperation and planning needed in the *Baseline* condition more stimulating than the more efficient *Adjust* technique. However, we argue that the additional cognitive resources available in the *Adjust* condition are beneficial in more realistic scenarios, where travel is just a byproduct of solving a higher-level collaborative task. In order to investigate this claim in more detail, the next section reports on the results of an expert review focusing on two-user navigation in a broader use-case scenario.

6 Expert Review of Joint Two-User Navigation

The previous study indicated that our implementation of virtual two-user formation adjustments is less laborious to operate and hence more time-efficient than adjusting user formations by physical walking. Nevertheless, the studied formations were restricted to passenger positions in four cardinal directions around the navigator, and the task solely focused on travel without a higher-level goal of joint navigation. In a qualitative expert review, we therefore aimed at investigating dynamic occurrences of situations requiring formation adjustments and the operation of our technique in a more realistic task scenario and a richer virtual environment. Moreover, we wanted to shed light on the complete process of joint navigation from *Forming* to *Adjourning* and analyze navigational strategies when giving users the opportunity to freely choose between individual and joint navigation. For this study, we used the same experimental setup as described in Section 5.1.

Fig. 8. Bird's eye view of the virtual environment used for our expert review. The orange and blue circles highlight the positions of the features that had to be located and presented by the first and the second user, respectively. The size of the virtual town model was 125m x 125m.

6.1 Participants

12 experts (3 females and 9 males) between 20 and 34 years ($M = 26.83$, $\sigma = 4.62$) participated in our study in pairs of two. All of them had been using head-mounted displays regularly for at least one year prior to the study. Also, participants had additional backgrounds in computer science, civil engineering, architecture, or combinations thereof. They were hence able to provide valuable feedback regarding our navigation techniques and to judge their potentials for domain-specific use cases.

6.2 Experimental Task

We simulated a situation in which two participants with different knowledge backgrounds meet in virtual reality and aim to share and discuss their expert knowledge with each other. This mediation between different user roles and their skills is a central task in architectural design reviews, collaborative construction processes, and urban planning [1, 28, 42, 51]. Before the VR exposure, each participant of a team was briefed about four imaginary background stories regarding small features in a virtual town model (see Figure 8). The task in virtual reality was to locate the corresponding features in the town and to present them to the other collaborator. To simplify the memorization process, all stories were deliberately kept short and simple to follow. The task was complete once all eight features and their stories were presented to the respective other user.

To fulfill this task, participants could freely choose between individual and joint navigation at any time. For *Forming* a navigational entity, a mutual confirmation mechanism was implemented by requiring both users to hold their virtual controller representations together for one second, resulting in a short animation to visualize the joining process. Regarding *Norming*, we used a navigator-passenger role distribution again, but this time, each user could become the navigator by activating target specification when no jump was currently planned by the other user. During target specification, the touchpad button of the passenger blocked the navigator's jump for the duration of the press, which could be used to indicate disagreement. *Performing* was supported by a refined implementation of *Multi-Ray Jumping* with formation adjustments ($d_{p\_min} = 0.46m$, $d_{p\_max} = 2.0m$, $d_{s\_min} = 0.0025m$, $d_{s\_max} = 0.015m$, $num\_dir = 8$) for group travel, a connecting line on the floor for group awareness, and the same audio connection and avatars as in the previous study for group communication. An instant transition without post-travel feedback was implemented to teleport both users to their targets. For *Adjourning*, each user could leave the group by singular confirmation using a separate button on the controller. A screenshot of an exemplary target specification process during joint navigation in the virtual town model is given in Figure 1.

6.3 Procedure

Participants arrived at our lab and signed an informed consent form. They were introduced to the two-user experimental setup and completed an interactive tutorial and training session in virtual reality, where the experimenter explained all navigational possibilities the system had to offer. Afterwards, each participant was given four paper sheets explaining one background story each, including images of the corresponding feature without revealing its placement in the context of the town. Both participants memorized their features before putting the head-mounted display back on. They entered the study environment, in which they searched for and presented their features to the other user. In parallel, the experimenter ensured that the task was fulfilled correctly by watching the mirrored HMD displays and listening to the audio stream. After all eight features were presented, the study concluded with a semi-structured interview that focused on navigational strategies, technique usage and use cases for individual and coupled navigation. The whole study took approximately 60 minutes to complete and was rewarded with an allowance of 10 Euros.

