Group Navigation in Multi-User Virtual Reality

Von der Fakultät Medien der Bauhaus-Universität Weimar zur Erlangung des akademischen Grades Doctor rerum naturalium (Dr. rer. nat.) genehmigte Dissertation in englischer Sprache von

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“Maybe a good start would be to recognize within yourself the ability to understand anything, as long as it’s explained clearly enough. And then go and ask for explanations.”

James Burke, British Science Historian

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Abstract

Multi-user virtual reality systems enable collocated as well as distributed users to perform collaborative activities in immersive virtual environments. A common activity in this context is to move from one location to the next as a group to explore the environment together. The simplest solution to realize these multi-user navigation processes is to provide each participant with a technique for individual navigation. However, this approach entails some potentially undesirable consequences such as the execution of a similar navigation sequence by each participant, a regular need for coordination within the group, and, related to this, the risk of losing each other during the navigation process.

To overcome these issues, this thesis performs research on group navigation techniques that move group members together through a virtual environment. The presented work was guided by four overarching research questions that address the quality requirements for group navigation techniques, the differences between collocated and distributed settings, the scalability of group navigation, and the suitability of individual and group navigation for various scenarios. This thesis approaches these questions by introducing a general conceptual framework as well as the specification of central requirements for the design of group navigation techniques. The design, implementation, and evaluation of corresponding group navigation techniques demonstrate the applicability of the proposed framework.

As a first step, this thesis presents ideas for the extension of the short-range teleportation metaphor, also termed jumping, for multiple users. It derives general quality requirements for the comprehensibility of the group jumping process and introduces a corresponding technique for two collocated users. The results of two user studies indicate that sickness symptoms are not affected by user roles during group jumping and confirm improved planning accuracy for the navigator, increased spatial awareness for the passenger, and reduced cognitive load for both user roles.

Next, this thesis explores the design space of group navigation techniques in distributed virtual environments. It presents a conceptual framework to systematize the design decisions for group navigation techniques based on Tuckman's model of small-group development and introduces the idea of virtual formation adjustments as part of the navigation process. A quantitative user study demonstrates that the corresponding extension of Multi-Ray Jumping for distributed dyads leads to more efficient travel sequences and reduced workload. The results of a qualitative expert review confirm these findings and provide further insights regarding the complementarity of individual and group navigation in distributed virtual environments.

Then, this thesis investigates the navigation of larger groups of distributed users in the context of guided museum tours and establishes three central requirements for (scalable) group navigation techniques. These should foster the awareness of ongoing navigation activities as well as facilitate the predictability of their consequences for all group members (*Comprehensibility*), assist the group with avoiding collisions in the virtual environment (*Obstacle Avoidance*), and support placing the group in a meaningful spatial formation for the joint observation and discussion of objects (*View Optimization*). The work suggests a new technique to address these requirements and reports on its evaluation in an initial usability study with groups of five to ten (partially simulated) users. The results indicate easy learnability for navigators and high comprehensibility for passengers. Moreover, they also provide valuable insights for the development of group navigation techniques for even larger groups.

Finally, this thesis embeds the previous contributions in a comprehensive literature overview and emphasizes the need to study larger, more heterogeneous, and more diverse group compositions including the related social factors that affect group dynamics.

In summary, the four major research contributions of this thesis are as follows:

- the framing of group navigation as a specific instance of Tuckman's model of small-group development
- the derivation of central requirements for effective group navigation techniques beyond common quality factors known from single-user navigation
- the introduction of virtual formation adjustments during group navigation and their integration into concrete group navigation techniques
- evidence that appropriate pre-travel information and virtual formation adjustments lead to more efficient travel sequences for groups and lower workloads for both navigators and passengers

Overall, the research of this thesis confirms that group navigation techniques are a valuable addition to the portfolio of interaction techniques in multi-user virtual reality systems. The conceptual framework, the derived quality requirements, and the development of novel group navigation techniques provide effective guidance for application developers and inform future research in this area.

Zusammenfassung

Multi-User-Virtual-Reality-Systeme ermöglichen es lokalen und räumlich getrennten Benutzer*innen, kollaborative Aktivitäten in einer immersiven virtuellen Umgebung auszuüben. Eine grundlegende Aufgabe in diesem Zusammenhang ist die Navigation von einem Ort zum nächsten als Gruppe, um die Umgebung gemeinsam zu erkunden. Die einfachste Lösung zur Realisierung dieser Mehrbenutzer*innen-Navigationsprozesse besteht darin, jedem*jeder Teilnehmer*in eine Technik zur individuellen Navigation zur Verfügung zu stellen. Dieser Ansatz führt jedoch zu einigen potenziell unerwünschten Begleiterscheinungen, wie zum Beispiel der Ausführung einer ähnlichen Navigationssequenz durch jede*n Teilnehmer*in, einem regelmäßigen Koordinationsbedarf innerhalb der Gruppe und damit verbunden der Gefahr, sich während des Navigationsprozesses zu verlieren.

Zur Überwindung dieser Problematiken erforscht die vorliegende Arbeit Gruppennavigationstechniken, die alle Gruppenmitglieder gemeinsam durch eine virtuelle Umgebung bewegen. Die vorgestellten Beiträge wurden von vier übergreifenden Forschungsfragen geleitet, welche sich mit Qualitätsanforderungen an Gruppennavigationstechniken, den Unterschieden zwischen lokaler und räumlich getrennter Teilnahme, der Skalierbarkeit von Gruppennavigation und der Eignung von Einzel- und Gruppennavigationstechniken für verschiedene Szenarien befassen. Die vorliegende Arbeit nähert sich diesen Fragen durch die Einführung eines allgemeinen konzeptionellen Frameworks sowie die Spezifikation zentraler Anforderungen an den Entwurf von Gruppennavigationstechniken. Die Entwicklung, Implementierung und Evaluation entsprechender Gruppennavigationstechniken demonstrieren die Anwendbarkeit des vorgeschlagenen Frameworks.

In einem ersten Schritt stellt diese Arbeit Ideen zur Erweiterung der Teleportationsmetapher über kurze Distanzen, auch Jumping genannt, für mehrere Benutzer*innen vor. Sie leitet allgemeine Qualitätsanforderungen zur Verständlichkeit des Gruppen-Jumpings ab und präsentiert eine entsprechende Technik für zwei lokale Benutzer*innen. Die Ergebnisse zweier Benutzungsstudien zeigen keine Einflüsse des aktiven oder passiven Jumpings auf Symptome der Simulatorkrankheit und bestätigen eine erhöhte Planungsgenauigkeit für den*die Navigator*in, ein verbessertes räumliches Verständnis für den*die Passagier*in und eine reduzierte kognitive Belastung für beide Rollen.

Danach untersucht diese Arbeit den Gestaltungsraum von Gruppennavigationstechniken in verteilten virtuellen Umgebungen. Basierend auf Tuckmans Modell der Kleingruppenentwicklung stellt sie ein konzeptionelles Framework zur Systematisierung der Designentscheidungen für Gruppennavigationstechniken vor und führt die Idee der virtuellen Formationsanpassungen als Teil des Navigationsprozesses ein. Eine quantitative Benutzungsstudie zeigt, dass eine entsprechende Erweiterung des Multi-Ray Jumpings für räumlich getrennte Dyaden zu effizienteren Navigationsabläufen und geringeren wahrgenommenen Arbeitslasten führt. Die Ergebnisse eines qualitativen Expert-Reviews bestätigen diese Er-

kenntnisse und liefern weitere Einsichten bezüglich der Komplementarität von Einzel- und Gruppennavigation in verteilten virtuellen Umgebungen.

Anschließend untersucht diese Arbeit die Navigation größerer Gruppen räumlich getrennter Benutzer*innen im Kontext von Museumsführungen und stellt drei zentrale Anforderungen für (skalierbare) Gruppennavigationstechniken auf. Diese sollen das Bewusstsein für laufende Navigationsaktivitäten fördern sowie die Vorhersehbarkeit ihrer Konsequenzen für alle Gruppenmitglieder erleichtern (*Verständlichkeit*), der Gruppe bei der Vermeidung von Kollisionen in der virtuellen Umgebung assistieren (*Hindernisvermeidung*) und die Platzierung der Gruppe in einer sinnvollen räumlichen Formation für die gemeinsame Betrachtung und Diskussion von Objekten unterstützen (*Blickoptimierung*). Die Arbeit stellt eine neue Technik zur Adressierung dieser Anforderungen vor, welche in einer initialen Usability-Studie mit Gruppen von fünf bis zehn (teilweise simulierten) Benutzer*innen evaluiert wurde. Die Ergebnisse zeigen eine einfache Erlernbarkeit für den*die Navigator*in und eine hohe Verständlichkeit für Passagier*innen. Darüber hinaus liefern sie wertvolle Erkenntnisse zur Entwicklung von Gruppennavigationstechniken für noch größere Gruppenstärken.

Abschließend bettet diese Arbeit die bisherigen Beiträge in einen umfassenden Literaturüberblick ein und betont den Bedarf zukünftiger Forschungsarbeiten zu größeren, heterogeneren und diverseren Gruppenkompositionen. Dies beinhaltet ebenfalls die Betrachtung der damit verbundenen sozialen Faktoren sowie deren Einfluss auf die Gruppendynamik.

Zusammengefasst lauten die vier wichtigsten Forschungsbeiträge dieser Arbeit wie folgt:

- die Einordnung von Gruppennavigationsprozessen als spezifische Instanz von Tuckmans Modell der Kleingruppenentwicklung
- die Ableitung zentraler Anforderungen an effektive Gruppennavigationstechniken zusätzlich zu aus Einzelnavigationskontexten bekannten Qualitätsfaktoren
- die Einführung von virtuellen Formationsanpassungen als Teil der Gruppennavigation und deren Integration in konkrete Gruppennavigationstechniken
- Nachweise, dass geeignet gewählte Vorschaumechanismen sowie virtuelle Formationsanpassungen zu effizienteren Navigationssequenzen für die Gruppe und geringeren wahrgenommenen Arbeitslasten für Navigator*innen und Passagier*innen führen

Insgesamt bestätigen die Ergebnisse dieser Arbeit, dass Gruppennavigationstechniken eine wertvolle Ergänzung zum Portfolio der Interaktionstechniken in Multi-User-Virtual-Reality-Systemen sind. Das konzeptionelle Framework, die abgeleiteten Qualitätsanforderungen und die Entwicklung entsprechender Gruppennavigationstechniken bilden eine relevante Wissensbasis für Anwendungsentwickler*innen und informieren zukünftige Forschung in diesem Gebiet.

Declaration of Authorship

I hereby declare on my honor that I have prepared this dissertation without the unauthorized assistance of third parties and without the use of any auxiliary materials other than those indicated. The data and concepts taken directly or indirectly from other sources are marked with a clear indication of the source. Parts of the work that have already been the subject of other examination processes are also clearly marked. The following persons have assisted me in the selection and evaluation of the presented content with specific contributions as described:

Prof. Bernd Fröhlich	Scientific supervision of the research presented in this thesis.
Pauline Bimberg	Co-author of the publications “Getting There Together: Group Navigation in Distributed Virtual Environments” [175] and “An Overview of Group Navigation in Multi-User Virtual Reality” [176] presented in Chapters 4 and 6, respectively. Pauline Bimberg’s Master’s Thesis on “Joint Navigation of Spatially Distributed Partners in Immersive Virtual Environments” (Supervision: Tim Weißker, First examiner: Prof. Bernd Fröhlich, Second examiner: Junior-Prof. Jan Ehlers) provided the foundations of the devised four-tier framework of group navigation techniques (Section 4.3) as well as the implementation and quantitative evaluation of the presented group navigation technique for distributed dyads (Sections 4.4.1 and 4.5). Moreover, she served as the experimenter for the user study presented in Section 3.5 and was a continued knowledgeable partner for discussions on my research after these initial contributions. Finally, she performed a full proofread of this thesis.
Alexander Kulik	Co-author of the publication “Multi-Ray Jumping: Comprehensible Group Navigation for Collocated Users in Immersive Virtual Reality” [178] presented in Chapter 3. Alexander Kulik accompanied my initial research steps that led to the first publication presented in this thesis. Together, we derived and formulated the presented notion of comprehensible group jumping (Section 3.3.6) and had productive as well as lively discussions on embedding the presented content into the overarching research context (Section 3.2).

No other persons were involved in the preparation of this dissertation. In particular, I did not use any form of paid assistance from intermediary or consulting services. Apart from the described allowances for the participation in the presented user studies, no one has directly or indirectly received monetary benefits from me for work related to the content of this thesis. The thesis has not been submitted to any other examination authority in the same or similar form, neither in Germany nor abroad.

I assure that I have told the truth to the best of my knowledge and have not concealed anything.

Weimar, 22nd November 2021
Tim Weißker

Ehrenwörtliche Erklärung über die Eigenständigkeit der Dissertation

Ich erkläre hiermit ehrenwörtlich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet. Teile der Arbeit, die bereits Gegenstand von Prüfungsarbeiten waren, sind ebenfalls unmissverständlich gekennzeichnet. Bei der Auswahl und Auswertung folgenden Materials haben mir die nachstehend aufgeführten Personen in der jeweils beschriebenen Weise geholfen:

Prof. Bernd Fröhlich	Wissenschaftliche Betreuung der Arbeit.
Pauline Bimberg	Co-Autorin der Publikationen „Getting There Together: Group Navigation in Distributed Virtual Environments“ [175] und „An Overview of Group Navigation in Multi-User Virtual Reality“ [176], welche in den Kapiteln 4 und 6 präsentiert werden. Im Rahmen von Pauline Bimbergs Masterarbeit mit dem Titel „Joint Navigation of Spatially Distributed Partners in Immersive Virtual Environments“ (Betreuung: Tim Weißker, Erster Gutachter: Prof. Bernd Fröhlich, Zweiter Gutachter: Junior-Prof. Jan Ehlers) entstanden die Grundlagen des aufgestellten Frameworks zu Gruppennavigationstechniken (Abschnitt 4.3) sowie die Implementierung und quantitative Auswertung der präsentierten Gruppennavigationstechnik für zwei verteilte Benutzer*innen (Abschnitte 4.4.1 und 4.5). Weiterhin engagierte sie sich als Versuchleiterin für die Benutzungsstudie in Abschnitt 3.5 und war eine kontinuierlich kompetente Partnerin für Diskussionen rund um meine Forschungsarbeiten nach diesen initialen Beiträgen. Nicht zuletzt las sie die vorliegende Arbeit Korrektur.
Alexander Kulik	Co-Autor der Publikation „Multi-Ray Jumping: Comprehensible Group Navigation for Collocated Users in Immersive Virtual Reality“ [178], welche in Kapitel 3 präsentiert wird. Alexander Kulik begleitete meine intialen Forschungsarbeiten, welche zu der ersten in dieser Arbeit präsentierten Publikation geführt haben. Zusammen erarbeiteten wir die präsentierten Qualitätskriterien für verständliche Gruppennavigation (Abschnitt 3.3.6) und führten lebendige und produktive

Diskussionen zur Einbettung der präsentierten Inhalte in den übergreifenden Forschungskontext (Abschnitt 3.2).

Weitere Personen waren an der inhaltlich-materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder anderer Personen) in Anspruch genommen. Außerhalb der beschriebenen Vergütungen für die Teilnahme an den präsentierten Benutzungsstudien hat niemand von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Ich versichere, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

Weimar, den 22. November 2021
Tim Weißker

Acknowledgments

A central leitmotif spanning across all contributions in this thesis is the idea of "getting somewhere together". While this is mostly interpreted in the spatial sense of navigating from one location to another, it also reflects the conceptual process that led to the completion of this thesis. I would like to sincerely thank everybody who accompanied me during the last years and contributed their energy to support my research.

First and foremost, I would like to express my sincere gratitude to my scientific supervisor Prof. Dr. Bernd Fröhlich for the tremendous amount of time and effort he spent on supporting me while being busy with numerous other responsibilities. His vision of studying group navigation techniques in multi-user virtual reality provided the basis for my research and therefore paved the way for the eventual completion of this thesis. He always believed in me and thereby motivated me to believe in myself even in more difficult times.

Furthermore, I would like to show my appreciation for Prof. Doug A. Bowman for agreeing to serve as an external reviewer for this thesis. He is a renowned researcher in the field, and his publications already guided my initial research steps in virtual reality when I was still a bachelor student. I am therefore particularly glad for his commitment and am looking forward to seeing him in the examination committee.

I would like to express another exceptional amount of gratitude to my partner and colleague Pauline Bimberg for her scientific as well as personal support in the last years. Starting in Pauline's Master's Thesis, we laid important foundations for several results presented in this thesis and continued sharing our research interests and opinions afterwards. She spent large portions of her time discussing my research and offered continued personal support in challenging times.

Next, I would like to thank my colleague and friend Alexander Kulik for his contributions especially at the beginning of my research career. His guidance and novel perspectives on the subject have led to inspiring discussions that allowed me to broaden my view and find my own research path among the plethora of concurrent alternatives. I regret that he decided to leave academia, but I hope that his intrinsic research spirit will still shape his future work.

I furthermore thank all the other members of the *Virtual Reality and Visualization Research Group* at Bauhaus-Universität Weimar for their technical as well as personal support during the time of my research. In particular, André Kunert has been a loyal companion and friend since my first steps in VR as a bachelor student and always had an open ear for both the scientifc and non-scientific challenges I had to face. I would also like to honorably mention Stephan Beck and Adrian Kreskowski for providing indispensable help with the back end code of the proprietary virtual reality software framework on which my developments are based.

Moreover, I appreciate the agencies that provided the necessary funding for my co-authors and me to conduct our research. In particular, the publications presented in this thesis have received funding from the European Union's Horizon 2020 Framework Programme for Research and Innovation under the Specific Grant Agreement No. 785907 (*Human Brain Project SGA2*), the German Ministry of Education and Research (BMBF) under grant 03PSIPT5A (*Provenance Analytics*), and the Thuringian Ministry for Economic Affairs, Science, and Digital Society under grant 5575/10-5 (*MetaReal*).

Finally, I would like to express my very profound gratitude to my mother Tanja Weißker and my grandparents Helga and Herbert Wagner. They always supported me in every way they could and continuously expressed their interest in my doings, particularly by being regular viewers of my conference talks in online streams.

In summary: *Danke an euch alle!*

Publications

The contributions of this thesis were manifested and presented to the international research community in four peer-reviewed scientific publications, which were accompanied by additional publications that covered aspects of single-user and group navigation in virtual reality. The complete list of literature references is provided in the following. The relationship between these publications is visualized in Figure 1.1 and discussed in Section 1.3 in more detail.

Publications Presented in this Thesis

Central Conceptual and Technical Contributions to Group Navigation in Multi-User Virtual Reality

T. Weissker, A. Kulik, and B. Froehlich. Multi-Ray Jumping: Comprehensible Group Navigation for Collocated Users in Immersive Virtual Reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 136–144, 2019. doi: 10.1109/VR.2019.8797807
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T. Weissker, P. Bimberg, and B. Froehlich. Getting There Together: Group Navigation in Distributed Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics*, 26(5):1860–1870, 2020. doi: 10.1109/TVCG.2020.2973474
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T. Weissker and B. Froehlich. Group Navigation for Guided Tours in Distributed Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics*, 27(5):2524–2534, 2021. doi: 10.1109/TVCG.2021.3067756
©2021 IEEE. Reprinted with permission in **Chapter 5**.

Survey and Discussion of Group Navigation Techniques in Multi-User Virtual Reality

T. Weissker, P. Bimberg, and B. Froehlich. An Overview of Group Navigation in Multi-User Virtual Reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 363–369, 2021. doi: 10.1109/VRW52623.2021.00073
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Lead- and Co-Authorships Outside of this Thesis

Overarching Foundations of Navigation in Virtual Reality

T. Weissker, A. Kunert, B. Froehlich, and A. Kulik. Spatial Updating and Simulator Sickness During Steering and Jumping in Immersive Virtual Environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 97–104, 2018. doi: 10.1109/VR.2018.8446620

P. Bimberg, T. Weissker, and A. Kulik. On the Usage of the Simulator Sickness Questionnaire for Virtual Reality Research. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 464–467, 2020. doi: 10.1109/VRW50115.2020.00098

Specific Technical Solutions for Interaction in Multi-User Virtual Reality

T. Weissker, P. Tornow, and B. Froehlich. Tracking Multiple Collocated HTC Vive Setups in a Common Coordinate System. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 592–593, 2020. doi: 10.1109/VRW50115.2020.00147

A. Kunert, T. Weissker, B. Froehlich, and A. Kulik. Multi-Window 3D Interaction for Collaborative Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics*, 26(11): 3271–3284, 2020. doi: 10.1109/TVCG.2019.2914677

C. Matthes, T. Weissker, E. Angelidis, A. Kulik, S. Beck, A. Kunert, A. Frolov, S. Weber, A. Kreskowski, and B. Froehlich. The Collaborative Virtual Reality Neurorobotics Lab. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1671–1674, 2019. doi: 10.1109/VR.2019.8798289

1

Introduction

1.1 Motivation

Multi-user virtual reality systems enable collocated as well as distributed groups to meet each other in shared virtual environments, often also referred to as collaborative virtual environments [35, 58] or social virtual reality [119, 144]. An overarching goal of these systems is to create a shared social experience that allows for intuitive forms of interaction and fosters a similar sense of togetherness and mutual understanding as a real-world encounter. Applications supporting appropriate forms of user representation and interaction should enable a group to perform a variety of collaborative activities like the joint exploration and inspection of the scene, guided tours, discussions about the observed content, and the formation of a collective understanding or decision.

