Going, Going, Gone: Exploring Intention Communication for Multi-User Locomotion in Virtual Reality

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Figure 1: We explore shared preview visualizations for point&teleport in multi-user scenarios to enable non-verbal intention communication for joint locomotion in Virtual Reality.

ABSTRACT

Exploring virtual worlds together with others adds a social component to the Virtual Reality (VR) experience that increases connectedness. In the physical world, joint locomotion comes naturally through implicit intention communication and subsequent adjustments of the movement patterns. In VR, however, discrete locomotion techniques such as point&teleport come without prior intention communication, hampering the collective experience. Related work proposes fixed groups, with a single person controlling the group movement, resulting in the loss of individual movement capabilities. To close the gap and mediate between these two extremes, we introduce three intention communication methods and explore them with two baseline methods. We contribute the results of a controlled experiment (n=20) investigating these methods from the perspective of a leader and a follower in a dyadic locomotion task. Our results suggest shared visualizations support the understanding of movement intentions, increasing the group feeling while maintaining individual freedom of movement.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *Social navigation.*

KEYWORDS

SocialVR, Locomotion, Teleportation, Multi-User, Connectedness, Virtual Reality

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1 INTRODUCTION

When we walk through the physical world together with other people, we unconsciously adjust our step frequency and length to constantly keep in close proximity to our travel companions. This spatial proximity enables communication within the group, enables situation understanding of the others' actions [32] and supports the feeling of social connectedness. In contrast, walking together in social Virtual Reality (VR) is often challenging: Widespread locomotion techniques such as point&teleport do not allow to anticipate the actions of other users, causing them to spontaneously disappear and emerge at a different location with each movement step. While this is convenient and efficient for fast navigation through virtual worlds from an individuals perspective, each movement tears the group apart, forcing users to constantly pay attention to the actions of others in order to re-form the group by resembling the locomotion step and negatively affecting social interactions of users [21].

Research proposed various approaches to support joint locomotion in VR. As a prominent example, Weissker et al. proposed multiple designs for group teleportation [41, 44, 45], allowing for simultaneous teleportation of multiple players. Here, a so-called navigator controls the movement of the whole group, consisting of the navigator and one or more passengers. However, this approach allows for no or little control of the passengers, prohibiting individual movement. However, Wang et al. [40] found that individual movement is preferred by users while movement controlled by others is most disliked, except for special use cases like guided tours. This leaves a gap between social but coupled group teleportation on one hand and individual teleportation, resulting in the potential splitting of a group on the other hand. Only little research investigated this intermediate of individual yet joint motion in VR, as known from the physical world.

To address this gap and provide further insights into collaborative teleportation in VR, we investigate the effects of shared trajectory visualizations on the understanding of movement intentions and social connectedness to a group while aiming for a maximum of individual freedom of movement. To that end, we deconstruct the individual teleportation preview and implement three shared visualization methods for teleportation that show (1) only the target, (2) only the direction, or (3) both. We evaluate these in a controlled experiment (n=20) investigating the methods from the perspective of a leader and a follower in a dyadic locomotion task. Here, we compare the three methods against a state-of-the-art point&click teleport and fixed group teleportation inspired by related work as baselines and contribute the results.

Our results show that participants better understand the movement intentions of their co-player with the proposed methods, resulting in a more convenient and easy joint movement through the virtual space. Participants like this additional information and appreciate their freedom of movement while still perceiving themselves as part of a group. Consequently, participants state they would like to use some of our proposed methods in the future.

2 RELATED WORK

To situate our work, we give an overview of 1) existing locomotion techniques for single users in VR, 2) state-of-the-art group locomotion techniques in VR, and 3) social aspects of motion.

2.1 Single User Locomotion in VR

Taking a look at existing single user VR locomotion techniques, several typologies exist. In a systematic literature review Boletsis [6] presents existing techniques and derives four main categories for single-user locomotion, dependent on the input modality: *Motion-based* and *roomscale-based* locomotion both use body motion in the physical world as basis for the translated locomotion in VR. Both result in continuous locomotion in the virtual space. While *roomscale-based* requires congruent physical and virtual spaces and translates the motion without adjustments, motion-based techniques can manipulate the motion during the translation into the virtual domain, e.g., through redirected walking [31, 33], by translating arm motion into walking [29] or using physical jumps [49] as input for a scaled jump in VR.

The *controller-based* locomotion uses a button or joystick input and translates it into a continuous motion in the virtual domain. In contrast to the prior three types, the *teleportation-based* locomotion results in a non-continuous motion, e.g., in the form of point&teleport [8]. This unique separation is already previously described by Slater and Usoh [37] in a broader context and divides interactions into *mundane* and *magical*. Here, mundane interactions reproduce an interaction from the physical reality, while magical interactions include all that are impossible in the physical world. In a recent update to the presented typology Boletsis and Chasanidou [7] further distinct *motion-based-teleporting* and *controller-based-teleporting*.

The perception of locomotion in the virtual domain differs strongly between continuous and non-continuous techniques. Continuous locomotion techniques more closely resemble movements familiar from the physical world, particularly without interruptions, and therefore pose less of a problem for collective locomotion. However, common side effects of continuous locomotion in VR are dizziness, (cyber)sickness, and nausea as described by Hettinger et al. [16]. As Jacob Habgood et al. [19] conclude from their study, non-continuous and discrete locomotion in the form of teleportation strongly reduces these negative side effects. Together with the ability to travel fast and precise through the virtual space, this makes point&teleport locomotion as introduced by Bozgeyikli et al. [9] the de-facto standard for many VR applications and is the most common form of locomotion on commercial social VR platforms [21]. In a comparison between different controller-based locomotion techniques Frommel et al. [14] conclude that the free point&teleport elicits the least discomfort and best ensures enjoyment and presence. Multiple variations and additions of the point&teleport exist, for instance, Funk et al. [15] enable users to adjust the post-teleport orientation, Matviienko et al. [27] allow movement in 3D space and Müller et al. [30] introduce an undo for teleport steps. Additionally, research explores different input modalities for teleportation like the feet[10, 39], the head's movement [11] and eye gaze[25]. While interesting and valuable, these works focus mainly on a single user and do not account for possible social disruptions.

2.2 Group Locomotion in VR

While the body of related work for single-user locomotion is well explored, multi-user locomotion remains niche and only recently received growing attention in the research community. As Weissker et al. [42] state, using single-user teleport in group scenarios can result in "*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*". As they further summarize, multiple forms of group locomotion exist that distinguish between collocated and distributed physical workspaces as well as the number of users in the workspaces. Azmandian et al. [3] investigated the possibilities of redirected walking in a multi-user context. With this as a continuous locomotion technique, the same advantages and disadvantages of single-player redirected walking come. Other examples of continuous multi-user locomotion include a car driving scenario [36] or a projector-based telepresence system [5]. However, these are physically coupled cases, which is not the focus of this work. In AltspaceVR[1] *PartyPortals* allow individuals or groups of individuals to travel to a different scene [21]. While this is a discrete travel, it focuses less on the actual locomotion but takes players to a different world.