6.4 Results

All expert teams could solve the task successfully taking between 6.6 and 14.0 minutes ($M = 9.9$ *min*, $\sigma = 2.4$ *min*) and performed a grand total of 683 individual and 510 joint jumps (including 169 jumps involving formation adjustments). In the following, we analyze which navigational strategies were adopted regarding the choice of individual and joint navigation (Section 6.4.1), how users distributed responsibilities for joint navigation (Section 6.4.2), how our implementation of formation adjustments was used (Section 6.4.3), and which domain-specific use cases for individual and joint navigation were discussed by our experts (Section 6.4.4).

6.4.1 Transitions between Individual and Joint Navigation

All participants decided to form navigational groups for solving parts of the study task, with the usage proportions of joint navigation varying between 41.8% and 95.9% of the task completion time ($M = 64.6\%$, $\sigma = 18.4\%$). Some teams mentioned that the main advantage of individual navigation is getting an overview of the environment using faster jumps than during joint navigation, where navigators took more care not to overwhelm their passenger with fast input sequences. A slight trend in this direction could be confirmed for the whole sample, where the mean target specification time was $0.598s$ ($\sigma = 0.85s$, 95% CI = [$0.535s$; $0.662s$]) for individual jumps and $0.830s$ ($\sigma = 1.02s$, 95% CI = [$0.721s$; $0.940s$]) for group jumps without formation adjustments. Joint navigation was appreciated for supporting collaborative work and discussions while preventing the partners from losing each other. This focused verbal communication more on the higher-level task than on concrete navigational instructions and meeting point negotiations. While one team decided on joint navigation for almost the whole task duration, two groups started the study with an individual exploration phase of the town before forming a group to guide each other around. The remaining three teams used more flexible mixtures between phases of individual and joint navigation, mainly switching to individual navigation to avoid physical walking in the tracking space for small viewpoint adjustments during maneuvering around the points of interest. Apart from that, these groups adjourned more frequently to check certain landmarks of the town on their own before re-grouping and guiding the other user to the points of interest.

6.4.2 Role Distributions during Joint Navigation

All teams could verbally coordinate themselves in a way that the presenting user of the next background story always operated the jumping technique, which was used to guide the other user to the corresponding feature in the virtual town. As a result, our implemented blocking feature to signal disagreement was hardly used and only rated helpful for collaborative virtual environments that do not support audio communications. When asked for their preferred role during navigation, only two users decided on the navigator role while the other ten users could not form a decision. Instead, they stated that their choice would be highly dependent on the current task and the division of responsibilities within the group. Throughout all participants, the visual feedback provided by *Multi-Ray Jumping* was deemed helpful for passengers to understand the navigator's intentions and the future formation of the group after the jump. In contrast to the results of our previous study, users did not report a lack of stimulation in the passenger role.

6.4.3 Formation Adjustments during Joint Navigation

The specification of virtual formation adjustments during jumping could be easily learned and operated by all participants. During joint navigation over longer distances, users frequently reestablished side-by-side formations after physical rotations to continue travel. Moreover, some navigators decided to place the passenger in front of them in order to allow them a free view onto the environment while being able to monitor their avatar for signs of confusion or disagreement. When approaching a point of interest, navigators used formation adjustments to place the group conveniently for its joint observation and discussion. The mean target specification time for jumps with formation adjustments was $1.810s$ ($\sigma = 1.00s$, 95% CI = $[1.659s; 1.963s]$) and hence longer than for group jumps without this addition, which is reasonable regarding the additional responsibilities of finding and specifying a suitable group constellation instead of keeping the relative user offset unchanged.

Despite being proposed as the boundary of intimate space in the real world, some teams considered the value of $d_{p\_min} = 0.46m$ too large and temporarily switched to individual navigation to jump closer to their partner. The discretization into eight placement directions was sufficient for generating a large number of formation adjustments while only requiring small physical corrections for directions that did not match the pre-defined axes. Nevertheless, some participants raised the question if applying appropriate filtering mechanisms to the touchpad data could achieve precision enhancements without imposing directional placement constraints. Two teams were also interested in adjusting the viewing orientation of the passenger in addition to the spatial arrangement of the group, which should be investigated in future work in more detail – especially since the combination of translational and rotational changes during jumping is usually criticized for impairing spatial awareness and user experience more than either of theses changes [8, 43]. Overall, virtual formation adjustments for group jumping were considered helpful by ten users. The remaining two found paying attention to their partner's position exhausting and favored a system-driven approach that automatically infers suitable formations upon the selection of a point of interest.