A prerequisite of these activities is the ability to stay together as a group while navigating through the virtual environment. Navigation involves the execution of virtual movements for every group member (travel) based on cognitive processes for planning and decision making (wayfinding) [20, 123]. While prior research has suggested a plethora of navigation techniques for single-user virtual reality (see [2, 114] for overviews), a central research question for multi-user systems is how these established techniques can be adapted or enhanced to specifically address group situations. While the simplest solution to realize multi-user navigation is to provide each group member with individual navigation capabilities, this approach entails some potentially undesirable consequences. These include the execution of a similar navigation sequence by each participant towards the common destination, a regular need for coordination within the group, and, related to this, the risk of losing each other during the navigation process.

A common approach for getting somewhere together in the real world while overcoming the aforementioned limitations is the joint use of a vehicle. Using a car or bus, for example, inherently results in joint travel for all occupants and therefore allows groups to stay together at all times. Moreover, while the *navigator* has the responsible task of operating the vehicle, the *passengers* can focus their attention more on each other and the surroundings. Given these pivotal advantages, the idea of being in a vehicle together is a promising mental model for realizing joint navigation processes in multi-user virtual reality as well. Prior research in this regard provided initial ideas for joint navigation techniques that consider all members of a group to be on an imagined virtual movement platform (e.g. [8, 10, 96, 149, 150]). This thesis will refer to this approach as *group navigation*.

> **Definition 1**
> Group navigation techniques in multi-user virtual reality move all group members through a virtual environment together.

Following the idea of a real-world vehicle, the most intuitive option is to assign the controls of the common movement platform to only a single (human or automated) navigator at a time rather than merging and applying the inputs of several users to the platform. Depending on the scenario, the concurrent cognitive task of wayfinding can be either achieved by agreements within the group (e.g. during an expert walkthrough) or also handled by the navigator to allow passengers to focus on other activities (e.g. during a guided tour).

Despite the inherent benefits of group navigation techniques over coordinated individual navigation, their realization in virtual reality entails several central research challenges that need to be addressed carefully. An important aspect in this regard is supporting spatial awareness during joint travel, with respect to which prior studies indicated potential disadvantages of passively-induced locomotion [3, 32] that could even lead to complete disorientation for teleportation-based travel in extreme cases [19]. This motivates further research into comprehensible navigation processes for multiple users controlled by a single navigator. As a basis for this, it is relevant to establish a shared understanding of who is participating, who is responsible for navigation at which point in time, what their intentions are for the group, and how these intentions relate to more higher-level activities in the virtual environment (cf. workspace awareness [68]). This might be even more challenging to achieve in distributed scenarios, where the presence of others is purely virtual and verbal communication may be affected by the quality as well as latency of the employed audio connection. In addition, while the membership and roles are easily identifiable in a real-world vehicle, users in virtual reality do not have to sit in specific seats to participate and to take over certain roles, which allows for more flexible changes in participation and responsibilities as the group progresses. This lack of constraints typically also leads to a variety of spatial group formations during joint travel, which results in additional challenges for the navigator of fitting the group through spatial constrictions [96] and placing the group appropriately such that everybody can observe a joint object of interest [4, 96, 150]. All of the aforementioned issues should be addressed with the goal of minimizing the occurrence of sickness symptoms during joint travel. This is especially important for passengers since previous observations in both virtual and real environments indicated potential negative effects of passively-induced movements also in this regard [46, 142, 156, 160].

While prior work tried to address some of the discussed challenges, research insights specific to group navigation techniques are rather sparse. The work in this dissertation addresses this research gap and motivates a more systematic exploration of the design space, the resulting requirements for specific scenarios, and corresponding realizations of group navigation techniques for different group compositions in immersive virtual environments.

1.2 Research Overview and Contributions

This thesis provides several conceptual and technical contributions to research on collocated and distributed group navigation techniques in multi-user virtual reality, which were guided by four overarching research questions:

Research Questions

RQ$_{\text{I}}$	What are the quality requirements for group navigation techniques and how can they be addressed?
RQ$_{\text{II}}$	How does the physical collocation or distribution of group members affect the process of navigating together?
RQ$_{\text{III}}$	What are the emerging challenges for the design of scalable group navigation techniques?
RQ$_{\text{IV}}$	Which situations particularly benefit from the availability of group navigation techniques, and in which situations is it more practical for group members to navigate individually?

This thesis approaches these questions by introducing a general conceptual framework as well as the specification of central requirements for the design of group navigation techniques. The development, implementation, and evaluation of corresponding group navigation techniques demonstrates the applicability of the proposed framework. While the presented research mainly focused on users with head-mounted displays, many of the presented developments are also applicable to projection-based virtual reality systems. The particular contributions presented in this thesis are as follows:

Multi-Ray Jumping: Comprehensible Group Navigation for Collocated Users in Immersive Virtual Reality (Chapter 3) presents ideas for the extension of the short-range teleportation metaphor, also termed jumping, for multiple users. From observations in a pilot study, it derives general quality requirements for the comprehensibility of the group jumping process. To meet these requirements, it proposes a novel *Multi-Ray Jumping* technique for collocated dyads that presents extended pre-travel information to inform the passenger when a jump is planned and to help both users understand where their respective destinations will be. The results of two user studies indicate that sickness symptoms are not affected by user roles during group jumping and confirm that the use of *Multi-Ray*

Jumping improves planning accuracy for the navigator, increases spatial awareness for the passenger, and reduces cognitive load for both user roles.

Getting There Together: Group Navigation in Distributed Virtual Environments (Chapter 4) explores the design space of group navigation techniques in distributed virtual environments and presents a conceptual framework to systematize the design decisions for group navigation techniques based on Tuckman's model of small-group development [166, 167]. The framework suggests that group navigation techniques should provide mechanisms for users to organize themselves in navigational groups (*Forming*), assign navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*). With respect to *Performing*, the work shows that the commonly employed combination of virtual translations by jumping and physical rotations to change direction often leads to involuntary group formation changes that have to be corrected by individual navigation every time they occur. To overcome this issue, it presents the idea of *virtual formation adjustments* during group travel and proposes an adaptation of *Multi-Ray Jumping* for distributed dyads allowing the navigator to change the spatial arrangement of the dyad as part of the jumping process. The results of a quantitative user study show that these adjustments lead to more efficient travel sequences and lower workloads imposed on the navigator and the passenger. In a follow-up qualitative expert review involving all four stages of group navigation techniques, the effectivity, efficiency, and comprehensibility of the proposed technique is also confirmed in a more realistic use-case scenario. Furthermore, the observations suggest that collaboration in distributed virtual environments benefits from fluent transitions between individual and group navigation.

Group Navigation for Guided Tours in Distributed Virtual Environments (Chapter 5) investigates the navigation of larger groups of distributed users in the context of guided museum tours. In addition to addressing general quality factors of virtual navigation known from single-user systems (e.g. [19]), it establishes that scalable group navigation techniques should foster the awareness of ongoing navigation activities as well as facilitate the predictability of their consequences for all group members (*Comprehensibility*), assist the group with avoiding collisions in the virtual environments (*Obstacle Avoidance*), and support placing the group in a meaningful spatial formation for the joint observation and discussion of objects (*View Optimization*). To address these requirements, it proposes a new group navigation technique and reports on its evaluation in an initial usability study with groups of five to ten (partially simulated) users. In particular, the technique relies on preview avatars for enhanced comprehensibility, the automatic prevention of jumps that would lead to virtual collisions or group separation, and the ability of the navigator to induce various types of virtual formation adjustments including a complete rearrangement of the group to certain functional formations (see [87]). The results indicate that the technique is easy to learn for navigators, comprehensible also for passengers, non-nauseating for both roles, and therefore well-suited for performing guided tours in distributed virtual environments. Moreover, the observations suggest that the requirements of *Obstacle Avoidance* and *View Optimization* seem to be the driving factors of complexity in even larger groups.

An Overview of Group Navigation in Multi-User Virtual Reality (Chapter 6) summarizes the previous contributions and embeds them in a comprehensive literature overview. It emphasizes that future research needs to study larger, more heterogeneous, and more diverse group compositions including the related social factors that affect group dynamics.

Overall, the research of this thesis confirms that group navigation techniques are a valuable addition to the portfolio of interaction techniques in multi-user virtual reality. The conceptual framework, the derived quality requirements, and the development of effective group navigation techniques provide guidance for application developers as well as inform future research in this area.

1.3 Overview of Publications

The research contributions of this thesis presented in Chapters 3, 4, 5, and 6 were published in four peer-reviewed scientific papers and presented to the community at associated international conferences. *Multi-Ray Jumping* appeared as part of the conference proceedings of the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), where it received a nomination for the Best Conference Paper Award [178]. *Getting There Together* and *Group Navigation for Guided Tours* both appeared as journal articles in special issues of IEEE Transactions on Visualization and Computer Graphics and were presented at IEEE VR in 2020 and 2021, respectively [175, 177]. The online presentation of *Getting There Together* in a distributed virtual reality system was chosen for the Best VR-in-VR Presentation Award of the conference. Finally, *An Overview of Group Navigation* appeared in the abstract and workshop proceedings of IEEE VR in 2021, where it was presented as part of the workshop "Finding a Way Forward in VR Locomotion" [176].

As visualized in Figure 1.1, the contributions presented in this thesis were accompanied by additional publications that covered aspects of single-user and group navigation in virtual reality. Two of these presented general thoughts and analyses on foundations of navigation in virtual reality which, although partially published later, directly informed the contributions of this thesis [15, 179]. These publications will be discussed in more detail when providing an overview of the research background in Chapter 2. The remaining three publications presented more specific technical solutions for supporting interaction in multi-user virtual reality, among which two focused on the development of expert workspaces using projection-based systems [99, 117]. The last publication presented a calibration system for multiple *HTC Vive* head-mounted displays used in collocated scenarios, which emerged as a byproduct of *Multi-Ray Jumping* and received the Best Poster Award of IEEE VR 2020 [180].

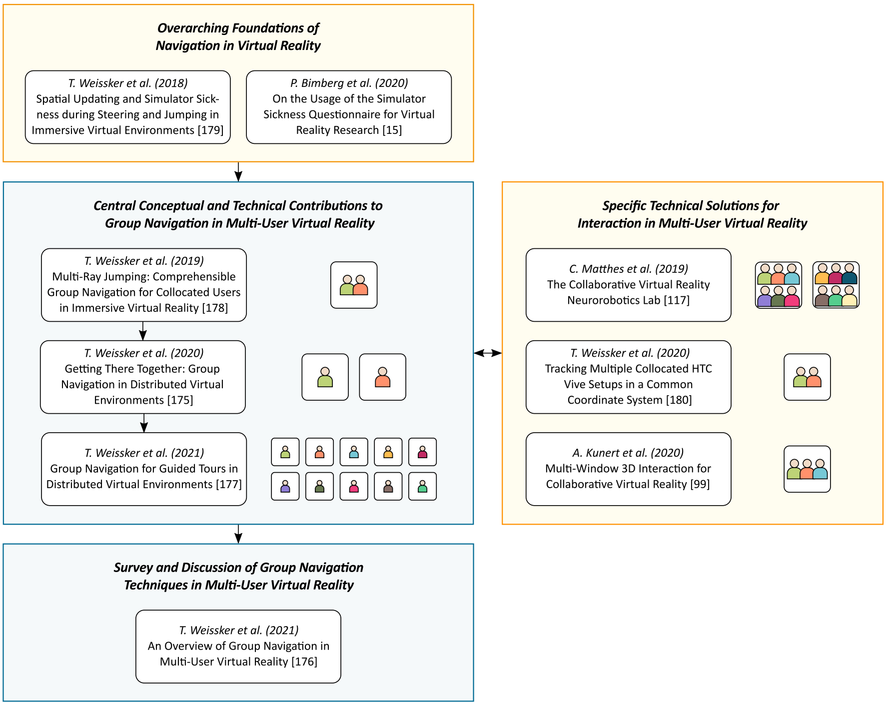

Figure 1.1: The four publications presented in this thesis (blue) were accompanied by five additional publications that partially covered aspects of single-user and group navigation in virtual reality (orange). As indicated by icons, the technical contributions in the respective papers are classified by the number of involved distributed workspaces and the number of collocated users within each of these spaces (see Chapter 6 for more details).

2

Research Background

The contributions of this thesis build upon a large body of previous research on both single- and multi-user navigation in virtual reality. While the three publications presented in Chapters 3, 4, and 5 each come with their own overview of specific related work, this chapter aims at providing a more general introduction to the overarching research context that informed the design and evaluation of all group navigation techniques presented in this thesis. Later, the fourth publication presented in Chapter 6 will supplement this overview by providing a more specific survey of prior approaches for realizing joint navigation in various collaborative virtual reality systems and discussing the presented research contributions to the field from a retrospective viewpoint.

2.1 A Process Model for (Group) Navigation

Navigation is one among three primary forms of user interaction in virtual reality alongside selection/manipulation and system control. Adapting a model proposed by Jul and Furnas [82], Darken and Peterson subdivided the navigation process into several connected steps depicted in Figure 2.1 [44]. Navigation typically starts with the cognitive definition of a goal and the selection of a strategy for its accomplishment. Three common types of goals for navigation are the naïve exploration of the virtual space, the search for a specific target location, and the execution of fine-grained movements for *maneuvering* around an object of interest [20]. In some cases, the need for achieving these goals comes as a consequence of performing a higher-level activity in the virtual environment [20]. With a defined goal and strategy in mind, the execution phase involves a continuous loop of performing travel, perceiving the surroundings, and assessing the progress. While the completion of a search task is defined by arriving at the intended location, exploration and maneuvering tasks usually require the visit of several intermediate locations until sufficient information on the environment or object is gathered. If the performed steps do not lead to the intended progress, the user must either adjust the strategy or redefine the overall goal. Generally, navigation techniques in virtual reality *have to* provide users with a way of performing travel and *may* provide additional functionalities to assist them with the surrounding cognitive processes for wayfinding.

If multiple users are experiencing the virtual environment together, staying together during and after travel requires coordination if only individual navigation techniques are available. One way of doing so is to discuss the next navigational (sub-)goal and strategy

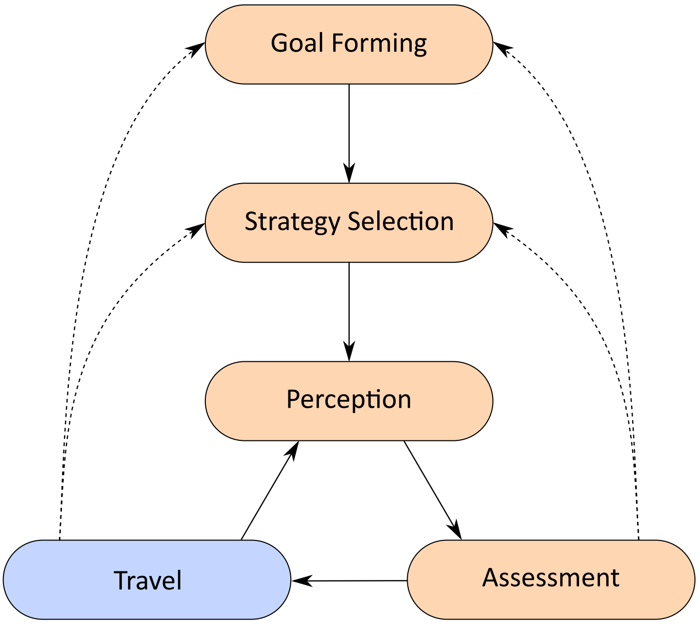

Figure 2.1: A process model for navigation adapted from Darken and Peterson [44], which highlights the relation of travel (blue) to various cognitive processes for wayfinding (orange). If multiple users are involved, group navigation techniques reduce process redundancy and coordination efforts for achieving a common navigational goal together.

beforehand such that every member can get there on their own. Alternatively, a single person can define the (sub-)goal and strategy and simplify the process for the others by going ahead and asking them to follow. Both of these options, however, require each member of the group to actively control, perceive, and assess travel towards the same target location. This redundancy requires everybody to allocate attentive resources for navigation and coordination efforts, which could be avoided. In more complex navigation tasks, individual navigation additionally comes with the risk of losing others during travel if the strategy was misunderstood or the other group members were moving too fast to follow.

Group navigation techniques as presented in this thesis aim to overcome these limitations by enabling the navigator to move the whole group. This approach ensures that the group stays together at all times during travel, does not require the execution of a similar navigation sequence by each member, and therefore minimizes the required coordination overhead. While this provides a strong simplification of the navigation process for passengers, it does not prevent them from contributing to goal forming, strategy selection, and the perception and assessment of progress by verbally communicating with the navigator if they so wish. Despite these advantages of group over individual navigation techniques, however, allowing the navigator to control travel for multiple users also increases the expressivity and therefore complexity of the navigator's interface, which leads to various novel design challenges with respect to providing effective, intuitive, and comprehensible navigation sequences for all involved users. This thesis derives the most important requirements in this regard and presents suggestions for corresponding group navigation techniques.

2.2 Selected Quality Factors for Group Navigation Techniques

Prior work established a large variety of quality factors and associated measurement methods to assess navigation techniques, covering a broad range from simple objective values like speed and placement accuracy to the analysis of complex cognitive constructs such as spatial awareness, scene recollection, and presence (e.g. [2, 19, 20, 81, 114, 136]). While the exact relevance of each quality factor may vary depending on the scenario or application in which the respective navigation techniques are used [19], particular aspects such as the prevention of simulator sickness or the support of spatial awareness present essential usability challenges that are of concern in most usage scenarios. This section reviews some of the quality factors that particularly informed the design and evaluation of the group navigation techniques presented in this thesis to provide some theoretical background for the discussions in the later chapters.

2.2.1 User Wellbeing

Since navigation is a fundamental form of user interaction in large virtual environments, an important goal of navigation techniques is the minimization of any detrimental effects on user wellbeing.

One of the most pertinent issues in this regard is the potential elicitation of sickness symptoms during travel, which can be provoked by a large variety of technical imperfections, specific design choices, and anthropologic factors (see [100, 136] for an overview). Particularly relevant for the design of navigation techniques, a prominent and widely-adapted theory hypothesizes that sickness symptoms are evoked by sensory mismatches between the visual and vestibular system of a user [100, 129, 136]. Moreover, research suggested that the risk of experiencing sickness symptoms is higher in head-mounted displays in contrast to other immersive hardware [90, 136, 156]. An increase in sickness is also hypothesized when travel is not actively controlled by the affected user [46, 142, 156, 160]. It is an ongoing debate how the severity of sickness symptoms can be quantified appropriately. Prior research proposed various approaches for inferring the amount of experienced sickness from questionnaires, postural instability, or biometric and physiological measurements [136]. One of the most common instruments in the virtual reality community is the *Simulator Sickness Questionnaire* (SSQ) by Kennedy et al., which was originally developed for military aviators in the 1990s [88]. While we provided a detailed reflection on the benefits and drawbacks of this questionnaire for virtual reality research in a separate publication [15], one of the most prevalent concerns is its lengthy administration, which often makes it too time-consuming for repeated measurements. In these scenarios, one-question surveys like the Fast Motion Sickness Scale (FMS) [89] or the obtainment of a discomfort score [57, 135] are usually more appropriate.

Another relevant aspect with respect to user wellbeing in multi-user scenarios is to ensure that socially appropriate distances between participants are kept at all times. This consideration goes back to proxemic theories from social anthropology that subdivide the space around a person into intimate space, personal space, social space, and public space depending on distance [71]. While the exact thresholds may vary between cultures and people, it was shown that another person intruding one's intimate space is often considered unpleasant in Western cultures if the intruder is not a close friend [56, 118]. Similar negative reactions to personal space violations were observed in distributed virtual reality systems even though there was no physical counterpart to the intruding virtual avatar [182]. As a result, several systems implement some form of protective mechanism to increase user comfort by preventing users from entering the personal space of others or at least making intruding avatars transparent [119].

The group navigation techniques presented in this thesis were designed with particular attention to these two aspects of user wellbeing. All techniques are based on the *jumping* metaphor for travel to minimize sensory conflicts (see Section 2.3) and were evaluated with respect to their elicitation of sickness symptoms in user studies. This was especially relevant since the use of head-mounted displays and the experience of travel controlled by another person were both considered precarious in prior work. The severity of symptoms was measured by either verbal assessments, the commonly employed SSQ [88], or a more lightweight discomfort score [57, 135] to facilitate repeated measurements where necessary. Regarding user distances, the techniques relied on the implicit abidance of personal space semantics during physical walking similar to the real world [40] and ensured that all forms of virtual travel did not allow for user placements with interpersonal distances closer than 0.46m, which is considered a plausible boundary between intimate and personal space in Western cultures [71].