As one of the few examples of discrete multi-user locomotion in VR, Weissker et al. [45] use the metaphor of a dyadic driver/passenger scenario in Multi-Ray-Jumping, where one player decides the teleport destination for two players. To make the aiming of the driver more comprehensible, instead of providing only one targeting ray, both players see two rays, one for the driver, and one for the passenger, translating the current spatial configuration to the target position. This incorporates the pointing aspects [1] of intention communication which is also assessed by Mayer et al. [28] in a multi-user VR context. In the follow-up paper by Weissker et al. [41], the passenger can now decide on the relative position before the joint teleport. Extending this concept further and beyond only dyadic scenarios, Weissker and Froehlich [44] allow for group teleportation for up to ten users with adjustable position configurations to be used in guided tour scenarios. Passengers of these studies did not report increased cybersickness or discomfort. With Holding Hands, Weissker et al. [43] propose a new interaction technique, allowing for a more dynamic forming and adjourning of a group. Here, users can choose to move as a group by holding their virtual hands together before performing a teleport. Users of this technique understand and like this metaphor if they are close friends. However, Weissker et al. [43] mention that this technique might result in unpleasant feelings for unacquainted participants.

Independent of VR, one central question is "What is a group?". Trying to understand what a group is and what is not goes beyond the scope of this work. We refer to a group as two or more users with the shared motivation of moving through space. As Weissker et al. [42] discuss in the limitations of their overview paper, passing over control to another person can dissatisfy people and is not the appropriate solution for all cases. Therefore, they identify the crucial need for further studies, investigating individual locomotion techniques that foster staying together as a group at the same time.

[1]https://altvr.com

2.3 Social Aspects of Motion

Besides the locomotion aspect of movement, it conveys many social cues mostly unnoticed on a daily base. Distance between people, rotation of bodies as well as mimicking a counterpart have a strong effect on interpersonal relations. Further, synchronized movements are linked to increased liking [17], higher cooperation [34], and trust [23] in between people. Synchronizing body movement to the sounds of a virtual counterpart further increases the partner's likeability according to Launay et al. [24] and "increase cooperation by strengthening social attachment among group members"[47]. Robinson et al. [35] use synchronized physiological data of two remote players to let them "control" their shared boat in a computer game to foster their connection and social closeness by joint movement. When moving in synchrony, individuals perceive themselves as part of an entity as Lakens [22] investigates. This follows the concept of common fate, discussed by Wiltermuth and Heath [47]. As Tarr et al. [38] demonstrate, these effects also apply to synchronized movements in VR. In a user study, they investigate the effects of synchronous and asynchronous movement of a small group of avatars in a VR environment and report greater social closeness of avatars that move synchronously. On the contrary, Kolesnichenko et al. [21] conclude from interviews with VR designers that far-distance teleportation, and therefore the breaking of a perceived group, negatively affects the social interactions of users. Further, in the context of personal space, movement plays an important role, as it can respect or violate personal space, both in the physical [46] and virtual world [21] in the context of social VR platforms.

With these pro-social effects established, the importance of coordinated interpersonal movement is apparent. However, without the interpersonal cues known from the physical world, adjusting motion to another person is challenging. While verbal communication is possible in many cases, Maloney et al. [26] point out the importance of non-verbal communication in VR scenarios.

3 CONCEPT

The previously discussed body of related work shows two completely different approaches for multi-user locomotion in social VR. On the one hand, the established single user point&teleport with maximum freedom of individual movement but no support for social closeness and, on the other hand, fixed group teleportation, with enforced group constellations but no individual movement possibilities. To narrow the gap between these two extremes, and discover potential intermediates taking advantage of different aspects of the two extremes, we propose and evaluate various techniques.

With both techniques relying on teleportation, we propose to extend point&teleport to facilitate the intention communication and joint motion of two players in VR, while maintaining freedom of individual movement. Further, as the current state-of-the-art point&teleport is already designed for good intention communication between the single player and a computer system, we take this available information and deconstruct it into components. Here, we identify the TARGET VISUALIZATION and DIRECTION VISUALIZATION as essential components of information and take them as the two dimensions of our design space. We derive the two levels *individual* and *shared* visualization for each dimension, resulting in a 2 x 2 space.

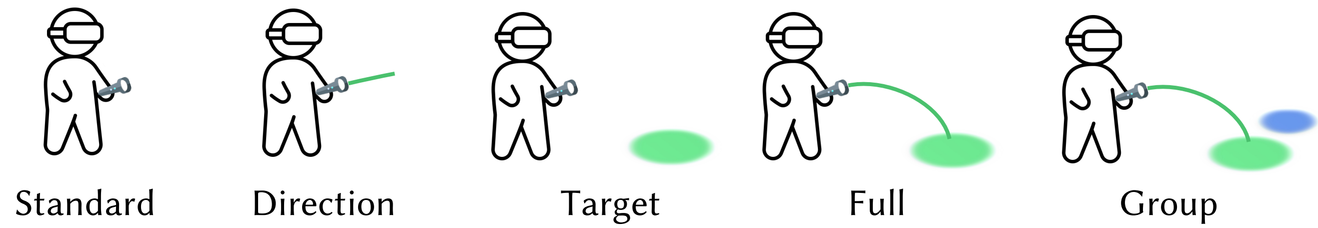


Figure 2: The five levels of the independent variable TECHNIQUE studied in the experiment when looking at the co-player. From left to right: STANDARD Teleport: no additional visualization, DIRECTION indication, TARGET indication, FULL preview and GROUP teleport with a full preview of the co-player plus indication of own target location.

4 METHODOLOGY

Aiming to find a halfway point between the current extremes of individual teleport with full control of individual motion but zero support for synchronization of collective movement and fixed group teleports with a driver-passenger configuration prohibiting individual movement but ensuring synchronization of movement and closeness, we evaluate different levels of shared visualization.

4.1 Design and Task

We design a task for two players in VR, consisting of an individual as well as a collective phase per condition resembling navigation decisions in everyday life. Participants move through a grid-based maze shown in Figure 3. Each intersection offers three paths, including the one leading to the intersection. While cities or buildings rarely follow this design strictly, perpendicular intersections are common decision points. However, as a grid with straight lines proved too easy to navigate through in preliminary tests, we offset every second row as depicted in Figure 3.

The goal for the participants in the first phase is to navigate through the maze and reach one of five possible target points. For each trial, we draw a random target element from a randomized list containing the five possible locations to stimulate participants using different paths through the maze. During this individual phase, participants can move freely, except for the GROUP condition, where individual movement is impossible. Once both players arrive at the target point, a prompt instructs them to return to the starting point, and either Player A or B should lead the way. We do not implement technical restrictions to enforce participants staying together to maintain the same amount of freedom as during the first phase. We allow participants to communicate verbally during the whole task. We designed our task in alignment with our institution's ethics, hygiene, and infection control guidelines.