6.4.4 Use Case Scenarios

Our experts with a background in architecture appreciated joint navigation in the context of virtual design reviews, in which user groups with different backgrounds inspect and evaluate the layout of a building together. Furthermore, they considered joint navigation with virtual formation adjustments as a "presentation tool" that experienced users can use to guide beginners around. After the presentation is finished, adjourning the group and navigating individually could help novices to deepen their understanding of certain aspects of the presentation. Our experts from civil engineering would like to perform structural health monitoring of buildings, bridges, and other objects in virtual reality. They suggested that individual navigation could be used by a single expert to identify potential damages, which could be shown to other experts using group navigation. Both architects and civil engineers mentioned, however, that additional collaborative tools like virtual annotation and object manipulation functionalities would be needed for their scenarios. Overall, all experts agreed that individual navigation is more fast-paced while joint navigation with virtual formation adjustments was considered more suitable for discussions, guided tours, presentations, and storytelling.

6.5 Discussion

While our first study focused on the operation of jumping techniques in isolation, a common high-level task and a more flexible distribution of travel controls resulted in a more realistic and ecologically valid experience in our expert review. Our results confirm that allowing users to switch between individual and group navigation can be beneficial for the collaborative work of spatially distributed participants. We therefore conclude that *Forming* and *Adjourning* mechanisms should be lightweight and easy to use to allow fluent transitions between individual and group navigation. Although our task could have been solved by individual navigation only, participants agreed that group navigation helped them to stay together to focus on the joint observation, discussion, and evaluation of virtual content. The addition of virtual formation adjustments allowed navigators to resolve problematic situations arising during group jumping and to direct passenger attention to interesting features without the need of giving verbal navigation instructions. Experts engaged in discussions of alternative implementations including different parametrizations of our technique, the usage of alternative input devices known from other HMD systems, and system-driven approaches to automate user placement. The benefit of individual navigation mainly lay in the affordance of more fast-paced travel sequences, which were used to obtain an overview of the environment and to select features to be discussed during group navigation. Overall, our system was rated as being useful for several use-case scenarios involving groups with different role constellations.

7 Conclusion and Future Work

In this paper, we described and explored the design space of group navigation techniques for distributed virtual environments. Our group navigation framework suggests that users need to be able to form navigational groups (*Forming*), distribute navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*). For *Performing* group navigation, we introduced the idea of supporting virtual formation adjustments as part of group jumping and evaluated a two-user implementation in both a controlled and a more realistic scenario. The observed large effect sizes in our quantitative user study indicate that virtual formation adjustments can make the group travel process considerably more efficient and contribute to a reduction in task load for the navigator as well as the passenger. Our qualitative expert review involved all four stages of the group navigation process in a more open and realistic use-case scenario and confirmed the effectiveness and efficiency of group navigation with virtual formation adjustments. Nevertheless, it also demonstrated the need to support smooth transitions between individual and group navigation depending on the current task and task sharing.

Future work will explore alternative techniques and mechanisms for all four stages of joint navigation and will particularly focus on larger groups. To assist the *Forming* process, additional mediators in the virtual environment can help users to find each other more easily or to quickly re-join groups that were previously adjourned. Regarding *Performing*, our implementation of virtual formation adjustments worked well for pairs of two participants, but the specification of multiple passenger positions during target specification might be too demanding. Instead, navigators could select from common group formations like side-by-side, vis-a-vis, L-shape, or circular arrangements. Alternatively, suitable formations could be automatically inferred by considering, for example, the visibility of a point of interest for each participant. Furthermore, *Performing* should support different travel metaphors such as steering, driving, or flying depending on the users' preferences and the virtual environment. In conclusion, we believe that future social virtual environments should allow all kinds of users to get somewhere together comfortably by using appropriate mechanisms for group *Forming*, *Norming*, *Performing*, and *Adjourning*.

Acknowledgments

Our research has received funding from the European Unions Horizon 2020 Framework Programme for Research and Innovation under the Specific Grant Agreement No. 785907 (*Human Brain Project SGA2*) and from the German Ministry of Education and Research (BMBF) under grant 03PSIPT5A (*Provenance Analytics*). 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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