2.2.2 Spatial Awareness

Another relevant quality factor for navigation techniques in virtual reality is their support for acquiring and maintaining spatial awareness. This umbrella term covers a variety of cognitive spatial abilities from the judgement of distances [122, 137] over path integration and spatial updating [91, 138, 139] to the formation of profound survey knowledge [157, 184]. While the choice of navigation techniques (e.g. [13, 19, 132]) as well as active/passive user roles during travel (e.g. [3, 32]) can facilitate or hinder the completion of spatial tasks, performance is also affected by various interpersonal differences in general spatial abilities. Among other factors, related work identified influences of gender [25, 42], age [163], and spatial activities in the childhood [51] as relevant factors to name just a few examples. In an attempt to isolate the influences particular to the use of navigation techniques, Bowman et al. suggested to focus on “the ability of the user to retain an awareness of her surroundings during and after travel” [19], which is a relevant foundation for the successful completion of any higher-level spatial task. As a result, navigation techniques should aim to avoid any form of momentary or permanent disorientation during travel. To measure how frequently particular travel techniques may result in disorientation, prior work suggested the execution of short travel sequences after which users were asked to locate a previously seen object [19], to indicate the previous location of an object that was removed during travel [132], or to point towards their origin of travel [13, 86]. While these measurements are similar to the ones used to assess spatial updating, the addition of response time as a dependent variable allows to distinguish between trials where users were immediately aware of their surroundings and trials where some time for reorientation was required before giving a correct answer.

In the context of group navigation techniques, retaining an awareness of the surroundings during travel is especially challenging for passengers since they are not actively controlling their movements through the environment. Moreover, being part of a group creates an additional interest in knowing how the other members are affected by the navigation process to facilitate further social interactions. Therefore, group navigation techniques should support the awareness of ongoing navigation activities and facilitate the predictability of their consequences for all involved users. The work of this thesis operationalizes this design philosophy that guided the development of all presented techniques into quality requirements for *comprehensible group navigation* (see Sections 3.3.6, 4.3.3, and 5.3.2). To evaluate disorientation during travel, the presented studies either focused on verbal user feedback to explicit corresponding questions in semi-structured interviews or employed an adaptation of the task setup by Bowman et al. asking users to locate previously seen object as quickly as possible for more formal analyses [19].

2.2.3 Workload

The completion of any task comes with an associated “cost incurred by a human operator to achieve a particular level of performance”, which is defined as *workload* by Hart and Staveland [73]. Since navigation in virtual reality is often a means to complete a higher-level activity in the virtual environment [20], it is crucial that navigation techniques aim to keep the incurred workload small in order to avoid taking too many resources away from a higher-level task and social activities with other users. The overall experience of workload is subjective and emerges from interactions between various circumstantial, task-related, and user-related factors [73]. While a lightweight design of navigation techniques mainly addresses a reduction of task-related influences, it also increases accessibility for users with different experience levels such that certain user-related influences might become less pronounced. The literature on navigation techniques in virtual reality proposed several quality factors that relate to this idea by aiming for a reduction of physical or mental demands during navigation. While ensuring user wellbeing (Section 2.2.1) and fostering spatial awareness (Section 2.2.2) are certainly also a part of workload reduction, the most general notions in this regard are *ease of learning* and *ease of use* (e.g. [19, 81]). The former focuses on the required effort of novices to become productive with the technique; the latter refers to the general physical and cognitive complexity required for operation [19]. The evaluation of both criteria is often based on qualitative assessments using observational and conversational methods from usability testing to identify deficiencies [145]. Quantitative measurements, on the other hand, include the required practice time to achieve a particular performance [148], the improvement of performance metrics over time [74], the amount of errors during operation [33], and relative rankings of tested techniques [79, 81]. Moreover, the widely-adapted and easy-to-administer NASA-TLX questionnaire developed by Hart and Staveland polls and merges quantitative user assessments regarding six central facets of perceived workload, which offers a general testing instrument to obtain and compare a single overall workload score for a certain task and condition [73].

As addressed in Section 2.1, group navigation techniques simplify getting to a new location together by decreasing process redundancy and coordination overheads, which contributes to the reduction of workload. On the other side, however, the increased responsibilities of the navigator as well as the passengers' efforts for understanding what is happening point towards potential increases in workload. To ensure that the effort added by the operation and understanding of group navigation techniques does not outweigh the reduction of process redundancy and coordination, the developments presented in this thesis aim at providing lightweight and understandable interfaces by extending well-established interaction workflows and visualizations from single-user systems. Different facets of workload like the ease of learning and use were evaluated by employing combinations of the above-mentioned measurement methods. For overall workload judgements, the user studies focused on Raw TLX scores as obtained by averaging the results of the NASA-TLX items without applying subscale weighting [72].

2.3 Travel Metaphors in Virtual Environments

Prior work introduced various techniques for supporting travel in virtual environments as well as several taxonomies to categorize and systematize these developments (see [114] for a recent overview). To explain the design choices made for the developments of group navigation techniques in this thesis, this section presents a brief assessment of commonly employed travel techniques in single-user systems with particular attention to the quality factors discussed in Section 2.2. The overview is guided by the classification of travel by Bowman et al. into five different underlying metaphors for its execution [20], among which a focus is set on *physical movements*, *steering*, and *target-based travel* since they are the most common in modern virtual reality systems. More exhaustive surveys of travel techniques in virtual reality are given, for example, in the works of Al Zayer et al. [2] and Luca et al. [114].

2.3.1 Physical Movements

Tracking physical movements and applying them to the virtual camera is arguably the most natural metaphor for travel and was shown to lead to improved degrees of presence, spatial awareness, and scene recollection compared to other metaphors (e.g. [147, 162, 169, 187]). However, the available space in which user movements can be tracked puts a strong limitation on the explorable parts of the virtual environment. Potential solutions to apprehend larger environments by physical movements include the use of treadmills (e.g. [43, 63, 83]), walking in place (e.g. [14, 158, 164]), redirected walking (e.g. [133, 161]), movement scaling (e.g. [77]), and resetting/reorientation techniques (e.g. [61, 110, 183]). However, many virtual reality setups simply resort to an isomorphic mapping of user movements in the available workspace and offer additional virtual travel techniques like steering (Section 2.3.2) and target-based travel (Section 2.3.3) for traversing larger distances. Following this thought model, the presented developments of group navigation techniques in this thesis allow all group members to adjust their position within the group by physical movements while the navigator can apply virtual travel to move the whole group together. A separate individual virtual travel technique for each group member can offer additional navigational freedom if required, for example, to allow the navigator to look ahead before taking the group along or to give passengers more options to optimize their viewing positions.

2.3.2 Steering

Steering is a versatile metaphor for controlling virtual travel by continuously specifying the intended speed and direction of movement, which is similar to operating a vehicle in the real world and therefore typically easy to learn and use. However, in virtual reality, steering creates a sensory mismatch as the resulting visual motion flow conflicts with the absence of a corresponding vestibular sensation, which is considered a plausible source of sickness symptoms (see Section 2.2.1). As a result, prior work suggested several approaches to mitigate the elicitation of sickness symptoms during steering, which include the dynamic reduction of the user's field-of-view [57, 109], the display of static rest frames [24, 186], and the generation of haptic cues during travel [111, 174]. Nevertheless, a key decision for the development of group navigation techniques in this thesis was to avoid the generation of conflicting visual motion flow completely by basing all designs on short-distance teleportation.

2.3.3 Target-Based Travel

Target-based travel requires the user to specify the desired destination and is then brought there automatically. In work prior to this thesis, we classified implementations of target-based travel by their employed method for *target specification*, the amount of *pre-travel information* presented to the user, the type of *transition* applied, and the amount of *post-travel feedback* presented to the user afterwards [179].

Particular choices in each of these phases can influence the technique with respect to the discussed quality factors. As an example, a continuously animated movement as the *transition* towards the target provokes a similar sensory conflict as in steering and is therefore often neglected in favor of a discontinuous (i.e. teleportation-based) transition to alleviate sickness symptoms. However, combining discontinuous transitions with allocentric methods for *target specification* like galleries [53], Worlds-in-Miniature [130], or Photoportals [98] puts a stronger focus on the easy and rapid acquisition of potentially far-apart destinations while spatial information to be acquired by traversing the routes between destinations is lost.

As a compromise between fully continuous and fully discontinuous travel, a prominent variant of target-based travel for head-mounted displays restricts target specification to an egocentric selection of a destination within the currently visible part of the scene (vista space, cf. [121]) using a straight or curved selection ray. As a result, getting to a far-away destination involves traveling to several intermediate targets, which puts more emphasis on the route towards the destination than a one-time transition while still allowing for discontinuous transitions to prevent sickness symptoms. In accordance with early experiments on discontinuous transitions in virtual environments by Bowman et al. [19], we chose the term *jumping* to denote this paradigm in prior work since it emphasizes the resemblance to a forward jump in the real world [179].

Definition 2

Jumping is an egocentric and range-restricted variation of target-based travel in which targets are specified in vista space.

Figure 2.2 summarizes the relationship between fully continuous steering, fully discontinuous teleportation, and the intermediate jumping metaphor in graphical form.

Several studies could confirm that jumping with discontinuous transitions can reduce sickness symptoms as compared to steering [34, 37, 55, 79, 132, 179]. While some studies even indicated that the distance restriction to targets in vista space might be sufficient to avoid negative effects on spatial awareness [34, 179], other results still pointed towards potential disadvantages of discontinuous over continuous transitions in this regard [13, 17, 132]. To reduce the risk of momentary disorientation after a jump, several variants of jumping build on supplementing the selection ray with additional *pre-travel information* like preview portals [110] or preview avatars [66, 188, 189] to make the viewing perspective after the jump more predictable for the operating user. Even in its basic form, however, jumping has become one of the most prevailing travel techniques for traversing virtual environments with head-mounted displays.

Because of this widespread popularity and the inherent benefits with respect to sickness reduction, the jumping metaphor with discontinuous transitions was selected as the basis for all developments of group navigation techniques presented in this thesis. The interac-

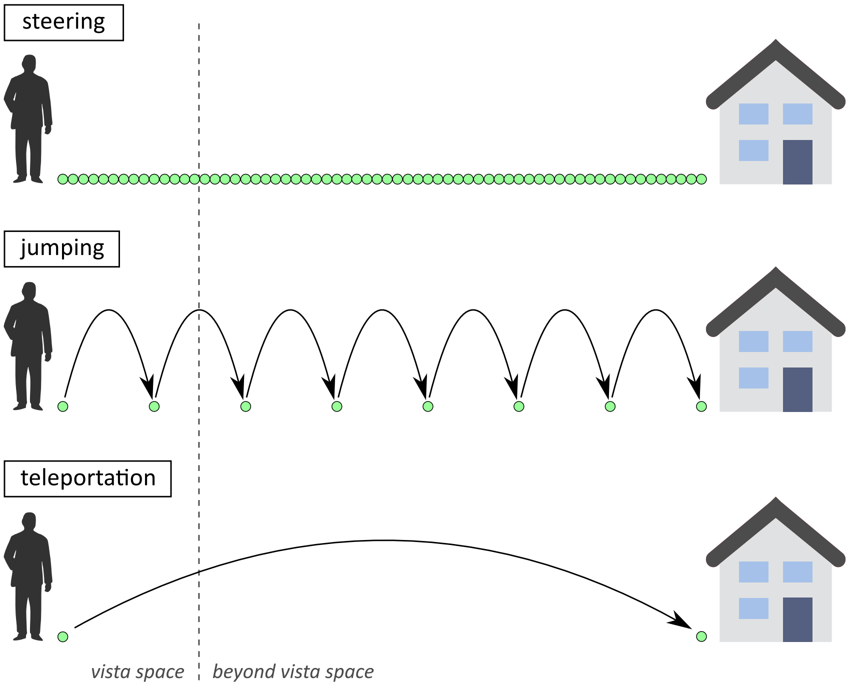

Figure 2.2: The jumping metaphor for virtual travel is located between fully continuous steering and fully discontinuous teleportation. In particular, each intermediate jumping target towards the final destination is in vista space of the previous one. Figure adapted from Weissker et al. [179].

tion designs particularly focused on providing seamless extensions of common single-user jumping implementations while providing enhanced *pre-travel information* to preview the consequences of the navigator's intended actions for all members of the group to prevent spatial disorientation. The presented solutions were evaluated in several user studies to judge their suitability for both the navigator and the passenger role.

2.4 Collaborative Navigation

Navigating through large virtual environments and locating the most relevant objects to inspect can be challenging alone, which motivated several approaches to realizing collaborative navigation assistance in prior work. If the employed hardware setup only supports one immersed user, prior work suggested increasing the involvement of non-immersed observers by showing auxiliary information like overview maps on a 2D display or even allowing them to place guiding geometries for the immersed user to improve collaboration (e.g. [7, 126, 173]). Asynchronous collaboration approaches, on the other hand, can enable users or application developers to prepare interesting routes and features within the system, which can then be used to provide navigation guidance for future users by applying automated movements (e.g. [9, 64, 141]), animating virtual agents to behave as guide avatars (e.g. [31, 124, 181]), or providing graphical widgets for assisted wayfinding (e.g. [30, 62, 171]).

While all of these approaches allow for basic forms of collaborative navigation to accomplish a certain activity, they all lack the component of a personal encounter. The representation of each user in a shared virtual environment, often also referred to as a collaborative virtual environment (CVE), addresses this issue by allowing "multiple people [to] co-exist, [be] aware of each other's presence (e.g. through avatars) and communicate" in a similar way to a real-world encounter [47]. In the desktop-based system of Dodds and Ruddle, for example, collaborators explored the environment using individual navigation capabilities but were provided with various auxiliary functionalities for cooperating on an architectural review task. Among others, these include visual highlights to see where other collaborators are located in the environment, portals to share the egocentric viewing perspectives of collaborators, and a teleportation feature to rapidly join other collaborators at their current location [47, 48]. Regarding more tightly-coupled collaboration in desktop-based systems, Benford, Greenhalgh, and Lloyd suggested the abstraction of spatially close users into *crowds* [10] or smaller social *formations* involving different user roles [112], which affected group communication and representation to improve internal joint activities as well as external recognizability. In their work, an early form of a group navigation technique was proposed as one of three variants of realizing *mobile crowds*, which suggested a common vehicle for a crowd that can be controlled "on behalf of their members" in order to go on a ride together [10]. However, the presentation of this variant of a mobile crowd was purely conceptual without any form of implementation or evaluation.

With the increasing affordability of virtual reality hardware and the ubiquitous availability of software systems for immersive collaboration, more recently also referred to as social virtual reality systems [92, 119], many of the early concepts presented for desktop-based systems are still valid. However, their realization in immersive virtual reality faces several novel challenges, for example, in the areas of fostering mutual awareness, reducing the risk of sickness symptoms, and providing spatial rather than conventional desktop user interfaces. With respect to collaborative navigation, the work in this thesis focuses on the design and evaluation of group navigation techniques as initially described in the form of a variant of mobile crowds by Benford and colleagues. After presenting the particular research contributions in the following three chapters, Chapter 6 will provide an exhaustive review of group navigation techniques for head-mounted displays as well as projection-based systems, which will allow to situate and discuss the presented contributions to the field from a retrospective viewpoint.

3

Multi-Ray Jumping: Comprehensible Group Navigation for Collocated Users in Immersive Virtual Reality

This chapter reports on joint work with Alexander Kulik and Bernd Froehlich at Bauhaus-Universität Weimar. It was published and presented at the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), where it received a nomination for the Best Conference Paper Award.

This research has received funding from the European Union's 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*).

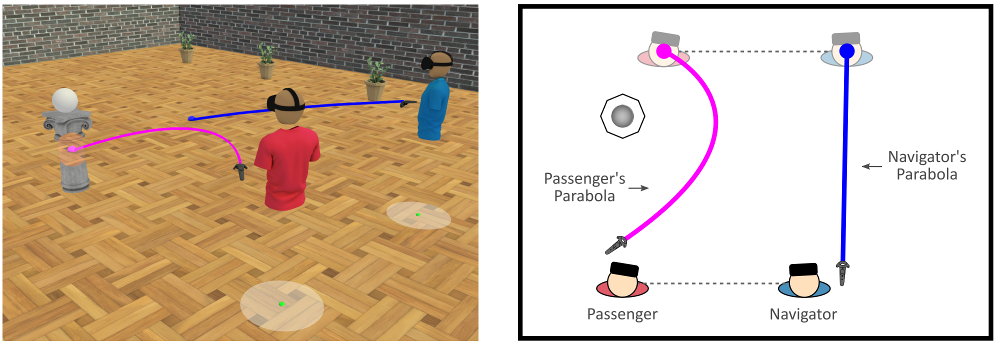

Figure 3.1: Target specification with Multi-Ray Jumping for two collocated users. While the navigator (blue shirt, right side) specifies a target using the blue parabola, the magenta curve adjusts accordingly to show the offset target location of the passenger (red shirt, left side). The initial direction of the magenta curve is defined by the passenger's controller.

Abstract

The collaborative exploration of virtual environments benefits from joint group navigation capabilities. In this paper, we focus on the design and evaluation of a short-range teleportation technique (jumping) for a group of collocated users wearing head-mounted displays. In a pilot study with expert users, we tested three naïve group jumping approaches and derived the requirements for comprehensible group jumping. We propose a novel Multi-Ray Jumping technique to meet these requirements and report results of two formal user studies, one exploring the effects of passive jumping on simulator sickness symptoms ($N = 20$) and a second one investigating the advantages of our novel technique compared to naïve group jumping ($N = 22$). The results indicate that Multi-Ray Jumping decreases spatial confusion for passengers, increases planning accuracy for navigators, and reduces cognitive load for both.

3.1 Introduction

Collaborative virtual reality systems enable collocated and distributed groups of people to meet and interact with each other in virtual environments. However, common virtual navigation techniques are not ideal for the joint exploration of large-scale 3D environments since they are designed for individual users and not for groups of users traveling together. In a guided virtual city tour, for example, the attendees might not always want to navigate individually to follow the guide along a path. Instead, the guide could navigate the whole group as a single entity, which leads to an asymmetric role distribution between the controlling *navigator* and multiple *passengers*. Passive locomotion, however, was shown to negatively affect spatial understanding in real-world settings [3, 142] and to increase the risk of simulator sickness in virtual environments [156, 160].

As a first step towards the joint navigation of user groups in immersive virtual reality, we investigated short-range teleportation techniques (jumping) for two collocated users. In a pilot study, six proficient virtual reality users compared three naïve approaches to group jumping. Based on their observations, we derived concrete requirements for *comprehensible* group jumping, that guided our development of *Multi-Ray Jumping*. This novel technique offers extended pre-travel information to help the passenger understand when a jump is planned and where the destination will be. It also facilitates jump planning for the navigator with information about the passenger's destination (Figure 3.1). *Multi-Ray Jumping* was evaluated in two formal user studies. First, we compared simulator sickness in the passenger role to active jumping as navigator ($N = 20$). Second, we quantified the benefits of the additional pre-travel information for navigator and passenger in comparison to a baseline from the pilot study ($N = 22$).

Workspace awareness as defined by Gutwin and Greenberg [68] emphasizes that an "up-to-the-moment understanding of another person's interaction with the shared workspace" is essential for group interaction. In particular, in situations when users are collocated in the real world and represented in the same spatial configuration in the virtual world, this is largely achieved by representing users by avatars. However, for group navigation, more than such an implicit awareness is needed as passengers are directly affected and not just the surrounding workspace. This is particularly important for navigation by jumping since large distances can be covered by a single jump. Passengers need to be able to anticipate the jump and comprehend where they are headed – potentially being able to mentally take the perspective of the target location. The navigator, on the other hand, must be aware of the passengers' locations and understand how they will be affected by the planned jump. The research presented in this paper explores which mediations are necessary in this regard and how they can be realized for two collocated users. More specifically, we make the following contributions:

- the concrete requirements for *comprehensible* group jumping elicited by a pilot study of three initial approaches for joint jumping of two collocated users
- the design and implementation of *Multi-Ray Jumping*, a novel technique for comprehensible group jumping
- indications that simulator sickness symptoms are not affected by active or passive user roles during jumping
- evidence that *Multi-Ray Jumping* increases planning accuracy for the navigator and improves spatial awareness for the passenger while imposing lower cognitive load in both roles

A core lesson learned from our studies was that group navigation requires a robust understanding of all navigation-related activities and their consequences among all participants. Based on our results, we believe that *Multi-Ray Jumping* provides this understanding and is a promising first step towards comprehensible, effective, and comfortable group navigation in collaborative virtual reality.

3.2 Related Work

Navigation is an interplay of the motor component *travel* and the cognitive component *wayfinding* [19]. While physical movement is the most natural form of travel in virtual reality, it is usually limited by the size of the available tracking area. Walking in place [164], redirected walking for one [133] and two users [6], scaling [77], and resetting techniques [183] can help to overcome this limitation, but they become impractical and exhausting in large environments. As a result, virtual navigation techniques like *steering* and *target-based travel* move the user in the virtual environment without requiring physical locomotion.

In contrast to free exploration techniques without navigational constraints, prior research presented steering techniques guiding a user along interesting paths and features of the scene to explore. In the river analogy, for example, users automatically follow a predefined path while having active control over small deviations to investigate nearby features [64]. Additionally, automated guide avatars can draw user attention to previously specified points of interest [181]. In our research, navigation and guidance are provided by a human user rather than by the system.