4.2 Independent Variables

As described in section 3, we investigate different levels of shared visualization and further assign each player a different role per condition. To discover the influence on the dependent variables, we vary these two independent variables (IV) with the following levels.

TECHNIQUE Based on the 2 x 2 design space and a variant of group teleport [45] as an additional baseline, we investigate five different levels (see Figure 2):

- ***STANDARD*** This level mimics a standard point&teleport, as used in many applications as the de-facto standard of single-player locomotion.
- ***DIRECTION*** Players can see the beginning of the other player's preview trajectory.
- ***TARGET*** Players can see the target location of the other player's teleport preview.
- ***FULL*** Players can see the full preview of the other player.
- ***GROUP*** Players can only teleport together as a fixed group, similar to Multi-Ray Jumping [45]. Both players see the full preview of the LEADING player, as well as a target visualization of the FOLLOWING player.

ROLE To account for different roles in social configurations, one of the two players leads the group:

- ***LEADING*** The player leads the other player.
- ***FOLLOWING*** The player follows the other player.

4.3 Dependent Variables

To assess the influence of the TECHNIQUES and ROLE, we survey the influence on the following measures:

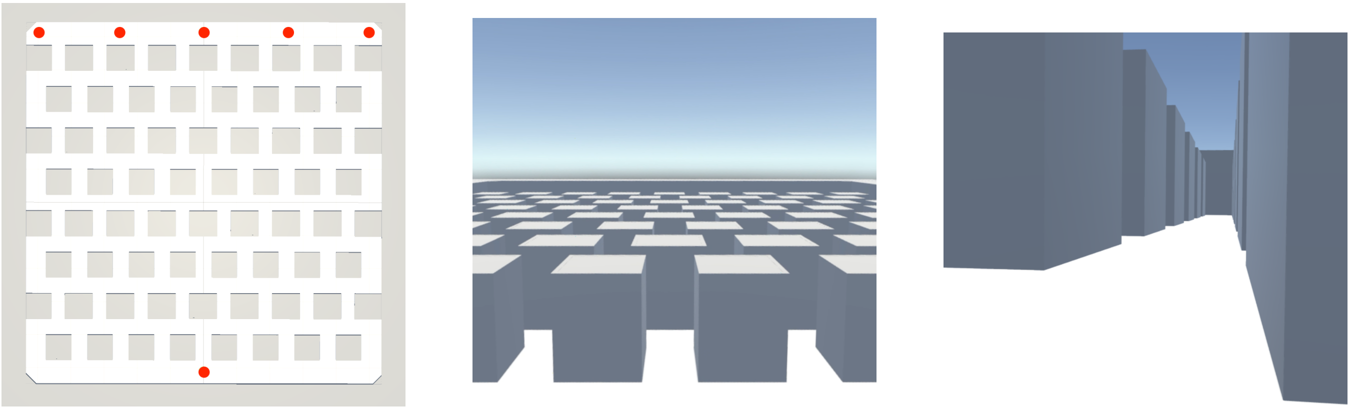
IOS Score The single item questionnaire Inclusion of Other in the Self (IOS) by Aron et al. [2] aims to identify changes in the perceived psychological closeness to the other player.

GEQ Score Here we use the Behavioural Involvement Component of the Social Presence Module in the Game Experience Questionnaire (GEQ) by [18] to measure how much attention players pay to their counterpart.

Custom Questionnaire The questionnaire on a five-point Likert scale holds eight items regarding GROUP-FEELING, FREEDOM OF MOVEMENT, INTENTION UNDERSTANDING, EASE OF STAYING TOGETHER, LOCATION AWARENESS OF OTHER, DESIRED FUTURE USAGE, CONVENIENCE OF USE and FEELING OF SUCCESS.

4.4 Apparatus

We implemented the virtual maze and the interaction techniques as detailed above as a multi-player VR application that was deployed on two connected computers with two head-mounted display (HMD)s using a shared tracking space.



(a) Top view of the maze (b) Maze from bird’s-eye view (c) Participants view into the maze

Figure 3: Three views of the maze (a) from top with the starting point at the bottom and the five potential target points (b) bird’s-eye view showing the maze blocks (c) Participants view into the maze along one row.

The virtual maze spans 110 x 110 meters built from 8 rows with a total of 68 cubes, with every second row offset to prevent a straight path through the maze from the starting point. The staggered rows contain one additional cube and are slightly elongated (10m x 11m x 10m). The remaining cubes have a height, width, and depth of 10 meters and are spaced 4.85 meters apart. The longer cubes are only 4.25 meters apart, and the rows are spaced 4.85 meters apart. Further, we implemented a basic player avatar consisting of only four components: A head, an upper body as well as two hands, each represented by capsules of different radii.

For the information visualizations, we use a line with a range of 0.9m for DIRECTION and a circle with a radius of 1.5m for the TARGET. For FULL, we use a line with a maximum length of 16.5m combined with the target circle. For the GROUP, we add one additional circle at the target location relative to the LEADING player’s location, maintaining the current spacial configuration of the players post-teleport. To distinguish the different teleportation representations, the own elements are colored blue and those of the other player green. Figure 4 provides an overview of the four visualizations. Here we exclusively vary preview visualizations of the co-players and leave the user’s own preview unchanged through all conditions.

We implemented the study design using Unity version 2021.3.1f1 and used Photon[2] PUN 2 to connect the two instances of the study application. We deployed the application on two computers (Intel Core i7-10700, 16 GB RAM, NVIDIA GeForce RTX 2060 SUPER and Intel Core i7-6700K CPU @ 4.00GHz, 16 GB RAM, NVIDIA GeForce GTX 1080). We used two Vive Pro HMDs with the corresponding controllers. The available tracking space was 3.5m x 2.2m. We ensured that the participants did not collide with each other or walls.

4.5 Procedure

After welcoming the pair of participants and briefly introducing the goal of the study, we ask them to fill out the consent form and complete a demographic survey. Participants have the opportunity to ask questions. Following this, we explain the task and the procedure in detail, elaborating on the two phases of the task as well as the techniques to be experienced. Before continuing we make sure to resolve all open questions and unclear points. We then assign the participants their respective workstations, which they will use for the entirety of the study to ensure correct assignment of the ROLE. Here, we also help the participants to put on their VR HMDs and ensure a safe standing distance between both players. Prior to starting the first condition, participants have the opportunity to familiarize themselves with the button assignments for the baseline teleport on the controllers. After checking again if there are unresolved questions, participants start with condition 1 of the experiment.

When both players arrive at the target location, they complete phase one of the condition. They now receive a prompt in VR, informing them to let the LEADING player guide the way back to the starting point. Again, when both players arrive at the starting location, condition 1 ends.

After this, we ask participants to take off their HMDs and take a short break. During this time, participants fill out the post-condition questionnaire consisting of the IOS, GEQ as well as our own questionnaire. When both participants are ready again, they put back on their HMDs and start with the next condition. After completing condition 10 as well as the post-condition questionnaire, participants fill out another questionnaire, comparing the experienced techniques. We then conduct a short, semi-structured interview with both participants to receive qualitative feedback about their experience. Overall the experiment lasts about 60 min. During the study we ask participants if they perceive any form of motion sickness as proposed by Keshavarz and Hecht [20], to be able to abort the experiment if participants feel unwell. We conduct the user study in fulfillment with the regulations in force during the time at our institution. We further disinfect all components participants interact with and ventilate the room in between the trials.

[2] https://www.photonengine.com/en-US/Photon

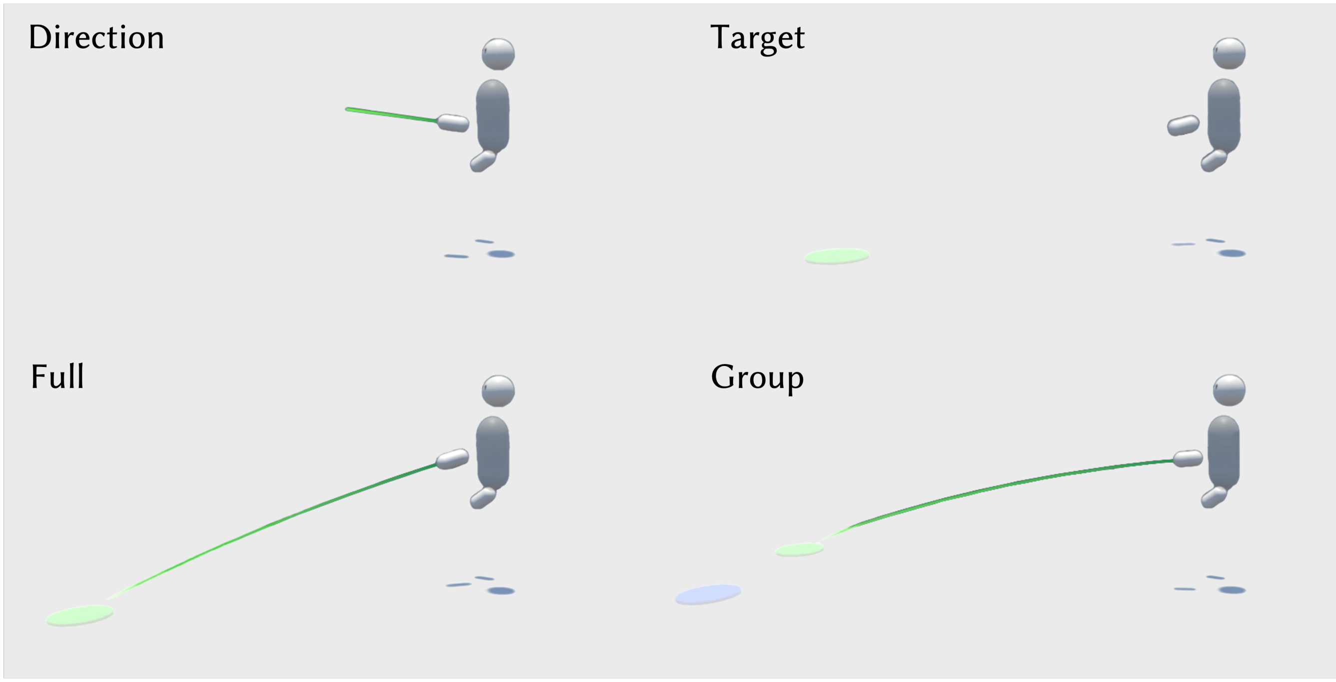


Figure 4: Four implementations of the independent variable TECHNIQUE studied in the experiment when looking at the co-player. From left to right, top to bottom: DIRECTION indication, TARGET indication, FULL preview and GROUP teleport with a full preview of the co-player plus indication of own target location.

4.6 Participants

We recruited 20 participants from our institution and compensate them with an equivalent of approximately 10$. Of the participants 8 identify as female and 12 as male. The participants age between 24 and 34 years, with an average of 27.6 years. 5 participants reported being an experienced VR user, 10 being a sporadic VR user and 5 having no prior VR experience. 16 participants stated to have normal or corrected vision and 4 to have not.

4.7 Analysis

Since the IOS is a single-item questionnaire, we take the ratings of the participants and compare them directly. According to the scoring guidelines of the GEQ, we score the Behavioural Involvement Component as an average of its items.

For the analysis of parametric data, we tested the data for normality of the residuals and sphericity assumptions with Shapiro-Wilk's and Mauchly's tests, respectively. If the assumption of sphericity was violated, we corrected the tests using the Greenhouse-Geisser method. If normality was violated, we performed a non-parametric analysis as described below. For significance testing, we used two-way repeated-measures ANOVAS to identify significant effects and applied Bonferroni-corrected t-tests for post-hoc analysis. Further, we report the generalized ETA squared η_G^2 as a measure of the effect and classify it in alignment with Bakeman [4] and use suggestions by Cohen [12] for small (> .0099), medium (> .0588), or large (> .1379) effect size.

For non-parametric analysis, we applied the Aligned Rank Transformation (ART) as proposed by Wobbrock et al. [48]. For significant results, we follow with the ART-C procedure as suggested by Elkin et al. [13].

5 RESULTS

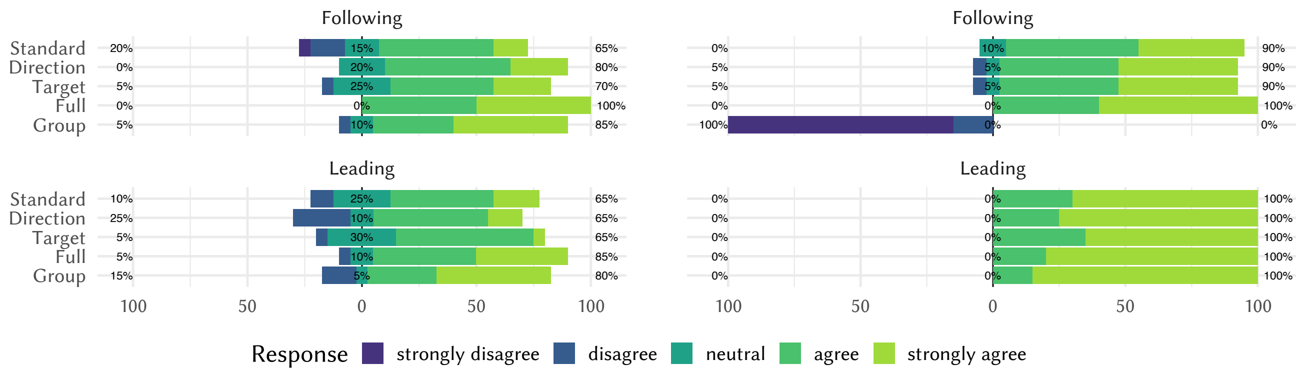
This section presents the results of our controlled user study.