In head-mounted displays (HMDs), especially, steering techniques have a high risk of inducing simulator sickness. One plausible reason for this is the sensory conflict between the visual and vestibular systems of a user [100, 134]. Fernandes and Feiner showed that field-of-view restrictions during movements can reduce these symptoms [57]. On the other hand, target-based travel by teleportation avoids the sensory conflict completely, and short-range teleportation (jumping) has become the de-facto standard for navigation in VR applications using HMDs. In the taxonomy of Bowman et al. [19], jumping can be described as a discrete selection of environmental/direct targets. Although jumping offers less spatial information for path integration, studies comparing jumping to steering confirmed effective navigation with significantly lower simulator sickness while spatial orientation and perceived presence did not seem to be affected [79, 179]. As a result, we focused on jumping techniques for effective and comfortable group navigation of HMD users. We used the classification scheme of Weissker et al. to describe our implementations in terms of target specification, pre-travel information, transition, and post-travel feedback [179].

Collaborative virtual reality systems allow multiple users to meet and interact with each other in real-time while exploring a shared 3D environment. This collaboration can be *collocated* for users in the same physical location and *distributed* between different locations via a network connection. Successful collaboration builds on mutual awareness and the effective negotiation of common goals. Gutwin and Greenberg introduced the concept of workspace awareness and suggested that it can emerge implicitly in real-world settings from consequential communication (perception of each other's activities), feedthrough (feedback of manipulated artifacts as perceived by others), and explicit communication. A fundamental basis for workspace awareness in HMD-based systems is the representation of users by avatars in the virtual world. Social meeting rooms like vTime[1] and AltspaceVR[2], for example, offer humanoid avatar representations for distributed users. For dispersed users in social virtual environments, Dodds and Ruddle presented methods to find and follow group members that are out of view [47, 48]. Our research focuses on navigation techniques supporting workspace awareness for groups of collocated rather than distributed users.

Collocated collaboration in virtual environments can be symmetric or asymmetric. In asymmetric settings, one or several users often use auxiliary information, e.g. presented on a desktop monitor, to guide an immersed user through the virtual environment [7, 125, 127]. In symmetric settings, with more than one head-mounted display operated in the same physical location, travel is often limited to physical walking. In the *EPICSAVE* project, for example, two tracked users could learn about and work on medical activities side by side [152]. The system of Roth et al. supported up to five users in a very large tracking

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[1] `http://vtime.net/`

[2] `http://altvr.com/`

space [144]. If multiple collocated users are provided with individual virtual navigation capabilities, the user configuration in the virtual world will diverge from the real-world situation. Lacoche et al. suggested mediators to convey the real-world positions of other users and visual barriers to avoid physical collisions [101]. In contrast, our approach is to retain consistent spatial user configurations between the real and the virtual interaction spaces and to provide techniques for joint navigation. Kulik et al. showed that this may lead to collisions with scene geometry during navigation and presented techniques to prevent those while steering through spatial constrictions [96].

Moving a group of collocated users implies an asymmetric role distribution of one *navigator* and multiple *passengers*. It was suggested to mitigate the resulting imbalance of awareness and control by a large stationary group navigation device, which facilitates the perception and negotiation of navigation control [8, 95, 96]. For jumping techniques, however, this approach appears overly laborious. Prior research also indicated a potentially increased risk of simulator sickness during passive locomotion through virtual environments [156, 160]. Moreover, passive locomotion can negatively affect the formation of spatial knowledge and scene understanding. Appleyard showed that participants who have actively explored a city by driving a car sketched more accurate maps than those who traveled by bus [3]. Chrastil and Warren's overview of studies on active and passive navigation in virtual environments lists examples that revealed similar disadvantages for passive navigation [32]. We aim to develop group navigation techniques that equally support spatial awareness and prevent simulator sickness for users in both roles.

3.3 Pilot Study: Expert Review of Group Jumping Techniques

In our design process of a group jumping technique for collocated users, we started with an initial expert review of three approaches motivated by related work (see Section 3.3.2) in a two-user virtual reality setup. Our system allowed both users to walk around in the shared tracking space but restricted the control of virtual navigation to a single user. Individual navigation for the passenger beyond walking was not possible, so the spatial user configuration in the virtual environment remained consistent with the real-world situation. Such a constrained collocated setup facilitates implicit awareness cues and explicit communication similarly to real-world settings.

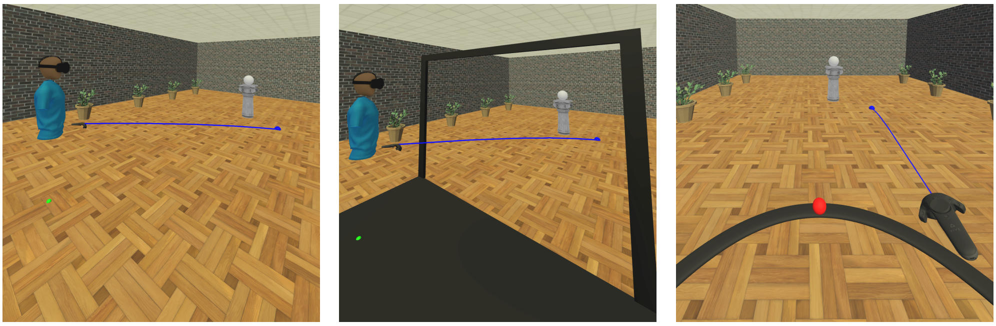
In this pilot study, we were interested to see (1) if existing jumping implementations can be directly used in such a setup and (2) if existing group navigation approaches from other systems can be adapted to target-based travel in head-mounted displays.

3.3.1 Experimental Setup

The VR setup consisted of two HTC Vive head-mounted displays offering both position and orientation tracking. Input was obtained using Vive handheld controllers. Two workstations were linked together and shared the same tracking space calibration. The tracking space was approximately 3m x 1.5m in size, allowing for a side-by-side user configuration in social space [70]. The virtual environment was rendered with a resolution of 1080x1200 pixels per eye and an update rate of 90 Hz. We measured an end-to-end latency of 12.5ms.

3.3.2 Conditions

Target specification for single-user jumping involves an egocentric selection of a target in the currently visible part of the scene (vista space), often using a parabolic pick ray (e.g. [13, 79, 179]). The ray and its intersection with the scene (pre-travel information) defines the navigator's position after the transition without applying changes to the viewing orientation. Post-travel feedback is usually not given in related work [179]. We evaluated three extensions of this basic single-user jumping for two collocated users with instant transitions called *Coupled*, *Vehicle*, and *Congruent* (see Figure 3.2). Our chosen avatar representation consisted of a wooden head with a head-mounted display, a shirt and a controller. We found this abstract representation suitable to support mutual awareness by providing more visual saliency than the representation of devices alone while not evoking uncanny feelings as known from imperfectly behaving avatars [151].



(a) In the *Coupled* condition, the same relative displacement as expressed by the navigator's input was also applied to the passenger's position to retain their spatial configuration.

(b) The *Vehicle* condition constrained *Coupled* jumping to locations that could be selected through a virtual window. Hence, larger changes of movement direction required virtual rotation.

(c) In the *Congruent* condition, the passenger was aligned with the navigator's virtual position for each jump. A compass widget (red sphere) indicated the navigator's viewing direction.

Figure 3.2: In our exploratory pilot study, we tested two-user implementations of three approaches for realizing group jumping. All screenshots are taken from the passenger's view, and the navigator is visualized by a head and body avatar.

Coupled

The most straightforward extension of single-user jumping for two users is to apply the navigator's relative change of position to the passenger as well. Hence, the group's spatial user configuration remains identical to the real world during travel. We refer to this first condition of our pilot study as *Coupled* group jumping (Figure 3.2(a)) and use it to analyze the direct applicability of a single-user jumping technique to a two-user scenario.

Vehicle

Prior group navigation techniques for projection-based multi-user displays consider all users in front of the projection screen traveling together on a shared vehicle or viewing platform [8, 95, 96]. Most of the vehicle's movements are applied in the directions defined by the visible parts of the scene through the projection screen. Larger changes of movement direction, therefore, require virtual rotation methods. This offers the advantage that all users share a similar viewing direction, which is not necessarily true in collocated HMD setups as the screens rotate together with the user. In our *Vehicle* condition, we analyze the applicability of the vehicle metaphor to jumping in head-mounted displays. We adapt the navigational constraints from projection-based setups and indicate the possible movement directions by a virtual navigation window (Figure 3.2(b)). Left and right rotations at constant angular velocity were initiated and terminated by button presses on the controller.

Congruent

Passengers are always offset to the navigator, which can lead to virtual collisions with the scene geometry in confined environments [96]. This situation is uncomfortable and not considered in many studies on passive navigation summarized by Chrastil and Warren [32]. Here, passive navigation means watching motion recordings from the navigator's point of view. In our *Congruent* condition, we analyze how well the concept of seeing the navigator's view during travel is received in a two-user HMD scenario. Our implementation allowed the navigator to initiate navigation by pressing a button, which triggered a slow-in-slow-out animation from the passenger's actual position to the navigator with a duration of 0.5s. This allowed the passenger to see the controller and jumping ray from the navigator's perspective. A red sphere on a ring surrounding the passenger indicated the current viewing direction of the navigator for improved mutual awareness. When the navigator pressed the button again, the passenger was moved back to their tracked position.

3.3.3 Procedure

Participants arrived at our lab and signed an informed consent form. Afterwards, the three techniques motivated in Section 3.3.2 were tested in a counterbalanced within-subjects design. The role of the navigator was taken by the experimenter for comparable interaction sequences across all participants. The participants experienced the role of the passenger.

Each technique was introduced with a short verbal explanation. Next, the experimenter performed nine jumps along a route through a virtual museum, thereby stopping and looking at various exhibits. The task of the passenger was to observe and understand the actions of the navigator as well as the exhibits being looked at. In the *Congruent* condition, participants were released to their actual positions at exhibits and moved back to the navigator before further travel. After testing each technique, users were asked for advantages, disadvantages, and general feedback in an open questionnaire. At the end, participants provided a preference ranking of the three techniques. The whole procedure took approximately 30 minutes to complete.

3.3.4 Participants

Six (two female and four male) student and research assistants between 21 and 28 years ($M = 24.0$, $\sigma = 2.65$) participated in this explorative study. All of them were proficient users of Virtual Reality and thus able to provide expert feedback.

3.3.5 Results and Discussion

The *Vehicle* condition was appreciated for being “fast and easy to understand” (P6) and for “jumps [that] cannot happen outside my field of view” (P4). On the other hand, participants complained about traveling through and standing in walls (P1, P5) because of their offset to the navigator. Their main point of criticism was the need for virtual rotation, which was considered “nauseating” (P4). One participant even had to “close the eyes for rotation to not get sick” (P5). Discrete rotations could be considered as an alternative to avoid continuous motion flow. However, it is subject to future research to find virtual rotation techniques that maximize spatial comprehensibility while minimizing simulator sickness. All participants named *Vehicle* as their least preferred technique.

Seeing the navigator’s view in the *Congruent* condition was said to feel “almost like you’re doing it yourself" (P4), and it was positively mentioned that “orientation was easy when in partner’s view" (P3). One participant, on the other hand, noticed that navigation “feels lonely” (P4), which we attribute to the incorrect spatial representation of navigator and passenger in the virtual world. In addition, users mentioned that the transition moving the passenger to and away from the navigator’s position "felt really tough" (P6), so a “slower transition animation" (P3, P6) was suggested. However, slower switching results in longer exposure times to visual motion flow, which can intensify simulator sickness symptoms. A jump-based transition, on the other hand, would need suitable feedback to minimize confusion about the immediate location changes. Half of the participants named *Congruent* as their most preferred technique.

The *Coupled* condition was mainly appreciated for its simplicity. Our participants deemed it “easy to understand” (P1, P6), “straightforward" (P2), and “more intuitive” (P3) than the other techniques. The problem of accidentally “standing in walls” (P5) resulting from the offset to the navigator was, nevertheless, also mentioned as a disadvantage here. Also, the inconsistency between indicated target of the navigator and actual landing position of the passenger made it "really difficult [...] to judge the target of the next jump" (P4). This was intensified by "obstacles" (P4) occluding the jumping ray and target. One participant also mentioned it's easily "possible to miss where the partner is pointing" (P3) since the passenger can still be busy looking at an exhibit while the navigator already plans the next jump in a different direction. In total, half of the participants named *Coupled* as their most preferred technique.

3.3.6 Requirements for Comprehensible Group Jumping

In summary, none of the tested implementations of group jumping was fully satisfying. A major complaint about the straightforward extension of single-user jumping in the *Coupled* condition was the frequently occurring confusion of passengers about their resulting position in the scene after a jump. Apparently, they often expected to arrive at the location indicated by the navigator since this was the only available target preview. This problem was intensified when parts of the navigator's parabola were occluded by the scene geometry. Moreover, our participants reported that they missed the planning phase of several jumps, which resulted in unexpected location changes and required spatial reorientation. They were also often placed into walls as it was difficult for the navigator to estimate the relative position of the participant and to incorporate this information into the planning process. The suggested constraints to the jumping direction (*Vehicle*) or the virtual passenger location (*Congruent*) solved some of these problems but introduced additional overheads and challenges to be solved separately. We thus review the observations in the *Coupled* condition in more detail and derive requirements for *comprehensible* group jumping.

Comprehensible group jumping techniques should foster the awareness of ongoing navigation activities and facilitate the predictability of their consequences for the navigator and all passengers. This implies the following interface requirements for passengers:

- a notification mechanism to raise attention when the navigator is planning a jump
- a clearly visible indication of the jump's target location for all participants (passengers and navigator) in order to make the jump predictable and avoid spatial confusion

For the navigator, the interface requirements for comprehensible group jumping can be summarized as follows:

- an indication of the current user configuration in the workspace to support the awareness of passengers and their agreement on the planned navigation
- a clearly visible indication of the jump's target location for all participants (navigator and passengers) to support a collision-free and precise placement of the group at the target location

3.4 The Multi-Ray Jumping Technique

Following our postulated requirements, comprehensible group jumping can be implemented in various ways. Most fundamentally, previews of the target locations of all involved participants must be provided. These previews can be simple location markers or semi-transparent copies of the current avatar representations at the planned location (ghost avatars). The latter implies an external view of the current group configuration, which offers additional situational awareness through body language. Passengers standing behind the navigator would become visible, and a jump could be interrupted if one or several avatars still seem to be busy at the current location. For the passengers, such an additional group representation might be less relevant. Instead, since we have noticed that the planning phase of a jump might go fully unnoticed, an always visible indicator about a planned jump may be more helpful.

Our *Multi-Ray Jumping* technique is an extension of *Coupled* group jumping with additional pre-travel information for enhanced comprehensibility. When the navigator plans a jump using this technique, a second parabola from the passenger's controller to the corresponding target position appears. To increase the awareness that the navigator is planning a jump, the secondary parabola starts from the passenger's controller in the respective pointing direction. This results in a curved path with a high chance that a considerable part is always visible. If necessary, the controller can also vibrate to attract attention when the navigator starts planning a jump. In certain situations, the secondary parabola may be occluded by scene geometry such that parts of it and the indicated target are not visible. We propose a see-through effect making scene geometry in front of the curve transparent to avoid these problematic situations. Target specification using *Multi-Ray Jumping* is shown in Figure 3.1.

Additional navigation rays connected to an input device per user afford equal access to navigation control. This can be useful for explorative scenarios without a clear role assignment of guide and attendee. In these cases, each user could simply take over the role of the navigator by pressing the button for target specification on their controller. If both users claim control over the group's navigation concurrently, the system can resolve the conflict in various ways. We suggest switching to individual target specification rays per user, which support the negotiation of a joint decision. Once this decision is made, one user decides to become the passenger by releasing their button again. The corresponding visualization returns to the secondary parabola introduced above, and the new navigator can jump the group to a specified target. If the passenger does not intervene, the navigator can assume agreement for the next jump.

3.5 Study 1: Simulator Sickness after Multi-Ray Jumping as Passenger

Jumping techniques were shown to reduce simulator sickness symptoms compared to steering in single-user scenarios [179], but potential differences between active and passive roles during group jumping are largely unexplored. Prior research on steering techniques indicated more severe sickness symptoms for passive over user-initiated steering [156, 160], which was also observed in real-world settings earlier [3, 142]. For our first formal study, we were wondering if similar effects of user control can be observed with *Multi-Ray Jumping*. Therefore, we compared simulator sickness in the passenger role of *Multi-Ray Jumping* to the baseline of active single-user jumping. For this study, we used the same experimental setup as our pilot study on group jumping techniques described in Section 3.3.1.

3.5.1 Conditions

In the *Active* condition, we tested a common implementation of jumping with a parabolic pick ray for target specification as an active navigator without any passengers. This single-user baseline is comparable to jumping implementations in related work, providing only the pick ray as pre-travel information, an instant transition, and no post-travel feedback. For the *Passive* condition, both the experimenter and the participant were present in the virtual environment, and the experimenter operated *Multi-Ray Jumping* in the navigator role. This ensured comparable interaction sequences to be observed by the participants in the passenger role. As in our pilot study, both users were represented with simple head and body avatars.

3.5.2 Procedure

Participants arrived at our lab and signed an informed consent form before testing *Active* and *Passive* exploration in a counterbalanced within-subjects design. Participants navigated or were navigated through 24 straight corridors of a virtual office building. The appearance of the corridors was similar to the environment shown in Figure 3.1. The distance to be covered through all corridors was 720m, but the lengths of the individual corridors varied. After each corridor, participants had to physically rotate by 90 degrees to face the next corridor, which ensured their attention during the experiment. After both conditions, participants were asked to fill in a Simulator Sickness Questionnaire (SSQ) [88], where 16 sickness symptoms are quantified on a 4-point Likert scale. Participants had a break of 5 minutes between the two conditions, and the whole procedure took approximately 30 minutes to complete. In accordance with previous findings in literature, we hypothesized that the *Passive* condition would lead to higher simulator sickness than the *Active* one.

3.5.3 Participants

20 participants (11 males, 9 females) aged between 22 and 46 ($M = 27.55$, $\sigma = 5.25$) with diverse backgrounds participated in this study. All participants received an expense allowance of 10 Euros for the successful completion of the experiment.

3.5.4 Results and Discussion

The total simulator sickness scores resulting from the SSQ were approximately normally distributed in both conditions. A paired-samples t-test did not show a significant difference between the means of the *Active* ($M = 23.0$, $\sigma = 20.02$) and the *Passive* ($M = 24.68$, $\sigma = 22.22$) conditions, $t(19) = 0.531$, $p = 0.602$, $r = 0.121$. Similar non-significant results were obtained for the subscales nausea (N), oculomotor disturbance (O), and disorientation (D). Figure 3.3 shows a per-participant scatterplot of the total SSQ scores in the *Active* and *Passive* conditions. We did not observe systematic order effects between both conditions. The mean value of all $Passive - Active$ differences was 1.68 ($\sigma = 14.18$) with a 95% confidence interval of $[-4.95; 8.32]$.

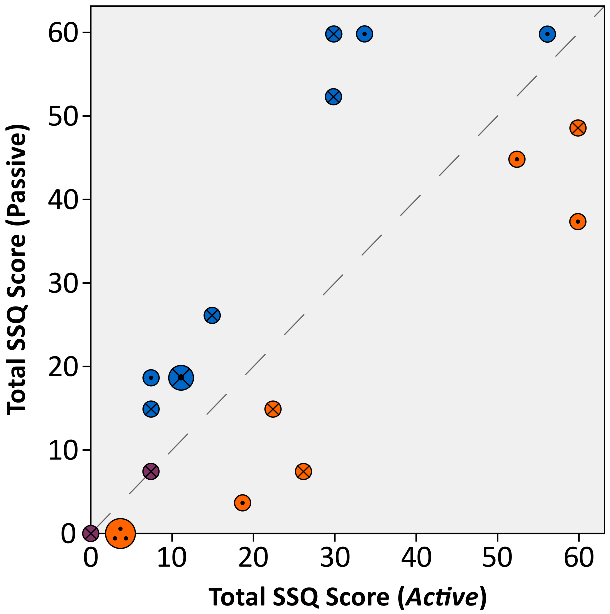


Figure 3.3: Per-participant scatterplot of the total SSQ scores after active and passive jumping. The dashed diagonal line represents no difference between both conditions. Circles in orange and blue mark participants with higher simulator sickness in the *Active* and *Passive* condition, respectively. A dot within a circle refers to the order *Active-Passive* while a cross represents the order *Passive-Active*. The larger circles subsume two and three identical cases.

Due to the scaling factor of the total SSQ score, an increase by one on any symptom results in an increase of the total score by at least 3.74. The four symptoms *General discomfort*, *Difficulty focusing*, *Difficulty concentrating*, and *Blurred vision* are taken into account twice, resulting in an increase of 7.48. As a consequence, even the upper bound of the confidence interval can already be achieved by a one-step increase on two of the 16 symptoms. Since the rating of symptoms is very subjective and also dependent on external factors, we therefore consider the differences represented by the confidence interval minimal. As a result, the data of this study provides an indication that the amount of simulator sickness perceived during *Multi-Ray Jumping* in the passenger role is close to the one during active single-user jumping. A significant negative effect of passive navigation, as in related work on steering, could not be observed.

3.6 Study 2: Advantages of Multi-Ray Jumping

We argued that the comprehensibility of group jumping techniques largely depends on clear previews of target locations for all involved participants. This additional pre-travel information facilitates the navigator's task of planning jumps and a passenger's anticipation of the next location in the scene. We believe that *Multi-Ray Jumping* offers significant benefits in that regard over a naïve implementation of *Coupled* jumping for two participants. In order to quantify these benefits, we conducted a second formal user study in which participants first experienced the passenger role (passenger task) before operating the techniques as the navigator (navigator task). To increase the reproducibility of our study, user activities in the corresponding other role were pre-defined. This means that the passenger was static in the navigator task while the navigator was animated with previously captured motion recordings in the passenger task.

3.6.1 Experimental Setup

The VR setup consisted of one HTC Vive Pro head-mounted display offering both positional and orientation tracking. Input was obtained using a Vive handheld controller. The tracking space was approximately 3m x 1.5m in size, and the virtual environment was rendered with a resolution of 1440x1600 pixels per eye and an update rate of 90 Hz. We measured an end-to-end latency of 12.5ms.

3.6.2 Conditions

Participants tested two jumping variants in a within-subjects design. The *Single-Ray* condition served as a baseline and represented a straightforward extension of single-user jumping for two participants. It was mostly identical to the *Coupled* implementation of our pilot study with the addition of a see-through effect when the navigator's ray and target were occluded by scene geometry from the perspective of the passenger. In the *Multi-Ray* condition, participants tested the implementation of *Multi-Ray Jumping* described in Section 3.4, also with an instant transition and no post-travel feedback. The order of techniques was counterbalanced across participants. However, both techniques were first presented in the passenger and afterwards in the navigator role.

In order to ensure similar distances to the second (simulated) user, participants were asked to stay within a circular area of diameter 0.75m in both conditions (see white circles on the floor in Figure 3.1). When a participant left this area, the scene lights of the virtual environment turned red to request the user to return. A small sphere on the floor always showed the user's projected head position to simplify this process. The distance of both circle centers was 2.4m, which guaranteed that both users within the circles always kept a distance in social space [70].

3.6.3 Experimental Tasks

We implemented two parametrizable tasks to quantify the passenger's spatial awareness after the jump as well as the navigator's planning accuracy and efficiency. In both tasks, four distinct spatial configurations of the two avatars were tested. They were either standing side by side or behind each other. These configurations were chosen as they frequently occur when starting in a side-by-side configuration and performing turns of 90° in the virtual world, e.g. while traveling through rectangular grid structures that are typical of many cities and office buildings. Figure 3.4 illustrates these spatial configurations for the passenger task.

Passenger Task

In the passenger task, we were interested to see if participants can anticipate the resulting spatial configuration after a jump and how long they need in order to reorient themselves. In a similar study on spatial awareness after passive navigation, Bowman et al. suggested measuring the time after travel to find a previously seen object in the scene and answering a simple two-option question on it [19]. We followed this approach but replaced the question on visible information with a rapid aimed movement towards a static object in the scene. At the beginning of each trial, the participant was placed 5m in front of a clearly visible pillar with a sphere as the target object on top. The navigator's avatar stood either to the left, to the right, in front of, or behind the participant (Figure 3.4). Participants had to press a button on the controller to request a recorded jump from the navigator, which moved them to one of five target positions around the pillar with a distance of 0.75m. After this jump, the task of the participant was to touch the sphere on the pillar with the controller as fast as possible. The dependent variable, hence, was the time between the jump and touching the sphere. We deliberately excluded target positions in front of the pillar as we intended to test spatial understanding rather than pure reaction to a visible target location. The pre-recorded actions of the navigator followed a strict procedure for each jump. First, the target specification ray was activated for two seconds while pointing downwards. Next, the parabola was moved towards the target position over a duration of

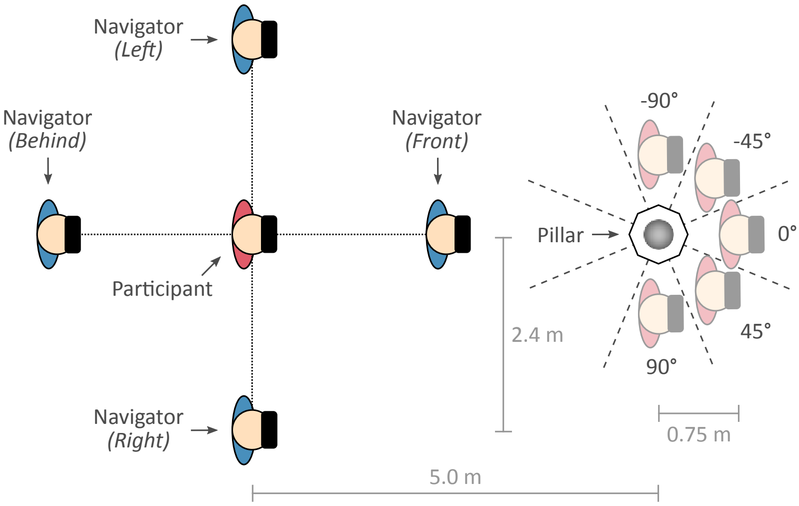


Figure 3.4: Participants in the passenger role were jumped by a pre-recorded navigator standing in one of four positions. The resulting passenger location after the jump was one of the five indicated positions around a pillar. We captured the reaction time to touch a sphere on top of this pillar as a measure of spatial awareness. The dashed lines emerging from the pillar illustrate the invisible sector borders that were used for our post-hoc task analysis in Section 3.6.7.

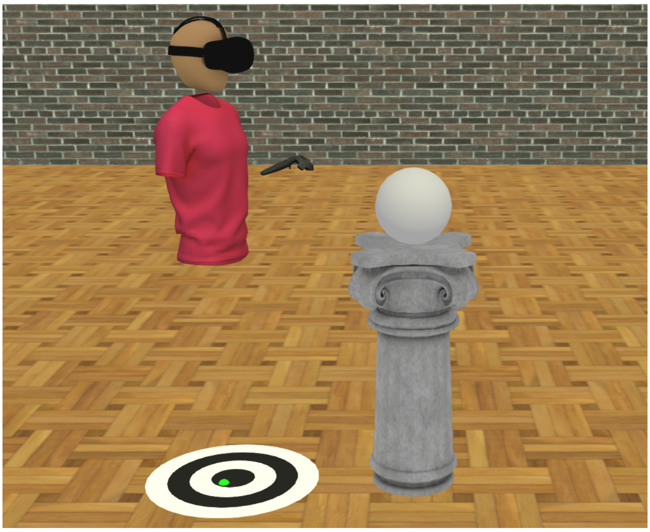


Figure 3.5: In the navigator task, the participant's task was to place the static passenger as close to a target's center as possible using only a single jump. Afterwards, a green sphere on the floor showed the passenger's projected head position and was used to compute the placement accuracy.

two seconds before initiating the jump. The placement deviation from the target location was lower than 0.05m in all recordings.

Navigator Task

The navigator task was motivated by guiding a museum tour in which the participant should move a passenger to specific locations relative to the exhibits. To remain consistent with the passenger task, we used a similar environment and spatial setup. In a trial of the navigator task, the simulated user was placed 5m in front of a pillar, and the participant in the role of the navigator appeared to the left, to the right, in front of, or behind them. One of five positions around the pillar was highlighted using a circular target. The task of the participant was to place the simulated user as close to the target's center as possible using a single jump (see Figure 3.5). The two dependent variables were the distance from the target's center (placement error) and the activation time of the target specification ray. In this part of the experiment, the simulated user was static.

3.6.4 Procedure

Participants arrived at our lab and signed an informed consent form. In the first part of the experiment, participants took the passenger role. They received an introduction sheet explaining the pre-recorded second user and the first jumping technique this navigator will use to move both users around. After putting on the head-mounted display, three jumps could be experienced without any specific task followed by seven training trials of the passenger task. During this phase, the experimenter was allowed to answer questions. Afterwards, participants completed 40 recorded trials in randomized order resulting from two repetitions of each combination of the four navigator positions (left, right, front, behind) and five target positions (−90°, −45°, 0°, 45°, 90°) illustrated in Figure 3.4. Lastly, we measured cognitive load using the Raw Task Load Index (RTLX), a simplified version of the NASA Task Load Index without subscale weighting [72, 73]. The procedure was repeated for the second jumping technique before the passenger part concluded with a break of 5 minutes. In the second part of the experiment, participants switched to the navigator role. For each jumping technique, they could first complete three free jumps and seven training trials of the navigator task. Afterwards, they completed the same 40 trial configurations as in the passenger task in a new randomized order. Again, navigating with each jumping technique was followed by the RTLX questionnaire. The study ended with a concluding questionnaire on overall technique preferences and demographics. The whole procedure took approximately 60 minutes to complete.

3.6.5 Hypotheses

In comparison to the *Single-Ray* implementation, we expected the *Multi-Ray* condition to improve the predictability of target locations for the passenger as well as the planning accuracy and rapidity for the navigator. In the passenger task, we hypothesized faster reaction times and lower cognitive load for the *Multi-Ray* condition:

H_1 The average reaction times in the *Multi-Ray* condition will be shorter than in the *Single-Ray* condition.

H_2 The cognitive load scores in the *Multi-Ray* condition will be lower than in the *Single-Ray* condition for the passenger task.

For the navigator task, we hypothesized smaller placement errors, faster target specification times, and lower cognitive load for the *Multi-Ray* condition:

H_3 The average placement errors in the *Multi-Ray* condition will be lower than in the *Single-Ray* condition.

H_4 The average target specification times in the *Multi-Ray* condition will be lower than in the *Single-Ray* condition.

H_5 The cognitive load scores in the *Multi-Ray* condition will be lower than in the *Single-Ray* condition for the navigator task.

3.6.6 Participants

22 participants (11 males, 11 females) aged between 21 and 30 years ($M = 25.95$, $\sigma = 2.69$) participated in the user study. All of them were either students or employees of our university. On a Likert scale from 1 (rarely) to 7 (often), participants rated their everyday usage of head-mounted displays very low ($Mode = 1$, $Mdn = 1$). All participants received an expense allowance of 10 Euros. To further increase motivation, the user with the best performance won a gift voucher worth 30 Euros.

3.6.7 Statistical Results

For presenting the results of our user study, we abbreviate the means, medians, and standard deviations by M, Mdn and σ, respectively. When analyzing data for normality, visual inspections of the normal QQ-plots were used in combination with Shapiro-Wilk Tests [154]. When data was non-normally distributed, we tried to apply a log_{10}-transformation to satisfy the assumptions of parametric tests. If this did not succeed, we used a non-parametric equivalent. 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 [38].

Passenger Task

The reaction times of all 40 recorded trials were averaged to a single time per participant and condition. The average time was $M_M = 0.90s$ ($\sigma_M = 0.42s$) in the *Multi-Ray* condition and $M_S = 1.44s$ ($\sigma_S = 0.48s$) in the *Single-Ray* condition. Using a paired-samples t-test, the log_{10}-transformed reaction times in the *Multi-Ray* condition were significantly lower than the ones in the *Single-Ray* condition, $t(21) = 8.08, p < 0.001, r = 0.757$ (large effect), which supports H_1. The RTLX questionnaire outputs an overall cognitive load score ranging between 0 and 100. A paired-samples t-test revealed that the cognitive load in the *Multi-Ray* condition ($M_M = 28.11$, $\sigma_M = 12.89$) was significantly smaller than in the *Single-Ray* condition ($M_S = 43.26$, $\sigma_S = 14.34$), $t(21) = 6.344, p < 0.001, r = 0.811$ (large effect), which supports H_2. *Multi-Ray* was preferred by 18 participants (≙ 81.8%) over *Single-Ray* for the passenger task.

In a post-hoc analysis, we investigated which task configurations in our study were particularly difficult to solve in the *Single-Ray* condition. For this purpose, we expected incongruent tasks like *[left, 90]*, where the navigator ray points to the left of the pillar but the participant lands right of it, to be more challenging than tasks without mismatches (e.g. *[left, -90]*). To formalize these task difficulties, we considered eight sectors around the pillar (illustrated as dashed lines in Figure 3.4) to define task difficulty by the sector distance between expected pillar direction when interpreting the navigator's ray and actual pillar direction after the jump. This resulted in a difficulty score between 0 (no mismatch) and 4 (maximum mismatch) for each task. Figure 3.6 shows the mean reaction times separated by task difficulty for both conditions. An overall Kruskal-Wallis test on the data showed significant differences in the reaction time distributions of the *Single-Ray* condition, $H(4) = 21.51$, $p < 0.001$. Post-hoc stepwise step-down analyses identified the two homogeneous subsets $[0,1,4]$ and $[4,2,3]$. For the *Multi-Ray* condition, no significant differences in distributions were observed, $H(4) = 2.664, p = 0.615$.

Navigator Task

In the navigator task, the placement errors and target specification times of all 40 recorded trials were averaged to single scores per participant and condition. A Wilcoxon signed-rank test showed that the median of placement errors in the *Multi-Ray* condition ($Mdn_M = 0.08m$, $\sigma_M = 0.03m$) was significantly lower than in the *Single-Ray* condition ($Mdn_S = 0.42m$, $\sigma_S = 0.42m$), $W = 0$, $z = -4.107$, $p < 0.001$, $r = 0.876$ (large effect), which backs H_3. However, the medians of the target specification times in the *Multi-Ray* ($Mdn_M = 2.97s$, $\sigma = 1.20s$) and *Single-Ray* condition ($Mdn_S = 3.29s$, $\sigma = 4.26s$) were not significantly different, $W = 80$, $z = -1.51$, $p = 0.131$. This contradicts H_4 although a medium effect size is visible ($r = 0.322$). Figure 3.7 shows a scatterplot of target specification time and placement error supplemented by boxplots for the individual variables (outliers excluded). Regarding cognitive load, a paired-samples t-test showed a significantly lower mean in the *Multi-Ray* condition ($M_M = 24.47$, $\sigma_M = 15.55$) compared to the *Single-Ray* condition ($M_S = 53.07$, $\sigma_S = 13.29$), $t(21) = 9.668$, $p < 0.001, r = 0.904$ (large ef-

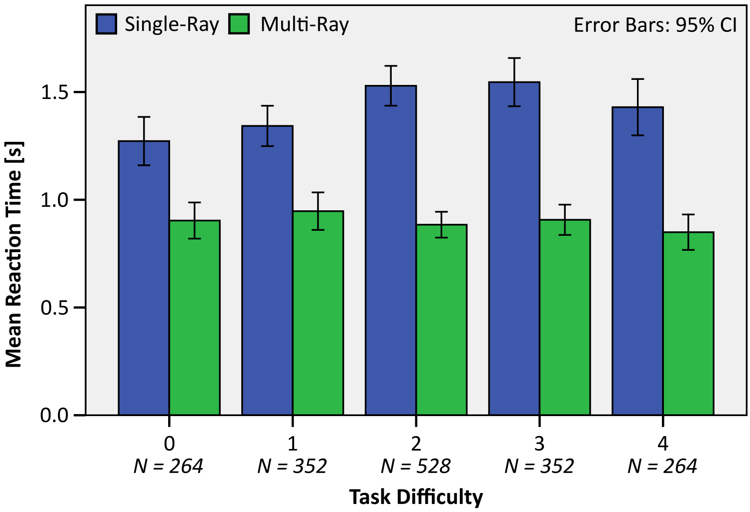


Figure 3.6: Mean reaction times with 95% confidence intervals over $N = 22 \cdot 40 \cdot 2 = 1760$ trials in the *Single-Ray* (blue) and *Multi-Ray* conditions (green) separated by expected task difficulty.

fect), thereby supporting H_5. *Multi-Ray* was preferred by 21 participants ($\triangleq$ 95.5%) over *Single-Ray* for the navigator task.

3.6.8 Discussion

In the passenger task, *Multi-Ray* clearly outperformed *Single-Ray* in terms of significantly shorter reaction times and lower cognitive load with large effect sizes, which confirmed H_1 and H_2. This implies that the additional pre-travel information given by the secondary parabola could be properly interpreted and beneficially used to spatially comprehend upcoming jumps, thereby also reducing cognitive load. Our post-hoc task analysis revealed that there are indeed task difficulty differences when using the *Single-Ray* technique. However, trials with the largest mismatches were not as difficult as expected. It seems that the plain 180°-mismatches in category 4 (*[left, 90]*, *[right, -90]*, and *[behind, 0]*) were more obvious to recognize and hence easier to integrate than expected. Using the *Multi-Ray* technique made the significant differences in task difficulty vanish, which indicates helpful mediations in both simple and more complex task configurations. In the navigator task, participants showed significantly lower placement errors and cognitive load in the *Multi-Ray* condition with large effect sizes, thereby confirming H_3 and H_5. Contrary to our expectations, however, the time spent for target specification was not significantly different in both conditions, which led to rejecting H_4. Nevertheless, Figure 3.7 shows that the data range in the *Single-Ray* condition is more than 2 seconds greater than in the *Multi-Ray* condition, which could be an explanation for the observed medium effect size. Hence, it seems that only a subset of participants spent more time for planning jumps in

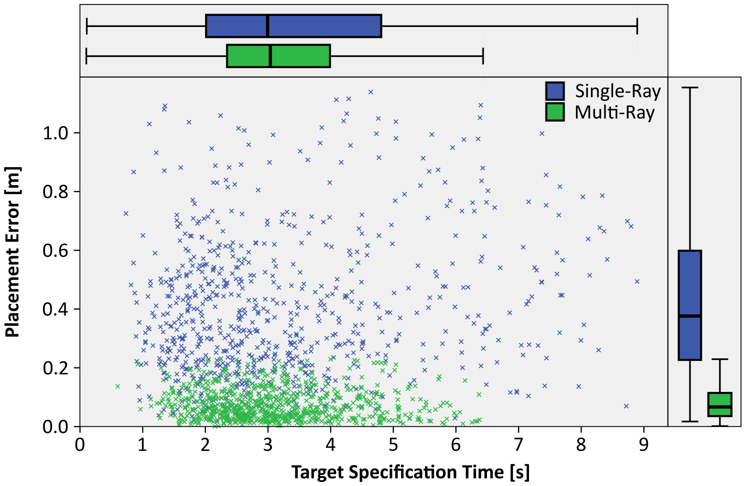


Figure 3.7: Time-Accuracy scatterplot of all trials of the navigator task without outliers and extreme values ($N = 1760 - 221 = 1539$). Additional boxplots show the distributions of values in the *Single-Ray* (blue) and *Multi-Ray* (green) conditions for both variables.

the *Single-Ray* condition, but this did not lead to an overall significant difference between the two techniques. In both cases, the correlation coefficients of target specification time and placement errors were small ($r = 0.178$ for *Single-Ray* and $r = -0.061$ for *Multi-Ray*), indicating that spending more time during target specification did not systematically help to improve placement accuracy.

3.7 Conclusion and Future Work

Collaborative virtual environments require comprehensible navigation techniques for both collocated and remote user groups. In this paper, we derived the requirements for comprehensible group jumping for collocated users wearing head-mounted displays. Comprehensible techniques need to foster awareness of ongoing navigation actions and make their consequences predictable for the navigator and passengers of a group. Our *Multi-Ray Jumping* technique implements these requirements using additional pre-travel information and consequently showed significant advantages over a straightforward extension of single-user jumping for two users. We therefore conclude that *Multi-Ray Jumping* is more comprehensible as it decreases spatial confusion for the passenger while increasing passenger awareness and thus planning accuracies for the navigator. In addition, *Multi-Ray Jumping* reduces cognitive load in both user roles, which makes it highly beneficial for the joint exploration of virtual environments. For the passengers, future work should investigate the effects of using *Multi-Ray Jumping* in more complex environments on higher levels of spatial awareness like landmark, route and survey knowledge [157].

Our research was primarily motivated by guided tours in virtual reality, where the role distribution of guide (navigator) and attendees (passengers) is inherent and does not change throughout the experience. In other scenarios, dynamic role assignments and cooperative planning can be more relevant. If voice communication enables negotiation, passengers can simply ask the navigator to choose a different navigation target or to stop executing a jump. We also discussed how *Multi-Ray Jumping* affords the fluent negotiation of control, making it well suited for scenarios with more balanced user contributions. A formal evaluation of interaction techniques for collaborative jump planning and dynamic exchange of roles is subject to future work.

Future work also includes extending *Multi-Ray Jumping* to more than two users and investigating its applicability to distributed scenarios. Regarding the former, adding an individual parabola for multiple passengers can easily lead to visual clutter. A solution for the passengers could be to hide the parabolas of the other passengers, which reduces the amount of curves to two as in our presented study. The navigator, however, should see at least the target positions of all involved passengers in order to plan meaningful jumps for the whole group, for example, by ghost avatars. In distributed scenarios, *Multi-Ray Jumping* needs to be complemented by effective coupling and decoupling mechanisms for enabling dynamic changes between phases of individual and group navigation.

4

Getting There Together: Group Navigation in Distributed Virtual Environments

This chapter reports on joint work with Pauline Bimberg and Bernd Froehlich at Bauhaus-Universität Weimar. It was published in IEEE Transactions on Visualization and Computer Graphics and presented at the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), where its online presentation in a distributed virtual reality system received the Best VR-in-VR Presentation Award.

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Figure 4.1: 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.

4.1 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 [166, 167], 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* [178], 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 leads 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,
- 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.