5.1 Reported Inclusion of Other in the Self

We found a significant ($F_{4,76} = 11.65$, $p < .001$) main effect for the TECHNIQUE on the IOS scale with a large ($\eta_G^2 = 0.38$) effect size. Post-hoc tests reveal significantly higher ratings for GROUP compared to all other levels (FULL: $p < .05$, all others $p < .001$). Further, we found significantly higher ratings for FULL compared to STANDARD ($p < .001$). We could not find a significant main effect ($F_{1,19} = .35$, $p > .05$) for ROLE nor interaction effects ($F_{4,76} = 1.18$, $p > .05$) between the two independent variables.

5.2 GEQ Score

Evaluating the Behavioral Involvement Component of the GEQ Social Presence Module, we found a significant ($F_{4,76} = 9.57$, $p < .001$) main effect for the TECHNIQUE on the GEQ score with an large ($\eta_G^2 = 0.17$) effect size. Here, post-hoc tests reveal significantly lower ratings for GROUP compared to all other levels (FULL, TARGET: ($p < .01$), STANDARD, DIRECTION: ($p < .05$). Again, we could not find



(a) GROUP-FEELING

(b) FREEDOM OF MOVEMENT

Figure 5: Participants' responses regarding (a) group feeling and (b) freedom of movement.

a significant main effect ($F_{1,19}$ = .19, p > .05) for ROLE nor interaction effects ($F_{4,76}$ = 1.62, p > .05) between the two independent variables.

5.3 Custom Questionnaire

After each condition, participants rate the eight items of our custom questionnaire on a 5-point Likert scale. Here we analyze the results of their answers to each statement.

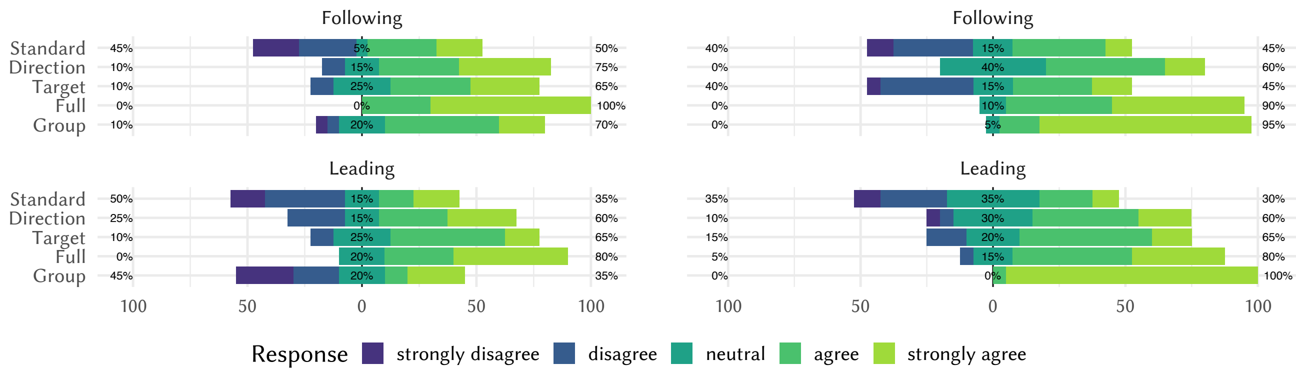
5.3.1 I felt like I moved through the virtual space as part of a group. We found a significant ($F_{4,76}$ = 4.97, p < .01) main effect for the TECHNIQUE on the feeling of being part of a group with a large (η^2_G = 0.21) effect size. Post-hoc tests reveal significantly higher ratings for GROUP compared to STANDARD (p < .01), TARGET (p < .05) and DIRECTION (p < .05) as well as significantly higher rating for FULL compared to STANDARD (p < .01), TARGET (p < .01) and DIRECTION (p < .05). We could not find a significant main effect ($F_{1,19}$ = 2.96, p > .05) for ROLE nor interaction effects ($F_{4,76}$ = 0.92, p > .05) between the two independent variables. The responses are illustrated in Figure 5a.

5.3.2 I felt in control of my own movement. We found a significant ($F_{4,76}$ = 63.29, p < .001) main effect for the TECHNIQUE on the understanding of the movement intentions with a large (η^2_G = 0.77) effect size. Post-hoc tests reveal significantly lower ratings for GROUP compared to all other levels (p < .001). We also found a significant ($F_{1,19}$ = 187.66, p < .001) main effect for ROLE on the understanding of the movement intentions with a large (η^2_G = 0.91) effect size. Here, Post-hoc tests reveal significantly higher ratings for LEADING compared to FOLLOWING (p < .001). We further found a significant ($F_{4,76}$ = 99.58, p < .001) interaction effect with a large (η^2_G = 0.84) effect size. While post-hoc tests revealed comparable (p > .05) ratings for LEADING and FOLLOWING over all levels of TECHNIQUE except for group port, the latter resulted in significantly (p < .001) higher ratings for LEADING compared to FOLLOWING. The responses are illustrated in Figure 5b.

5.3.3 I did understand the motion intentions of my co-player. We found a significant ($F_{4,76}$ = 9.07, p < .001) main effect for the TECHNIQUE on the understanding of the movement intentions with a large (η^2_G = 0.32) . Post-hoc tests for the TECHNIQUE reveal significantly higher ratings for FULL compared to all other levels (DIRECTION: p < .05, TARGET: p < .01, all others: p < .001). Further, we found significantly higher ratings for DIRECTION compared to STANDARD. We also found a significant ($F_{1,19}$ = 10.90, p < .01) main effect for ROLE on the understanding of the movement intentions with a large (η^2_G = 0.36) effect size. Post-hoc tests for ROLE reveal significantly higher ratings for FOLLOWING compared to LEADING (p < .01). We could not find significant interaction effects ($F_{4,76}$ = 1.74, p > .05) between the two independent variables. The responses are illustrated in Figure 6a.

5.3.4 It was easy to stay together as a group. We found a significant ($F_{4,76}$ = 33.21, p < .001) main effect for the TECHNIQUE on the EASE OF STAYING TOGETHERwith a large (η^2_G = 0.64) effect size. Post-hoc tests reveal significantly higher ratings for GROUP compared to all other levels (p < .001) as well as significantly higher ratings for FULL compared to STANDARD (p < .001), TARGET (p < .001) and DIRECTION (p < .01). Further, post-hoc tests reveal a significantly higher rating for DIRECTION compared to STANDARD (p < .05). We could not find a significant main effect ($F_{1,19}$ = .03, p > .05) for ROLE nor interaction effects ($F_{4,76}$ = 1.98, p > .05) between the two independent variables. The responses are illustrated in Figure 6b.

5.3.5 I always knew where the other player was. We found a significant ($F_{4,76}$ = 37.04, p < .001) main effect for the TECHNIQUE on the awareness of the other person's location with a large (η^2_G = 0.66) effect size. Post-hoc tests reveal significantly higher ratings for GROUP compared to all other levels (p < .001). We also found significantly higher ratings for FULL compared to all other levels, except for GROUP (DIRECTION:p < .05, others:p < .001). We also found a significant ($F_{1,19}$ = 15.85, p < .001) main effect for ROLE on the awareness of the other person's location with a large (η^2_G = 0.45) effect size. Post-hoc tests for ROLE reveal significantly higher



(a) INTENTION UNDERSTANDING

(b) EASE OF STAYING TOGETHER

Figure 6: Participants' responses regarding (a) intention understanding and (b) ease of staying together.

ratings for FOLLOWING compared to LEADING ($p < .001$). We further found significant ($F_{4,76} = 5.20$, $p < .001$) interaction effects with a large ($\eta_G^2 = 0.21$) effect size. While post-hoc tests reveal comparable ratings for all TECHNIQUES but DIRECTION over both levels of ROLE, we found significantly ($p < .05$) higher ratings for DIRECTION with FOLLOWING compared to LEADING. The responses are illustrated in Figure 7a.

5.3.6 I want to use this technique to navigate through virtual worlds together with others in the future. We found a significant ($F_{4,76} = 9.30$, $p < .001$) main effect for TECHNIQUE on the rating of potential future use of the experienced technique with a large ($\eta_G^2 = 0.33$) effect size. Post-hoc tests reveal significantly higher ratings for FULL compared to all other levels ($p < .001$). Further, we found a significant ($F_{1,19} = 7.35$, $p < .05$) main effect for ROLE with a large ($\eta_G^2 = 0.28$) effect size. Post-hoc tests reveal significantly higher ratings for FOLLOWING compared to LEADING ($p < .05$). We further found significant interaction effects ($F_{4,76} = 3.37$, $p < .05$) with a large ($\eta_G^2 = .15$) effect size between the two independent variables. However, post-hoc tests did not confirm ($p > .05$) this observation. The responses are illustrated in Figure 7b.

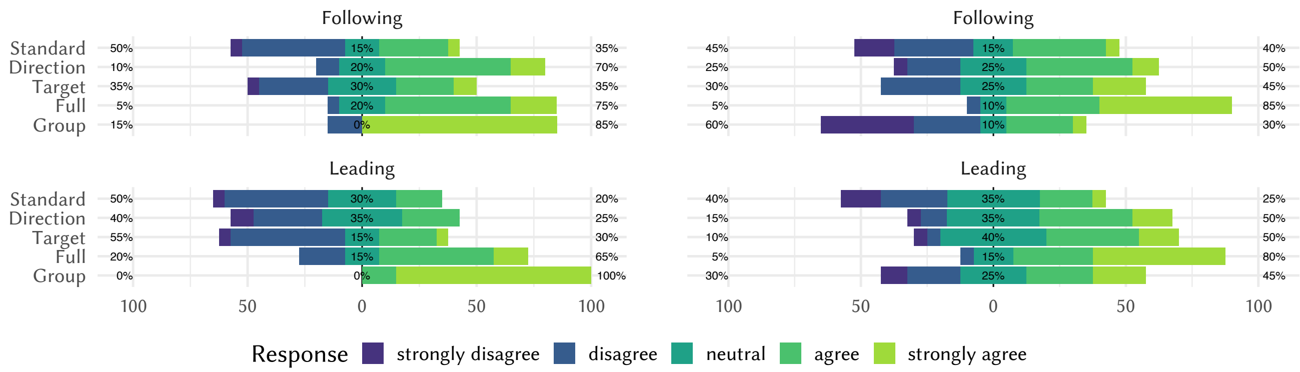
5.3.7 The technique was convenient to use. We found a significant ($F_{4,76} = 5.44$, $p < .001$) main effect for the TECHNIQUE on the convenience of use with a large ($\eta_G^2 = 0.22$) effect size. Post-hoc tests reveal significantly higher ratings for FULL compared to all other levels (GROUP: $p < .05$, others: $p < .001$). We found no significant ($p > .05$) main effect for ROLE. However, we found significant ($F_{4,76} = 4.12$, $p < .05$) interaction effects with a large ($\eta_G^2 = 0.18$) effect size. While we found comparable ratings between all TECHNIQUES except FULL for FOLLOWING, for LEADING we found significant lower rating for STANDARD compared to FULL ($p < .01$) and GROUP ($p < .05$). The responses are illustrated in Figure 8a.

5.3.8 I felt like I solved the task successfully. Again, we found a significant ($F_{4,76} = 7.26$, $p < .001$) main effect for the TECHNIQUE on the perceived success with a large ($\eta_G^2 = 0.28$) effect size. Post-hoc tests reveal significantly lower ratings for GROUP compared to FULL($p < .001$), TARGET($p < .001$) and DIRECTION($p < .01$). We also found a significant ($F_{1,19} = 15.61$, $p < .001$) main effect for ROLE with a large ($\eta_G^2 = .45$) effect size. Here, Post-hoc tests reveal significantly ($p < .001$) lower ratings for FOLLOWING compared to LEADING. We further found significant ($F_{4,76} = 16.33$, $p < .001$) interaction effects with a large ($\eta_G^2 = 0.46$) effect size. While we found significantly ($p < .001$) higher ratings for LEADING compared to FOLLOWING with GROUP, the ratings were comparable ($p > 0.05$) with all other levels of technique. The responses are illustrated in Figure 8b.

5.4 Qualitative Feedback

Participants overall liked our techniques and commented that "*it was a very fun experience*" (P7). Participants liked the additionally provided information. While many comments praise the FULL condition, other comments favor the more subtle approach of DIRECTION or TARGET, which provide enough information without cluttering the field of view. They also liked that their own and other preview elements have different colors. P5, for instance, stated that the "*different color coding helps to differentiate the green is my buddy and the blue is mine*". The feedback for GROUP was rather negative, mostly because of the missing individual involvement and movement of the passive part, but also because the leader did not feel like part of an actual group anymore. In the following, we detail on the qualitative feedback for each level of TECHNIQUE.