4.2 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 [7, 23, 125, 126]. Symmetric setups, on the other hand, provide immersive display hardware for all involved users, allowing collocated (e.g [1, 99, 144, 152]) and distributed users (e.g. [8, 26, 106]) 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" [35]. 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* [128], 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

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[1] `https://steamcommunity.com/steamvr`

[2] `https://www.vrchat.net/`

[3] `https://www.againstgrav.com/rec-room`

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 [20] and inevitable to apprehend spaces of environmental and geographical scale [121]. It is subdivided into the motor component *travel* and the cognitive component *wayfinding* [20]. 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 [44]. 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 [58, 140]. 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 [100]. This effect is especially critical in head-mounted displays (HMDs) as opposed to other display media [156], but it can be mitigated by dynamic field-of-view modifications during travel [57]. Travel by teleportation, on the other hand, reduces sensory mismatches and was shown to result in lower simulator sickness than basic steering techniques [34, 132, 179]. In particular, short-range teleportation with egocentric target specification (jumping) has become a popular technique for single-user travel in HMD environments [179], and several implementation variants of jumping showed promising results regarding spatial awareness, presence, and user experience [17, 21, 79, 132, 179]. Generally, jumping techniques consist of a method for *target specification*, the display of *pre-travel information*, a *transition* mode, and optional *post-travel feedback* [179]. 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 [178]. 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 [35]. 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 [178], 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) [166, 167]. 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 [47, 48].

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 [10]. 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 [8]. 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.

4.3 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 [18]. 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 4.2). We suggest that CVEs implementing joint navigation need to specify rules and mechanisms for all four phases, which will be detailed in the following.

4.3.1 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 [166]. 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 [47]. We generalize this idea and suggest that group forming implementations can vary between several degrees of explicitness and user involvement. Without any claim to

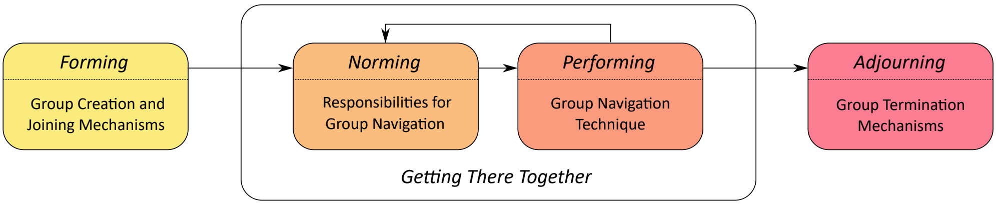

Figure 4.2: The realization of joint navigation in collaborative virtual environments requires support for four different stages of group work following Tuckman's model of small-group development [166, 167]. In our framework, we suggest that users need to organize themselves in navigational groups (*Forming*), 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 [47] or spatial user arrangements like F-formations [41, 115], 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 [10].

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 [47].

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. [8]) participating in remote collaboration may require a fully static navigational group assignment for the whole duration of participation [178]. 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 4.5).

4.3.2 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. [103, 107, 108, 113]), 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 [103, 107]).

Weighting All users of a group can provide travel inputs simultaneously, but the inputs of different users have different influences on the overall result [103, 108]. 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* [178]. While this control scheme can be realized by the physical access to a shared input device in collocated setups [8, 96], 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 [113] 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 predefined or automatically generated paths similar to system-guided travel for single users [64]. 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.

4.3.3 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 [44], 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 [10, 65], attenuation [47, 48], or cancellation [65] 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 [47, 48] or to understand each other's technical limitations like tracking boundaries, fields of view, or network latencies [60].

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 [96] and different conceptual approaches to two-user jumping [178]. 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 [178]. Examples for distributed users traveling together include the two-group steering technique by Beck et al. [8] and the concept of mobile crowds presented by Benford et al. [10]. 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.

4.3.4 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.

4.3.5 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 [47, 48], 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.

4.4 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 [87]. 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 [178]. 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 the 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 [8, 96, 178]. 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 [178]. Since research on single-user jumping in virtual environments indicated negative effects of combined translational and rotational jumps on spatial awareness and user experience [21, 132], we decided to focus our research on the adjustment of translational offsets while keeping the users' viewing directions unchanged during the jump.

4.4.1 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.

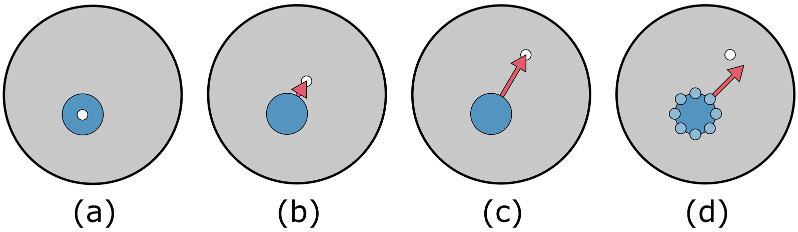

Figure 4.3: Exemplary specification of a relative passenger placement vector on the round touchpad of the navigator. In each illustration, the white circle represents the current touch coordinates of the navigator. See Section 4.4.1 for additional explanations.

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 4.3a). 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 4.3b and 4.3c). 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 4.3d). Additional visualizations of these axes around the currently specified target point can mediate the available options for passenger placement, which is illustrated in Figure 4.1 (left) for the inputs shown in Figure 4.3d. 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).

4.4.2 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.

4.5 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.

4.5.1 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.

4.5.2 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 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 4.4.1. 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 [71]. 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.

4.5.3 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 [87] or the joint navigation through narrow pathways [96], 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 4.4, 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 between 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 4.1. 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

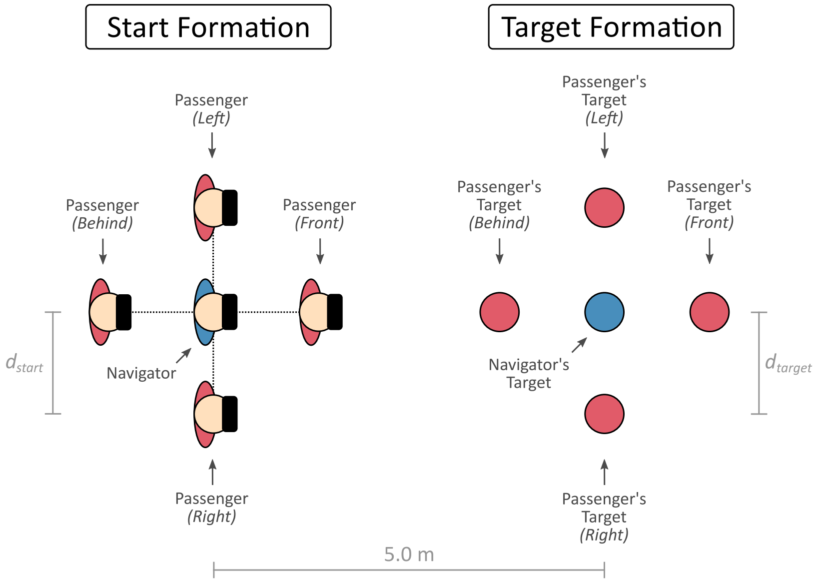

Figure 4.4: For a task item, navigator and passenger started in one of four configurations with varying interpersonal distances. The task involved to jump and potentially adjust the group's formation at the target, either by physical walking (Baseline condition) or by specifying virtual formation adjustments during the jumping process (Adjust condition).

$right$	→	$right$
$left$	→	$right$
$right$	→	$front$
$right$	→	$behind$
$behind$	→	$right$
$front$	→	$right$
$behind$	→	$front$
$front$	→	$behind$

×

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

Table 4.1: 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.

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 4.5.

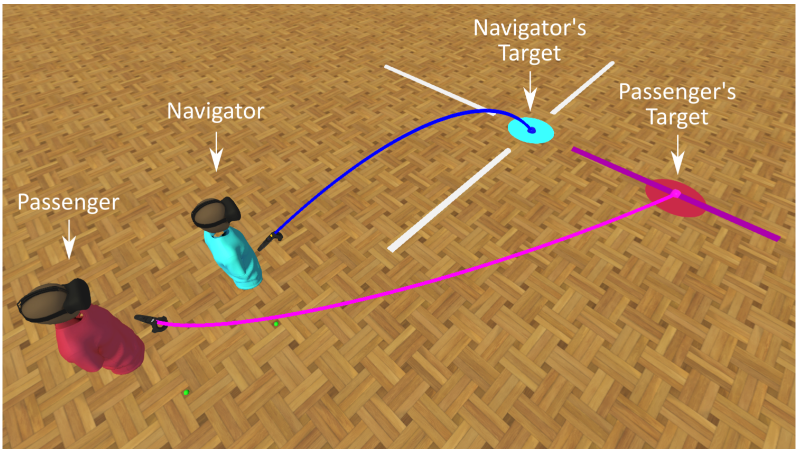

Figure 4.5: Screenshot of two users completing the task item $[behind, 1m] \rightarrow [right, 2m]$ in the *Adjust* condition of our user study. The specification of virtual formation adjustments allows the navigator to directly place the passenger to the right of them during the jump.

4.5.4 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 [72, 73], 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.

4.5.5 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.

4.5.6 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 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), $Mdn = 5$, $\sigma = 1.55$.

4.5.7 Statistical Results

When analyzing data for normality, visual inspections of the normal QQ-plots were used in combination with Shapiro-Wilk Tests [154]. 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 [38].

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 4.6.

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

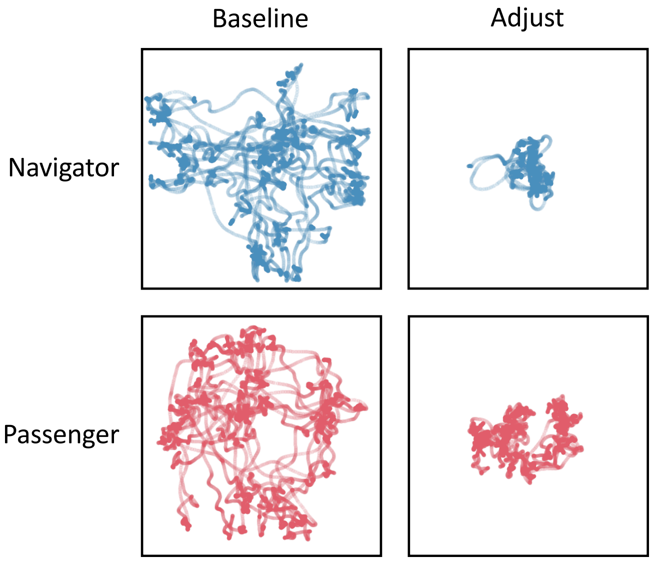

Figure 4.6: Motion maps of an exemplary participant team, which indicate the tracked physical walking patterns of navigator and passenger throughout all task items in both the *Baseline* and the *Adjust* condition.

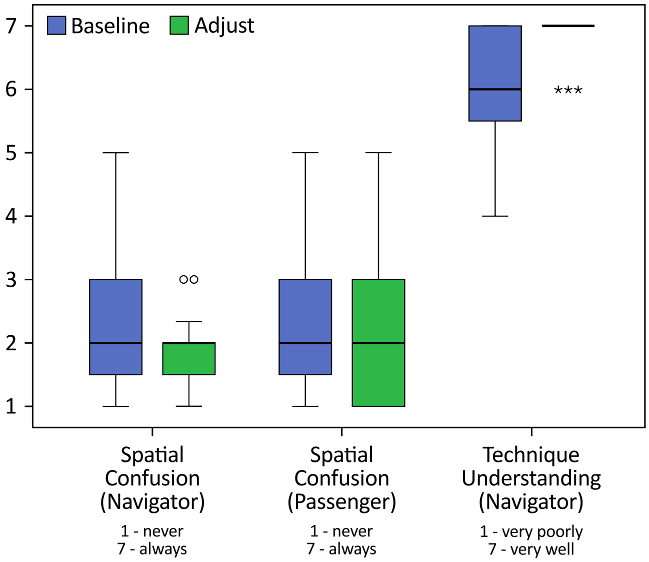

Figure 4.7: Distributions of user responses rating the amount of spatial confusions during jumping (both user roles) and the understanding of technique operation (navigator only) after each condition on a discrete ordinal scale from 1 to 7.

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 4.7 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.

4.5.8 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 4.7). 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.

4.6 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 4.5.1.

4.6.1 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.

4.6.2 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, 93, 131, 170]. 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 4.8). 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

Figure 4.8: 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.

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 4.1.

4.6.3 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.

4.6.4 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, how users distributed responsibilities for joint navigation, how our implementation of formation adjustments was used, and which domain-specific use cases for individual and joint navigation were discussed by our experts.

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.

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.

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 [21, 132]. 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.

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.

4.6.5 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.

4.7 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*.

5

Group Navigation for Guided Tours in Distributed Virtual Environments

This chapter reports on joint work with Bernd Froehlich at Bauhaus-Universität Weimar. It was published in IEEE Transactions on Visualization and Computer Graphics and presented at the 2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).

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Figure 5.1: Top: Five distributed users discuss with each other in a virtual museum. The group's spatial extent is visualized on the floor by the convex hull of the projected head positions. Bottom Left: The guide of the group plans a jump to another exhibit and rearranges the group to a circle formation for improved joint observation. Bottom Right: After the jump, the group ends up in the specified formation.

Abstract

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

5.1 Introduction

The ongoing global health crisis has moved most social gatherings to online spaces. While conventional conferencing tools provide a 2D video stream of each participant, social virtual reality systems enable users to meet and interact with each other in a 3D environment using head-mounted displays and controllers. However, navigation through these environments is usually performed on a per-user basis only [92, 119], which leads to additional coordination efforts when planning to get to a new destination together. This overhead is especially pronounced in guided tour scenarios, where there is often a strong asymmetric distribution of knowledge between the guide and the attendees [12]. As a result, individual navigation responsibilities might distract attendees from the actual content of the tour, and the overall pace of the tour is slowed down by the required coordination efforts.

To overcome these drawbacks, prior research motivated the use of group navigation techniques in distributed virtual environments [175]. However, it is a responsible task for a guide to take over the navigation for the whole group, which requires a high degree of awareness of the current and future configurations of the group to avoid inconvenient positions and collisions. Attendees, as well, must be able to understand and predict what will happen to them and the group as a whole. While previous work introduced predictable, easy to learn, and non-nauseating group navigation for distributed dyads [175], group sizes for guided tours are often larger and these quality factors more difficult to achieve.

Therefore, this paper addresses the central research question of how effective group navigation can be realized in larger distributed group settings. We started by consulting related literature on group navigation to derive requirements for performing guided group tours in distributed virtual environments. Based on the common travel metaphor of short-distance teleportation (jumping) in social VR systems [92, 179], we developed solutions for each of the formulated requirements to design the first group navigation technique for more than two distributed users. In an initial usability study, proficient users of virtual reality systems evaluated the conduction of and participation in guided group tours using a virtual indoor exhibition as the scenario. Our research led to the following contributions:

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

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

5.2 Related Work

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

5.2.1 Individual Navigation in Virtual Reality

Navigation through virtual environments requires cognitive *wayfinding* processes and a *travel* technique allowing the user to execute movements to a new location [20]. Physical walking within the available workspace is deemed the most natural form of travel that can lead to high amounts of presence [169]. For multiple users sharing the same workspace, strategies for collision-avoiding redirected walking were suggested [6, 49, 105]. Virtual travel techniques, on the other hand, usually require less space and are therefore often adopted for covering larger distances in the virtual environment. However, anecdotal evidence suggests that many users even prefer virtual travel for small viewpoint adjustments that could be easily covered by physical walking otherwise [94, 175]. Two common metaphors for virtual travel are steering- and target-based approaches. Steering requires the continuous specification of the desired direction and speed of motion similar to driving a vehicle in the real world. In virtual environments, however, the resulting conflict between the visual and vestibular systems is often deemed a plausible cause of simulator sickness [45, 100, 136]. The severity of sickness symptoms can be reduced by displaying rest frames [24] or by reducing the user's field-of-view during travel and hence minimizing the amount of visual flow in the periphery [57, 109]. Target-based approaches, on the other hand, often avoid visual flow completely by teleporting the user instantaneously to the specified target. In particular, short-distance teleportation in vista space (often referred to as *jumping*) has become a prominent travel metaphor in applications for head-mounted displays [92, 179], and several studies confirmed that jumping can significantly reduce simulator sickness compared to steering [34, 37, 55, 79, 132, 179]. For this paper, we therefore decided to focus our research on the virtual jumping metaphor for groups of multiple users. It is important to note, however, that some researchers also use the term *jumping* to denote physical upward movements of the user for locomotion [76, 165, 185], which is beyond the scope of this paper.

5.2.2 Group Navigation in Multi-User Virtual Reality

A group consists of two or more individuals who are linked by their membership in a way that the actions and thoughts of one member can influence the others [59, chpt. 1]. As a result, group sizes are diverse and can range from dyads working together over small groups exploring a museum to large crowds and audiences, where one member starting to clap or chant might motivate the others to join. Multi-user virtual reality systems can enable both physically collocated and spatially distributed users to meet and form groups with each other in a shared virtual environment. As a result, group interactions in VR can be classified by the number of involved distributed workspaces and the number of collocated users situated within each of these spaces (see Figure 5.2). Motivated by the current pandemic circumstances and the available commercial social VR platforms [119], we focused our research on systems that support one immersed individual per workspace and therefore fully rely on distributed rather than collocated collaboration.

Most of such systems provide independent virtual navigation on a per-user basis (see [4, 54, 67, 102, 153] for projection-based systems and [75, 104, 155, 159, 172] for head-mounted displays). While recent studies showed that individually navigating dyads could outperform individuals in the acquisition of survey knowledge [22], others lamented that individual navigation can lead to difficulties staying together, finding each other, or understanding spatial references [172, 175]. This strongly motivates the use of group navigation techniques for distributed setups, but the design, realization, and evaluation of such techniques has received only little attention in prior research. In a review of commercial social virtual reality applications, Kolesnichenko et al. reported about mechanisms that allowed users to form groups in order to switch between different virtual environments together [92]. For group navigation within the same virtual environment, Weissker et al. introduced a framework stating that group navigation techniques in distributed virtual reality should allow users to form navigational groups (*Forming*), distribute navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*) [175]. For the *Performing* phase, the authors suggested a two-user jumping technique, in which an operating navigator could take a nearby passenger along when executing a jump. For this purpose, when the navigator specified their target position

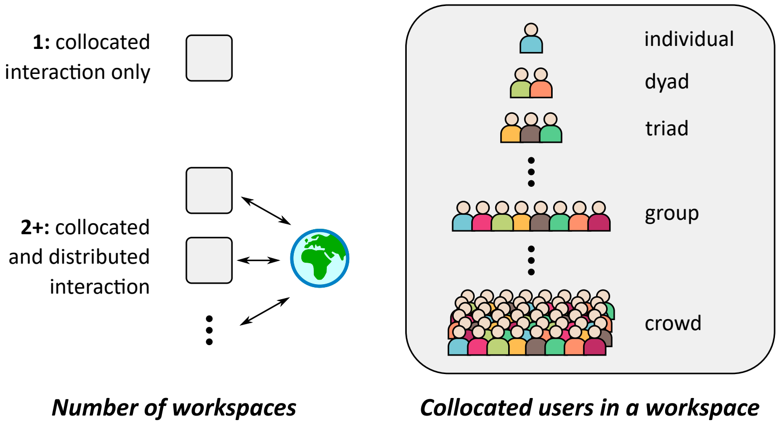

Figure 5.2: We classify group interactions in virtual reality by the number of involved distributed workspaces (left) and the number of collocated users within each of these spaces (right). This paper focuses on group navigation techniques for distributed groups with one person per workspace.

using the conventional parabolic pick ray, the offset target position of the accompanying passenger was previewed by an additional secondary target ray starting from the passenger's controller. The comprehensibility of this approach was already evaluated positively in previous work for two collocated users, but the spatial synchronization between user positions in the physical and virtual space (implemented for improving mutual awareness in collocated setups) required dyads to perform frequent walking to adjust their spatial formation in certain situations, e.g. after turning at corners, to fit through spatial constrictions, or to investigate objects from different perspectives [178]. As a result, the follow-up work for two distributed users additionally allowed the navigator to adjust the spatial formation of the dyad virtually, i.e. without requiring physical walking. In particular, when planning a jump, the navigator could specify the passenger's new target position relative to their own one using the touchpad of the controller. This enhancement enabled navigators to perform travel sequences more efficiently, and the accompanying two target rays were deemed a helpful visualization by both navigators and passengers [175].

Nevertheless, two central aspects of the proposed technique design limit its scalability to groups of more than two users. First, displaying an individual visual ray to communicate each participant's target position can easily seem chaotic and difficult to decode. As visualized in Figure 5.3, this is especially true when the spatial formation of the group is planned to change during the jump. Second, the specification of virtual formation adjustments using the approach from prior work becomes increasingly challenging with larger groups since the navigator would have to manually specify new target positions for each individual passenger when planning a jump. In this paper, we present the design, implementation, and evaluation of a distributed group navigation technique that addresses

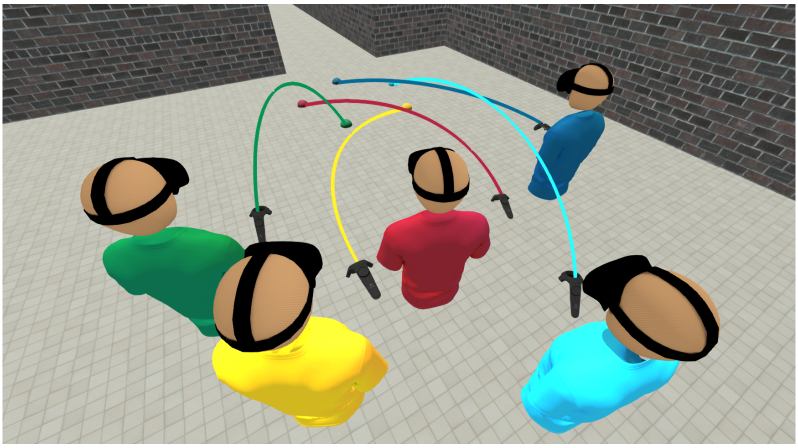

Figure 5.3: In prior work for dyads, displaying one target ray per user was deemed helpful and comprehensible for joint navigation [175, 178]. However, for larger groups, tracing one target ray per user can be confusing, especially if the formation of the group changes during the jump.

these limitations to make group travel feasible and understandable for group sizes beyond dyads.

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

Guided tours are shaped by interactive exchanges between the guide and the individual attendees rather than by pre-defined sequences of movements and explanations [12]. As a result, a central task of the guide is to engage with the attendees to adjust the pace and content with respect to their interests and capabilities. In current commercial social VR systems, the main forms of exchange include audio communication using built-in headsets in the head-mounted displays as well as a basic set of gestures and expressions that can be generated with a user's avatar [92, 119]. In this section, we investigate how group navigation techniques can and should build upon these means of communication to allow a guide to perform a tour effectively and efficiently while giving attendees enough freedom for individual engagement.

5.3.1 Advantages of Group over Individual Navigation

Prior work motivated that successful remote collaboration benefits from fluent transitions between individual and group navigation [175]. Similarly, a guided tour might consist of loose phases where attendees explore on their own and close phases where the attendees strictly follow the narrative of the guide. We believe that group navigation can be especially beneficial for the latter type and argue that *Forming* and *Adjourning* navigational groups should be lightweight to support easy transitions between the two types of phases. For the close phases, we identify two central advantages of group over individual navigation:

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

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

5.3.2 Requirements for Group Navigation Techniques

While the general quality factors for virtual travel like sickness-prevention, ease of learning, spatial awareness, and presence [19] also apply to group navigation, additional requirements specific to multi-user navigation can be derived based on prior work on collocated and distributed group work. Especially, the handling of the navigation controls for the whole group by the guide must be used responsibly. It is therefore a key requirement for the guide to conduct group navigation at an appropriate pace and to moderate the tour appropriately such that the group can understand what is happening and what to expect. To support this goal, the group navigation technique itself should provide *comprehensible* feedback mechanisms to improve mutual awareness and make the navigation process predictable:

Comprehensibility Performing techniques should "foster the awareness of ongoing navigation activities and facilitate the predictability of their consequences for the navigator [guide] and all passengers [attendees]" [178]. In particular, this means that each attendee should be able to understand and predict the navigational actions that the guide is applying to them and the group as a whole. The guide, on the other hand, should have an understanding of the future spatial formation of the group and how to predict and prevent undesired arrangements.

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

Obstacle Avoidance Performing techniques should provide mechanisms that assist with avoiding collisions with objects in the virtual environment during travel [96]. In particular, the group should be able to fit through narrow aisles and confined spaces without any user being navigated out of bounds.

View Optimization When arriving at a certain object or area of interest, Performing techniques should provide mechanisms that support placing the group in a meaningful spatial arrangement for the joint observation and discussion of the respective content [96, 150, 175].

While these adjustments could be realized by individual user movements every time they are required, it is usually more comfortable and efficient to adjust the group's spatial arrangement virtually [96, 175]. In collocated setups, these individual virtual viewpoint adjustments per user would lead to spatial desynchronization and therefore disrupt the joint perception of a spatially consistent workspace [28, 96, 101]. In the scenario of distributed users, on the other side, group formations in the virtual environment are not bound to a physical counterpart and can therefore be adjusted more easily to meet certain criteria. As a result, we propose the following approach to *Obstacle Avoidance* and *View Optimization* in distributed virtual environments:

Virtual Formation Adjustments Performing techniques should allow the system and/or the users to adjust a group's spatial arrangement without requiring individual movements in order to meet the requirements of *Obstacle Avoidance* and *View Optimization* (cf. [8, 175]).

While there might be a large variety of group formations that are beneficial for *Obstacle Avoidance* and *View Optimization* in a given situation, observations from the real world indicate that people tend to assume certain characteristic formations when walking, observing, and discussing together [40, 87]. In his seminal work on spacing and orientation in co-present interaction, social anthropologist Adam Kendon identified so called functional formations (*F-Formations*) that help members of a group to organize their interactions and attentive resources in a meaningful way [87]. *Circle* formations, for example, create a shared transactional space for the exchange about a common theme. Current VR systems for distributed users motivate the creation of these formations as conversational anchors by placing campfires or round tables with exhibits into the virtual environment [119]. Two people often tend to be *vis-à-vis* or *L-shaped* [87]. If members of a group would like to focus their attention more on watching something in the distance rather than mutual interactions, they establish a *side-by-side* formation. A *horseshoe* formation offers a good compromise between observing something in the distance and talking about it within the group. When implementing *Virtual Formation Adjustments* for group navigation, we believe that it is helpful to support the creation of these or related F-Formations to conform to the requirement of *View Optimization*.

On the other hand, there are several approaches to supporting the requirement of *Obstacle Avoidance* with *Virtual Formation Adjustments*. In a few cases, it might be sufficient to only rotate the group in its current formation to create a collision-free user placement in the virtual environment. Other situations, however, might require increasing or decreasing the group's spatial extent to distribute users around a larger object of interest or to fit through narrow passages. The most extreme reduction of a group's spatial extent is to virtually overlay the positions of all users during travel, which requires hiding the avatars of the other users and impairs mutual awareness and interactions [119, 178]. Thus, we argue that *Virtual Formation Adjustments* for group navigation should allow reducing the group's spatial extent while still ensuring that appropriate distances between all users are kept [71]. A tradeoff between these two conflicting goals could be achieved, for example, by rearranging users in a compact *grid* formation (similar to a bus in the real world) or even a *queue* formation for very narrow spaces. When increasing the group's spatial extent, on the other side, it should be assured that users do not lose track of the other group members and the guide as they get more dispersed across the environment. As a result, we argue that solutions to *Obstacle Avoidance* can come in many different forms, which require group navigation techniques to offer strategies for rotating, scaling, or completely rearranging the group.

5.4 A Group Jumping Technique for Guided Tours

The formulated requirements for realizing group navigation in the context of guided group tours can be implemented in various ways. In this section, we present and justify one way of addressing these requirements using jumping as the core travel metaphor. As a development platform, we used a proprietary virtual reality software system for rapid prototyping to create a shared networked virtual environment, which served as a basis for the developments presented in this paper. This system allowed distributed users to join with an *HTC Vive Pro* head-mounted display, to be represented as a basic avatar, and to communicate with other users using the built-in headsets of the display in a classic non-spatial audio channel. We identified this as a basic feature set that is supported by all commercial social VR systems reviewed in the surveys of [92, 119] and aimed at building our group jumping technique for guided tours on this common ground. This makes our technique independent from additional awareness mechanisms like spatial audio, animated high-fidelity avatars, and voice indicators that can be seen in some more advanced systems.

5.4.1 Group Representation

Avatars in our system consist of a virtual head with a head-mounted display, a shirt, and controller geometries (see Figures 5.1 and 5.5). We found this abstract representation suitable to support mutual awareness by providing more visual saliency than the representation of devices alone while not evoking uncanny feelings as known from imperfectly behaving avatars [151]. We suggest additional visualizations for the guide to improve recognizability, e.g. an icon on their shirt and/or crown above their head as illustrated in Figure 5.1. Since feet are usually not tracked in common head-mounted display setups, we project each user's head position onto the floor and display a sphere in the color of the user's shirt to improve depth perception. For members of a group, we also continuously display the convex hull of these points as an indication of the group's current spatial extent in the virtual space (similar to the concept of *group graphs* presented in related work [47, 48]), which can be used to judge the necessity of measures for *Obstacle Avoidance* and *View Optimization* during group travel.

5.4.2 Group Travel

Many commercial single-user applications for the *HTC Vive* family established the use of the controller's round touchpad button for jumping. It is customary to press and hold this button to activate target specification, select the target using a parabolic pick ray, and release the button for confirmation. We aimed at building upon this workflow to allow the guide to initiate, plan, and execute jumps for the whole group. An exemplary interaction sequence for executing a group jump is shown in Figure 5.5 and will be explained in the following.

Initiating Formation-Preserving and -Changing Jumps

Following our previous requirement analysis on group navigation, the guide may need to rotate the group, change its spatial extent, or rearrange participants completely to achieve *Obstacle Avoidance* and *View Optimization*. To address all of these possibilities, our technique distinguishes between the two modes of *formation-preserving* and *formation-changing* jumping, which have to be toggled before pressing the touchpad down for target specification. Formation-preserving jumping is the default and allows relocating the group in its current formation with potential adjustments only to its rotation and spatial extent. Formation-changing jumps, on the other hand, allow rearranging the group to a pre-defined formation and have to be toggled explicitly. To do so, the guide can open a radial menu around the touchpad by pressing the controller's menu button. The touchpad is then visually subdivided into four regions that correspond to different group formations when pressed down (see Figure 5.5a and 5.4). As group discussions are often focused on a particular object or region of interest, we decided to provide the *circle* and *horseshoe* formations for supporting joint observations. To achieve collision-free group placements when traversing narrow aisles, we offer *grid* and *queue* formations for space reduction.

Once the guide decided on a formation-preserving or a specific formation-changing jump, they start the target specification process by pressing the touchpad down. Afterwards, the mechanisms shown in the following sections are identical for both types of jumps.

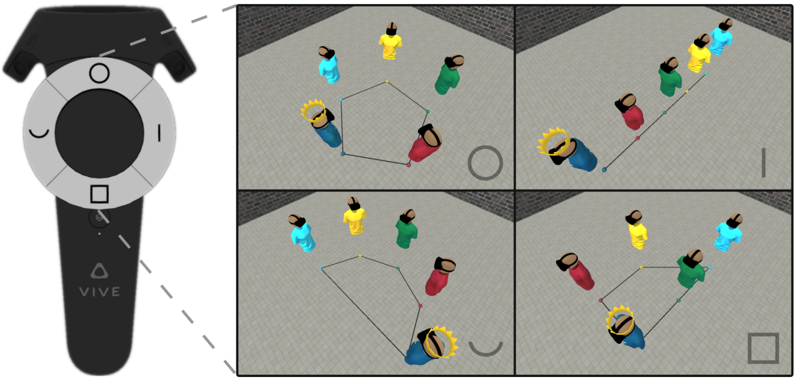

Figure 5.4: In our implementation, the guide can choose between four pre-defined group formations to initiate target specification for a formation-changing jump: circle, queue, horseshoe, and grid.

Target Specification and Comprehensibility Mechanisms

As explained in Section 5.2.2, the use of additional target rays to mediate user destinations seems to be restricted to dyads. For larger groups, we therefore decided to show secondary target rays only to their respective users and to mediate the group context by preview avatars (see also [52, 130, 189]) visible for all group members.

When the guide presses the touchpad down, the current avatars of the group become semi-transparent to avoid occlusions and to indicate their transitional state (see Figure 5.5b). The conventional parabolic pick ray starting from the guide's controller is used to determine an intersection point with the scene, but unlike in single-user jumping, we propose that this position is used as the new centroid of the group's convex hull instead of the guide's personal target position. The centroid is a more relevant point for the group as a whole and a more suitable anchor for rotations or changes in spatial extent. Preview avatars and a preview convex hull are then displayed around the specified centroid and allow to predict the group's spatial arrangement at the target as visualized in Figure 5.1 (bottom left). Nevertheless, we believe that a visual target ray from the guide's controller to the group's new centroid might be a conflicting cue to the guide's off-centroid preview avatar. As a result, we suggest hiding the parabolic pick ray in favor of a curved feedback ray going to the actual target position of the guide in the preview. In Figure 5.5b-d, the centroid of the group is located below the globe while the guide's visual ray always goes to their target position. As suggested in previous work on two-user jumping, attendees can see an additional curved ray from their controller to their personal target position [178].

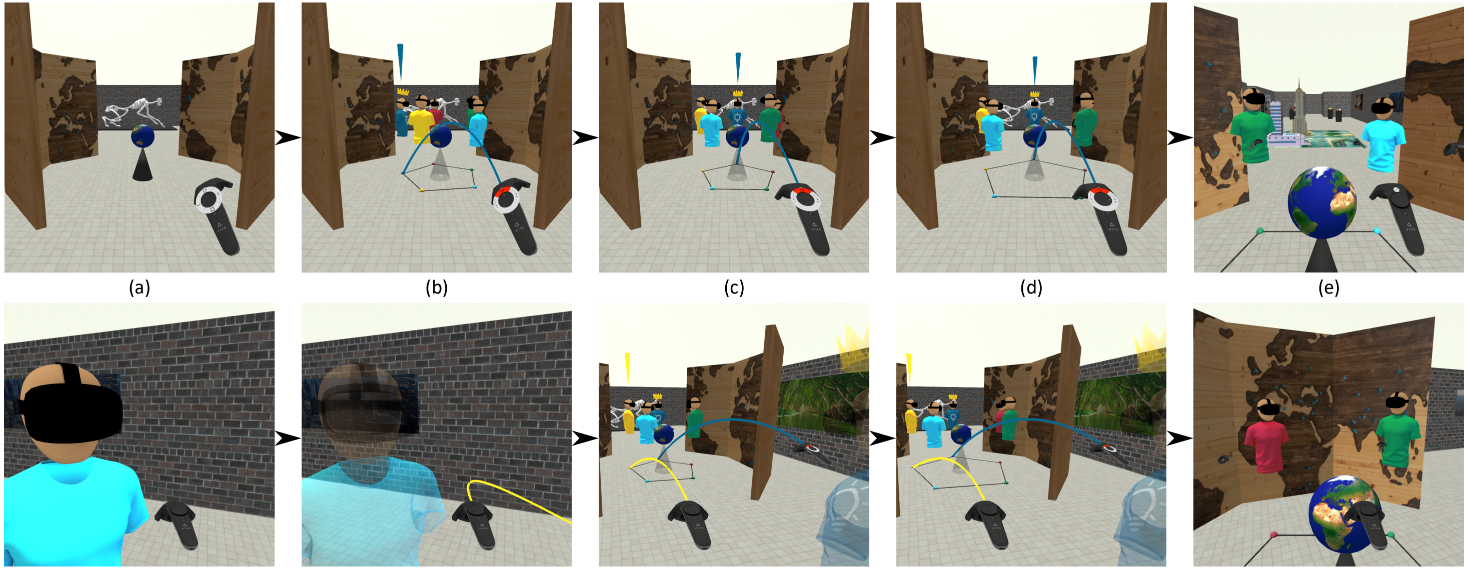

Figure 5.5: Interaction sequence for executing the *formation-changing* jump in Figure 5.1 from the guide's (top row) and the yellow attendee's (bottom row) point of view. (a) The guide opens the radial menu around the controller's touchpad to select a formation. The attendee may be interacting with another group member and therefore not looking in the same direction as the guide. (b) The guide selects a circle formation by pressing and holding the touchpad button in the respective segment. Preview avatars allow the guide to predict how the group will be arranged after the jump. A secondary target ray only visible to attendees as well as the faded main avatars direct attendees' focus of attention towards the preview avatars. (c) The roll angle of the guide's controller allows rotation of the previewed group formation around its centroid. Attendees will always know where they will jump to when tracing their personal target ray. (d) Radial swipes on the touchpad of the guide's controller specify the spatial extent of the group. (e) When the guide has ensured that everyone is ready and releases the touchpad button, the group will be teleported as indicated by the preview avatars.

As these rays always emanate in the direction given by the respective controllers, attendee awareness is also raised if a jump is planned outside their field of view (see Figure 5.5b).

For rotating the group around its centroid, the guide can use the otherwise unemployed roll angle of their controller, which is amplified such that all potential rotations of the group can be achieved by comfortable wrist rotations (see transition from Figure 5.5b to c). Furthermore, the guide can perform radial swipes on the touchpad (similar to the Pie Slider technique [97]) to scale the previewed group formation around its centroid (see transition from Figure 5.5c to d). The minimum selectable size of the group in this process is computed ensuring that no user pair will ever jump into each other's intimate space, which is usually defined by an interpersonal distance of 0.45m [69, 71]. Scalings that violate this constraint are clamped and previewed at the smallest possible group size. If the guide is unsatisfied, target specification can be aborted without jump execution by pressing one of the grip buttons on the controller. These buttons require slightly more effort to reach and are therefore good candidates for destructive actions that should not be triggered by accident. If the guide, however, is satisfied with the shown preview, they can release the touchpad to execute the jump (see Figure 5.5e).

Interaction of Preview Avatars and the Environment

To achieve the requirement of *Comprehensibility* for all involved users during target specification, it is vital that everybody is able to see the provided preview avatars and rays to understand what will happen next. While we already discussed the semi-transparency of the current avatars in that regard, certain parts of the group preview at the new target might still be occluded by objects in the environment. Figure 5.6 shows an example of such a situation, where the preview avatars would be occluded by walls for the leftmost users if no countermeasures were taken. We therefore suggest making occluding scene objects translucent such that an obstruction-free view can be ensured for all participants.

With the requirement of *Obstacle Avoidance* in mind, we implemented a simple heuristic that constantly checks for collisions of the previewed convex hull with the scene's geometries. Colliding edges are highlighted in red and signal to the guide that improvements might be required. This computationally inexpensive approach allows the guide to already detect many cases in which users might be moved out of bounds, placed inside of obstacles, or separated from each other. In the situation of Figure 5.6, one user would be separated from the rest of the group by a wall if the jump is executed, which can be disturbing. More sophisticated obstacle avoidance techniques could consider, for example, users inside the convex hull, arbitrary floor geometries as well as lines of sight between users and objects of interest.

5.4.3 Discussion of Interaction Design

As guided tours usually are highly dynamic and dependent on the individual attendees, our described group navigation technique allows the specification of versatile group transitions

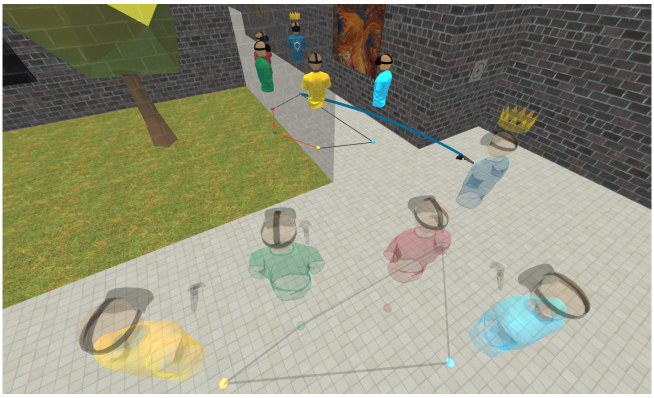

Figure 5.6: If the preview avatars are occluded for participants, we suggest fading the corresponding scene geometries. If the previewed convex hull intersects with obstacles, the respective edges are colored in red.

for different situations. While our proposed solution is only one of many options on how the formulated requirements can be fulfilled by a group navigation technique, it builds upon prior research on two-user jumping and requires only one controller per user to operate. As a result, a potential second controller could be fully employed for more use-case specific features and interactions. Our formations for formation-changing jumps were chosen to match the characteristics of museum-type indoor environments and can be easily replaced or extended by other application- or environment-specific formations if required. All in all, the large navigational freedom of our technique might also make it more complex to learn and operate, which was an important subject of investigation in our initial usability study described in the next section.

Two aspects of our proposed technique give particular rise to debate. First, when performing a formation-changing jump, there is a multitude of ways to arrange users within the desired target formation. While our current solution always places users in a fixed order with the same interpersonal distance for neighbors, more sophisticated approaches could consider social ties and relationships between users, the surrounding objects, or information from the formation before the jump to derive more advanced placement suggestions. As we acknowledge that this might be a parameter to fine-tune for a specific composition of group members and virtual environment, we focused our initial usability study on a more general evaluation of our technique, in which one of our research questions (RQ_2) asked if the provided preview avatars and target rays were sufficient for achieving *Comprehensibility* independent of particular placement heuristics for formation-changing jumps.