5.4.1 Full Preview. We received a lot of positive comments about the FULL level, for instance: "*I liked the Full Preview version best, it involves you in the movement but still makes it easy to navigate together*" (P4), "*i like this one*" (P3), or "*best style for navigating together*" (P4). Participants especially appreciated staying in touch with the other player. For instance, P16 "*found the "Full Preview" the most pleasant to stay in touch with the partner*", and P20 liked "*most the combination of target and direction preview"*". 14 out of 20



(a) location awareness of other

(b) desired future usage

Figure 7: Participants' responses regarding (a) location awareness of others and (b) desired future usage.

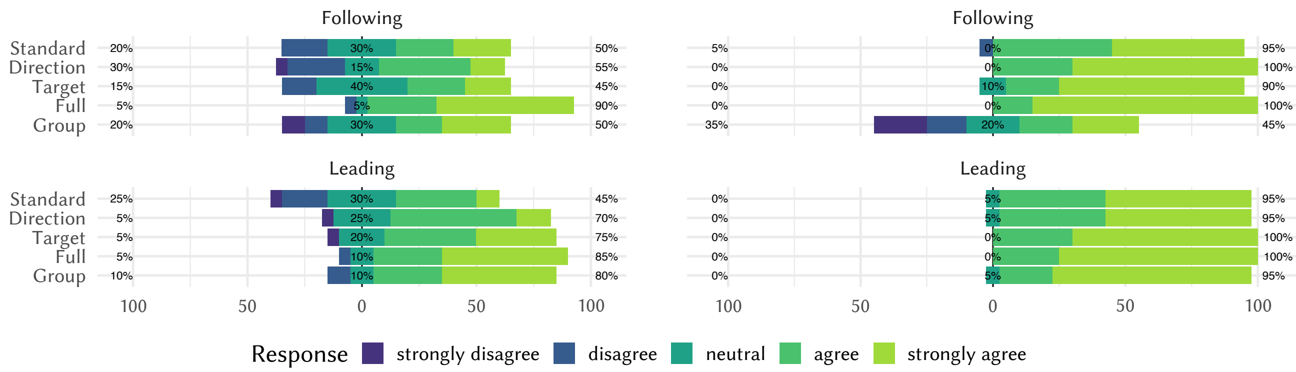
participants commented positively about the available information about the other's intention. Many participants further commented that they like their individual control (P5, P6, P16-P19) and also found this technique very efficient and fast (P8, P11-P16, P20). While feedback for FULL was in general very positive, participants raised concerns regarding its scaleability because it "*could be confusing when there are too many players around -> lot of light beams*" (P12).

5.4.2 Group Teleport. Participants perceived the GROUP technique very differently, depending on their role. One participant stated that they "*hate the group teleport as a follower but love it as a leader.*" (P5). Other participants stated that "*as a leader the group teleport was extremely efficient, but it wasn't fun at all.*" (P3), "*its more fun when you're the one leading*" (P3), and "*you should do this with a nice partner*" (P2). 19 out of 20 participants disliked having no control over their own movements, even though they noticed and commented on its efficiency (P3, P6-P9, P15, P19). To give one example, P4 noted that "*the group teleport is of course super easy in regards of moving/staying together but is not really fun as only one has the control and it excludes the other one from the experience*". P15 even stated that "*with a Group Teleport, you have too little freedom of action of your own and feel more like you're watching your teammate play.*" and also "*(...) you don't feel like you are moving as a group, but rather as one person.*". Similarly, P17 commented to be "*quite disconnected from the other person*".

In contrast, participants still liked the fact that they could relax (P3, P6, P9, P12) and that movement is very clear (P4, P11, P18, P19), evident by many statements, for example: "*lean back and relax, just glued to the leader*" (P12). They further commented on advantages, for instance, that "*it has potential, since it gives freedom for the follower to fulfill a second task.*" (P1) or that it is an "*interesting way to show new players the game and related features*" (P6).

5.4.3 Direction Visualization. Participants liked the DIRECTION technique because it was easy to use (P6, P7), "*very intuitive*" (P8) and "*straight forward*" (P8). They commented positively about the subtle amount of information, for instance, P20 noted that "*the line indicator was long enough to know the direction the partner was moving but not too long that it would distract a lot*" and "*general movement direction was clear, but not to much information*". Additionally, P15 found that "*the teleportation direction of the teammate was displayed without cluttering the world with arrows*". It also helped to understand the movement intentions of the other, as evident, for instance, by quotes like "*the intention of the other was visible*" (18), or "*teleportation direction of the other recognizable, one could follow the partner well*" (P11). Numerous participants further liked that they "*can see where the other person is intending to go but both can move independently*" (P4), as well as that they "*saw where the other one intended to go, but the other person was still moving independent from me/my movement*" (P4). In essence, the DIRECTION technique was found to be "*nice for navigating together through the space*" (P4).

5.4.4 Target Visualization. Overall we received positive feedback for the TARGET technique. Participants liked that they can move independently (P4, P15, P16, P18, P19) and positively commented that they could understand the co-player's intentions (P1-P4, P8-P12, P16, P18-P20), as evident, for instance, by P4 stating to "*have some indication where the other one is going through the dot on the floor but can still move independently*". P19 specifically commented on the positive effects when leading the group: "*It was easier since the other player followed me I knew when I saw the circle of him that he was still following me.*". P15 commented on the more minimalist visualization and liked that "*the world looked less sensory overloaded by not seeing the arc in the teammate*". However, participants also found it harder to navigate with this technique when the other person was fast or already far away (P1-P4) or just found it generally more difficult (P4-P6, P10, P13, P15-P17). Participants further mentioned that they had to focus more on the floor instead of looking up (P6, P15, P17). Four participants also mentioned that they were often missing the direction indication (P5, P16, P19, P20). For instance, P16 noted that they "*could not see the "line" where my partner is aiming to teleport, which makes it harder to follow him.*".



(a) convenience of use

(b) feeling of success

Figure 8: Participants' responses regarding (a) convenience of use and (b) feeling of success.

5.4.5 Standard Teleport. For STANDARD as the baseline technique, participants commented rather negatively, especially after experiencing the other methods. They commented that it is harder to stay together (P6, P8, P13, P15-P17, P19, P20) and disliked not understanding the intentions (P9, P12-P14, P18). Nine participants explicitly stated that they are missing indicators (P2, P5, P6, P9-P11, P14, P16, P18), especially that the "*beam should be recognizable*" (P11). Two participants stated that it is less fun (P5, P6) and "*not collaborative*" (P6).

When asked about what they like, P10 radically said: "*Nothing. I want an indicator where the other is pointing*". On the positive side, participants liked their freedom of movement (P1, P12, P16, P18-P20) and also found this technique less disturbing (P12), realistic (P12, P15), easy to use (P2-P4, P7), and natural (P12, P15).

6 DISCUSSION

In our experiment, we found varying strengths and weaknesses of the different techniques, including the two baseline conditions. Evaluating our results, we found the three proposed TECHNIQUES to be promising intermediates between the respective advantages and disadvantages of the established single player point&teleport (STANDARD) and fixed group teleports (GROUP). We achieve comparable ratings for the group feeling between some TECHNIQUES and GROUP while still maintaining comparable ratings for the perceived control of the own movement compared to STANDARD. However, each of the TECHNIQUES possess different benefits and drawbacks, which we will discuss in this section.

6.1 The Freedom of Single User Teleport Negatively Affects Joint Locomotion While Enforced Group Locomotion Limits the Freedom

Comparing today's state of the art in social VR locomotion techniques, we found that our results confirm the strength and shortcomings of STANDARD and GROUP established by related work. While GROUP unsurprisingly remains unmatched in the ease of staying together as well as the knowledge about the other player's location, our data demonstrates that the passive role of this method was strongly disliked by the participants. Interestingly and in contrast to our expectations, GROUP did not receive the highest scores for GROUP-FEELING. Further, the Behavioural Involvement Component of the GEQ Social Presence Module GROUP received the lowest ranking, indicating that here, players did not pay attention to what the other player is doing. On the other hand, STANDARD is among the highest rated TECHNIQUES in terms of freedom of movement while receiving the lowest ratings for the EASE OF STAYING TOGETHER and LOCATION AWARENESS OF OTHER as well as one of the lowest rating for the GROUP-FEELING. Consequently, these two techniques represent the two fringes of a spectrum between absolute individual freedom on the one hand and a (forced) group coherence on the other hand. Our data suggests that both approaches show positive characteristics but also impose a negative impact on the experience. These findings, therefore, call for novel joint locomotion techniques that address the individual problems of the techniques while retaining their benefits.

6.2 The Direction Visualization Offers Less Information Compared to Target, but Users Receive More of It

When evaluating our data, we found DIRECTION, TARGET and FULL all to be promising intermediates between the advantages of single-player locomotion (STANDARD) and fixed group teleports (GROUP). For most measures, we found higher ratings compared to the STANDARD.

Comparing TARGET and DIRECTION, TARGET provides more information in the form of the actual target location of the other player (from which the direction follows implicitly). However DIRECTION was perceived to be more useful (compare e.g. Figure 6b). We attribute this effect to the closer proximity of the direction ray to the other player's location in comparison to the target circle, making it easier to associate and better visible whenever the other player is in the field of view. Especially for the following player, DIRECTION proved to be more helpful for the LOCATION AWARENESS OF OTHER as well as the EASE OF STAYING TOGETHER in contrast to TARGET. We explain this effect with the increased distance of the following user to the target of a teleport of the leading user. Given that participants moved through a maze that required turns into corridors, the target frequently left the view of the following user. In contrast, the DIRECTION was visible to the following user as long as the leading user was visible but misses to present the target compared to FULL. Here, we conclude that FULL presents users with all necessary information about the other player’s intentions to stay together as a group while maintaining individual freedom of movement. Especially with a look towards an increasing number of co-players, the effectiveness of more subtle TECHNIQUES like DIRECTION with fewer visual clutter might out weight more dominant ones like FULL.

6.3 The Full Visualization Balances the Requirements of the Following and Leading Users

Interestingly, the perception of the advantages and disadvantages of the different TECHNIQUES strongly depends on the player’s role in the dyadic setup. That is, depending on their role in the dyadic setup, players further either prefer DIRECTION or TARGET. Leading players found TARGET to improve the EASE OF STAYING TOGETHER compared to the following player. On the contrary, the following players perceived DIRECTION more helpful on the LOCATION AWARENESS OF OTHER compared to the leading players. We attribute this to the visibility of the available information from the perspective of the respective players. When leading a group, seeing the target circle of the co-player next to one-selves or the own target location, provides sufficient information to know the other player is close by. However, when following, the target location of the other might be around the next corner already, making it useless. Hence, the information in which direction the leading player will disappear proves sufficient to follow. We found that FULL mitigated the discrepancy of the required information about the co-player’s actions for both roles as it combines both components of the information. Over all measures, we found only neglectable differences between the rating of FULL over both ROLES, underlining its effectiveness for both of the two roles. Another approach to solve the discrepancy could be the implementation of asymmetric information visualization. However, this would only be possible if the roles are fixed, like in our study task, but not if players switch roles dynamically. Therefore, based on our results, we propose to use FULL for most situations for both, leading and following users.

7 LIMITATIONS AND FUTURE WORK

Our data as well as comments from participants prove the need for and effectiveness of intention communication in multi-user VR scenarios facilitating collective yet self-directed ways of joint movement. We are confident that our work can serve as a base for future work to further improve on these challenges. However, our study design and results impose limitations, which we discuss in this section.

7.1 Real-World Applicability and Transferability

In our experiment, we opted for an intentionally artificial task to explore the advantages and disadvantages of our techniques. We chose this approach to provide a robust baseline not influenced by specific characteristics of more specific collaboration scenarios. We are convinced that our results can provide valuable insights that generalize to other tasks and scenarios, such as many future social VR applications where some form of intention communication would be useful. However, we acknowledge that other scenarios might yield other results. Therefore, verifying these locomotion-based findings in less specific scenarios, e.g. with locomotion as a side-task, are crucial next steps for future work. Further, with the results on hand from our locomotion-focused experiment, the question of transferability to beyond-locomotion tasks emerges. Identifying potential use cases, investigating the transferability of our findings, and deriving design recommendations for these are necessary steps to conclude on these challenges.

7.2 Scalability of the Proposed Techniques

In the presented experiment, we focused on two-user scenarios. We opted for this approach as we wanted to understand the basic interpersonal effects happening during joint locomotion in social VR scenarios. However, future systems will not be restricted to two persons, therefore, the scalability of the proposed techniques remains an open challenge. The more people use a technique like FULL at the same time, the more visually cluttered the virtual scene gets. Investigating more minimalistic visualizations like DIRECTION again in such a context is an essential next step for future work.

7.3 Privacy of Locomotion Information

Similar to the scalability challenges, multi-user settings also impose privacy issues that we did not address in our experiment. For future systems, where users meet strangers in anonymous online settings, privacy concerns regarding the shared motion information will rise. This includes, for example, the question of who is allowed to know where one is going at any given time. In this case, users must be able to individually define the scope of the information shared. Social Media platforms with different settings for different groups of people could be role models to solve this. Future work is necessary to further explore the privacy implications and present potential means to mitigate them.

8 CONCLUSION

In this paper, we explored how shared teleport visualizations of movement direction and target can affect the understanding of movement intentions and social connectedness in a group while maintaining maximum individual freedom of movement. For this, we conducted a controlled experiment comparing three new methods with the two baselines point&teleport and group teleport. We found promising results showing that shared visualizations promote understanding of movement intentions and strengthen the sense of group while maintaining individual freedom of movement. Thus, our work contributes a key building block to future free, yet collaborative exploration of social VR environments.

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