Second, jumping implementations in virtual reality can theoretically introduce changes to the users' positions and viewing directions. The most common variant, sometimes referred to as *partially concordant* jumping [29, 86], only shifts each user's viewpoint while keeping their global viewing directions unchanged. As a result, all changes in viewing direction must be generated by physical rotations. *Discordant* jumping, on the other hand, uses auxiliary mechanisms to specify a new viewing direction to be set in addition to the change in position. In our technique, the motivated formations for formation-changing jumps all come with an inherent idea of viewing directions for each individual user that seem to be suitable candidates for automatic view direction adjustments during jumping. *Circle* and *horseshoe* formations, for example, build on the importance of shared eyelines for conversations [87, 119] while users in the space-compressing *grid* and *queue* formations might benefit from looking into the same direction for traversing the scene (similar to a vehicle in the real world). When rotating the group in a formation-preserving jump, on the other hand, adjusting each user's viewing direction accordingly can improve visual consistency of the other users' avatars before and after the jump. As a result, automatic view direction adjustments seem to be advantageous for reducing the number of physical rotations required. However, related work on discordant jumping usually reports on negative effects regarding spatial orientation and user comfort [21, 29, 86, 132]. To improve our understanding of the advantages and disadvantages of automatic view direction adjustments using our technique, we decided to gather more user feedback on this subject in our initial usability study by formulating and evaluating a corresponding research question (RQ_3).

5.5 Initial Usability Study on Guided Group Jumping

Since the ongoing global pandemic circumstances and the related safety measures of our university prevented us from carrying out a user study with a large participant sample, we decided on an initial usability study, more particularly a single-condition assessment test [146], of our technique with an emphasis on qualitative measures. This procedure allowed us to explore how well users can learn to perform realistic tasks with our technique and identify potential usability deficiencies. Based on the general workflow of usability testing, we started by formulating the following research questions:

RQ_1 Is the operation of our group navigation technique learnable and suitable for moderating guided tours?

RQ_2 Are the preview avatars and target rays comprehensible visualizations for predicting what will occur to oneself and the group?

RQ_3 What are the perceived advantages and disadvantages of automatic view direction adjustments during group navigation?

RQ_4 Does the prolonged use of our group navigation technique induce symptoms of discomfort?

RQ_5 What are the differences when navigating a small group of five users compared to a larger group of ten users?

To answer these questions, we chose the scenario of tours through a virtual museum (see Figure 5.7) and recruited participants familiar with VR systems. To be compliant with prevailing heath regulations, we invited only two participants per session, who later formed a virtual group with the experimenter and additional simulated users to achieve more reasonable group sizes for guided tours.

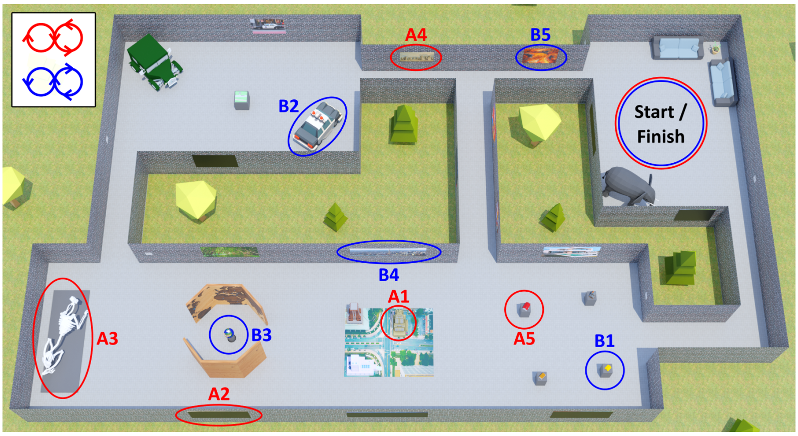

Figure 5.7: Top view of the museum in our initial usability study. The guided tours to be conducted by participant A and B, respectively, both started in the welcome lounge (top right), followed a figure-eight pattern through the rooms, and covered five exhibits to be presented to the group.

5.5.1 Experimental Setup

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

5.5.2 Experimental Procedure and Methods

Participants arrived in pairs at our laboratory and were briefed about the scope of the experiment. They were informed that they would be distributed to separate rooms and meet again virtually as part of a group with the experimenter and additional simulated users that should be treated as if they were real humans. We emphasized that both participants would take turns in being the guide for performing joint tours and that we would record all inputs for further analyses. Participants gave their written consent by signing a form before continuing. Once everybody was separated and put their head-mounted display on, participants and the experimenter had a short verbal chat in the welcome lounge of the virtual museum to ensure that participants could identify the avatars of the others and that the audio channel was working correctly. They were also introduced to the simulated users, whose head direction always automatically followed the current guide's viewpoint. Afterwards, the experiment followed the structure shown in Figure 5.8.

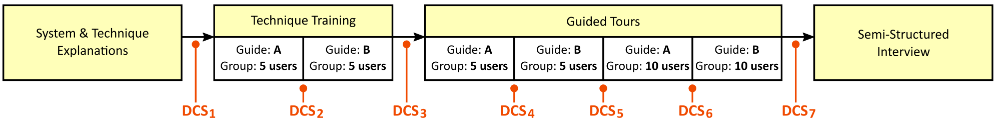

Figure 5.8: Procedure diagram of our initial usability study (introduction and conclusion omitted for simplicity). After the initial technique explanations by the experimenter, Participants A and B took turns in training and performing guided tours for the rest of the group. At various points across the study, we asked participants for their current discomfort score (DCS) to be able to intervene if necessary.

System and Technique Explanations First, the experimenter assumed the role of the guide in a group of five users (i.e. two additional simulated users) and showcased all features and navigational possibilities the system had to offer in an order similar to Section 5.4. Participants in the attendee role could observe the guide's controller and actions during jumping, understand the preview avatars and their personal target rays (RQ_2), and ask questions if necessary. The experimenter also demonstrated the optional addition of automatic view direction adjustments and underlined that participants would be asked to form an opinion about its utility later (RQ_3). In this phase, we only measured the total duration to get an impression on how long an exhaustive presentation of all features including follow-up questions may take (RQ_1).

Technique Training Afterwards, the guide's controls were passed on to the first participant to try all group navigation features of the technique on their own while the other participant could still observe as an attendee. The operating participant should replicate the same series of jumps as the experimenter in the previous phase to ensure that all features were understood and operated at least once. Particularly, the experimenter configured the system such that the participant could experience jumps with and without automatic view direction adjustments (RQ_3). Next, the same process was repeated after passing controls to the second participant. We silently measured the duration of each participant's training to avoid pressure. Moreover, we asked participants to think aloud as they progressed and asked follow-up questions where appropriate (RQ_1), a methodological mixture of a *concurrent think aloud* and *concurrent probing* protocol [11]. After both participants were done, we conducted a short interview in VR on their opinions regarding automatic view direction adjustments during jumping (RQ_3) and asked them to decide whether they would like to perform the rest of the study with or without this optional addition. We asked for this decision early in the study to allow for a fallback option if participants felt uncomfortable about virtual rotations as reported in previous work [21, 29, 86, 132].

Guided Tours (5 users) The guide's controls were passed back to the first participant, who was tasked to conduct a guided tour for the whole group through the museum. Since both participants were unfamiliar with the environment prior to the study, we displayed the intended route, five exhibits of interest, and a one-sentence fact about each of these exhibits using orange arrows and highlights (see Figure 5.9). These helper visualizations were only visible for the guide while the other user in the attendee role had to rely on the guide's narration. In particular, the task of the guide was to move the group along the displayed route, ensuring that everyone could follow along, place the group with respect to the featured exhibits, and to communicate the additional facts to them. After completing the tour, the controls were passed to the second participant and the process repeated with a different tour layout. To be comparable, both tour layouts started and concluded in the welcome lounge and followed a figure-eight pattern through the rooms and aisles of the museum (cf. Figure 5.7). For both tours, the five exhibits of interest were chosen to include one of the large exhibits (A3/B2), one of the medium-sized exhibits (A1/B3), one of the small exhibits on a pillar (A5/B1), and two of the wall-mounted images (A2;A4/B4;B5). During the tours, the experimenter assumed the role of a silent attendee to observe how guides were performing in this task (RQ_1). The system recorded all head and controller inputs for further analyses.

Guided Tours (10 users) After completing both tours, we added five additional simulated users and asked participants to repeat their tours using the previously described procedure. This allowed us to draw conclusions on the applicability of their acquired knowledge and training to a larger group (RQ_5).

Semi-Structured Interview In a final interview, we questioned both participants about their experiences using our technique focusing particularly on the aspects formulated in our research questions. This methodology is commonly referred to as *retrospective probing* [11]. Finally, each user was asked individually to provide a numeric rating for each feature of our technique on a scale from 0 (very disturbing) to 10 (very helpful), where 5 was labeled neither disturbing nor helpful.

To ensure the continuous wellbeing of our participants during the study (RQ_4), we repeatedly asked each user of a team for their discomfort score (DCS) at the measurement points illustrated in Figure 5.8 using the question "On a scale of 0-10, 0 being how you felt coming in, 10 is that you want to stop, where are you now?" [57, 135]. This wording was previously deemed suitable for detecting the onsets of simulator sickness and considered more feasible to administer for repeated measurements compared to the commonly used SSQ [15, 135].

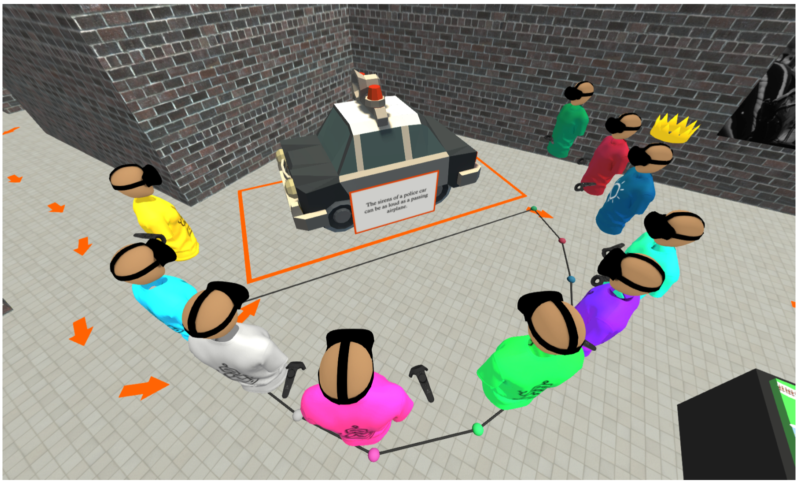

Figure 5.9: A guide, two real attendees, and seven simulated attendees observe a virtual car as part of a guided tour in the 10-user condition of our usability study. The orange arrows, highlights, and additional information panels were visible to the guide but not the attendees to simulate the common asymmetric knowledge distribution in guided tours.

5.5.3 Participants

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

5.5.4 Results and Discussion

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

Technique Operation (RQ_1)

System and technique explanations took an average of 10:06min ($\sigma = $ 0:55min) per team, followed by an average of 4:58min ($\sigma = $ 1:23min) of technique training per participant.

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

Comprehensibility of Jumping Previews (RQ_2)

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

Automatic View Direction Adjustments (RQ_3)

After the technique training phase, only 2 out of 12 participants decided against automatic view direction adjustments for completing the guided tours [T3]. Consistent with reasons mentioned in previous work [21, 86, 132], they found automatic view direction adjustments to be "too disorienting" [T3A] and valued the increased individual freedom of physical rotations [T3B]. The remaining users, on the other hand, appreciated the increased efficiency of automatic view direction adjustments for jointly observing an object or direction of interest together [T1, T2, T4, T5, T6] while frequent physical rotations were even deemed "too exhausting" [T5]. Our preview avatars were explicitly mentioned for also conveying view direction changes comprehensibly [T1, T2, T4, T6]. Some participants even suggested view direction as another freely adjustable parameter during target specification instead of defaulting to the fixed directions for formation-changing jumps shown in Figure 5.5 (left) [T1, T2]. Based on related work, we were surprised about these positive reactions, which motivate more formal future research on the effects of preview avatars on spatial orientation and user comfort during automatic view direction adjustments.

Discomfort Scores (RQ_4)

Except for uncomfortable heat developments due to the prolonged use of head-mounted displays [T1, T2, T5, T6], participants did not report any symptoms of simulator sickness or discomfort. This is underlined by the discomfort scores voiced during the course of the study as visualized in Figure 5.10, which had a median between 0 and 0.5 with standard deviations between 0.67 and 1.76 at all measurement points. We neither observed an increase of discomfort scores over time nor relationships between the discomfort score and the guide/attendee role assignment or gender. The unique maximum score of $DCS_5 = 6$ was given by a guide after accidentally stepping outside the calibrated area and colliding with a real-world obstacle. They declined the offer for a break and already felt better at the next measurement point ($DCS_6 = 2$). We therefore conclude that the discomfort introduced by operating and experiencing guided tours using our technique is negligible, which is consistent with previous comparisons of active and passive two-user jumping through virtual environments [175, 178].

Scalability (RQ_5)

Participants did not report on major problems of navigating the 10-user compared to the 5-user group with "no big differences" in technique operation [T4] and "surprisingly sim-

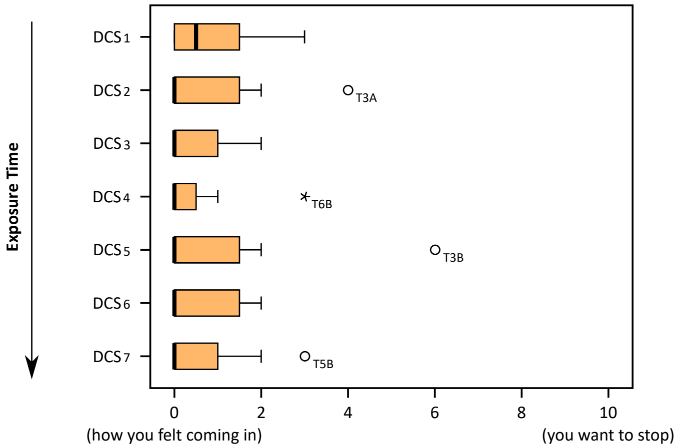

Figure 5.10: Boxplots showing the distribution of discomfort scores (DCS) at the measurement points illustrated in Figure 5.8. $N = 12$ per boxplot. Circles and asterisks denote outliers and extreme values based on Tukey's fences with $k = 1.5$ for outliers and $k = 3.0$ for extreme values [168].

ilar" interaction sequences [T5]. Nevertheless, users claimed that finding suitable group placements was more challenging in corridors and around exhibits [T1, T2, T3, T6]. For exhibits, this often resulted in smaller interpersonal distances than in the small group since all avatars had to be placed within the available space without occluding the view of others. However, planning user formations did not seem to take longer based on the recorded visibility durations, which were 2.89s ($\sigma = 1.29$s) and 2.46s ($\sigma = 0.99$s) per jump for the small and large group, respectively. For narrow spaces like corridors, guides claimed an increased preference of the *grid* over the *queue* formation in the larger group [T1, T4, T5, T6]. Indeed, the proportion of *grid* jumps compared to all formation-changing jumps went from 3.7% ($\sigma = 6.1\%$) in the small to 27.4% ($\sigma = 22.5\%$) in the large group. While all teams deemed a group size of 10 to be still manageable using our technique, they suggested that even larger groups could benefit from a more spacious virtual environment [T1-T6] and an adapted choice of formations for formation-changing jumps like a circle with multiple shifted rows or a "cinema seat" arrangement [T3, T4]. With these changes, even group sizes of up to 20-30 users were considered plausible for performing guided tours [T5]. Nevertheless, due to the large number of avatars, participants also raised the question if attendees really need to see each other during a tour or if merging at least sub-groups to a single viewpoint could also be a viable alternative [T2]. Based on related work on guided tours [12], however, we would suggest providing mechanisms for these cases that allow individual attendees to step out of the crowd to interact with the guide if necessary. If all attendees should be able to see and interact with each other at all times, we conclude that the complexity of group navigation increases with group size, where the requirements *Obstacle Avoidance* and *View Optimization* seem to be the key driving factors.

Individual Feature Ratings

At the end of our study, participants were asked to provide individual numeric ratings of certain aspects of our technique from 0 (very disturbing) to 10 (very helpful), which aimed at summarizing their voiced opinions in the semi-structured interview. As the overview of responses in Figure 5.11 shows, all features received very positive median scores between 9 and 10, which indicates a high level of acceptance for our group navigation technique across our participants.

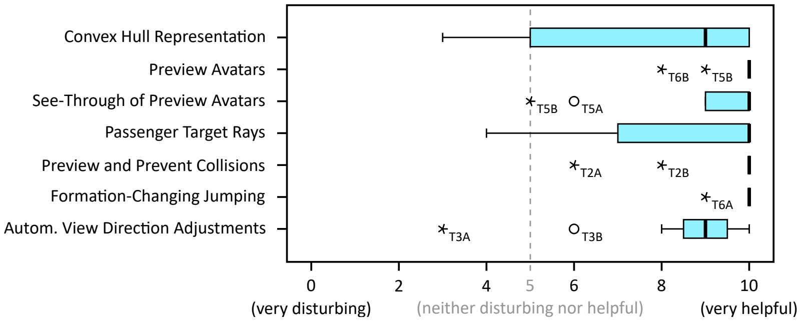

Figure 5.11: Boxplots showing the distribution of responses to our concluding feature scoring questionnaire, where each feature was rated on a scale from 0 (very disturbing) to 10 (very helpful). $N = 12$ per boxplot. Circles and asterisks denote outliers and extreme values based on Tukey's fences with $k = 1.5$ for outliers and $k = 3.0$ for extreme values [168].

Summary and Limitations

Our study results indicate that effective, comprehensible, and learnable group navigation techniques can be realized for guiding small groups through distributed virtual environments (RQ_1, RQ_2). Across all teams, we received particularly positive feedback regarding the use of preview avatars for role-independent *Comprehensibility* as well as collision previews and formation-changing jumps for *Obstacle Avoidance* and *View Optimization*. In particular, passive movement in the attendee role did not seem to lead to increased discomfort or confusion if the guide performed all actions with a reasonable pace (RQ_4). This result underlines that the guide should watch their attendees for signs of distraction or confusion to adjust the pace of the tour if necessary. Moreover, the guide's narration can complement the visualizations of the group navigation technique if they are unsure about the attentiveness of particular attendees. The majority of users (10 out of 12) preferred automatic view direction adjustments during group jumping over physical rotations for their efficiency and underlined the preview avatars' comprehensibility also in this regard (RQ_2, RQ_3). Future more formal research is required to analyze the effects of view direction adjustments on spatial awareness and to investigate sources of discomfort for individuals. Overall, the discussions with the participants in our study gave us valuable insights on how certain aspects of our proposed jumping technique could be tweaked for specific use cases/user preferences and how it could be extended to guide even larger user groups, where the requirements *Obstacle Avoidance* and *View Optimization* seem to be the driving factors of complexity (RQ_5).

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

5.6 Conclusion and Future Work

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

Future work might focus on the suitability of alternative travel metaphors for group navigation like steering, flying, or long-distance teleportation. This is especially motivated by related work that, despite the general acceptance of jumping for minimizing simulator sickness, observed small subsets of “telesick” users who seem to have more problems with jumping over its alternatives [36, 37]. While we believe that our requirements still apply to other metaphors, their implementations will certainly differ. Formation-changing transitions for steering, for example, should put a much stronger focus on optimizing the paths to be traversed by each user since prolonged visual flows as well as crossings with other user paths could easily introduce discomfort. For long-distance teleportation, as another example, additional views such as portals or worlds-in-miniature are required to be able to evaluate previews of the group at the destination.

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

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

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

An Overview of Group Navigation in Multi-User Virtual Reality

This chapter reports on joint work with Pauline Bimberg and Bernd Froehlich at Bauhaus-Universität Weimar. It was published in the abstract and workshop proceedings of the 2021 Conference on Virtual Reality and 3D User Interfaces (VRW) and presented at the workshop "Finding a Way Forward in VR Locomotion".

This research received funding from the Thuringian Ministry for Economic Affairs, Science, and Digital Society under grant 5575/10-5 (*MetaReal*).

Besides the following teaser image, figure references were adjusted to refer to prior occurrences in this thesis.

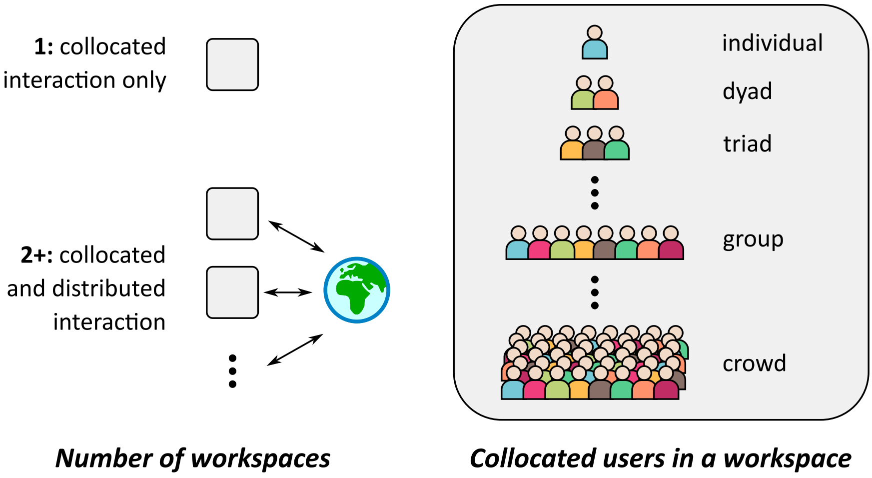

Figure 6.1: We classify group navigation techniques in virtual reality by the number of involved distributed workspaces (left) and the number of collocated users situated within each of these spaces (right).

Abstract

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

6.1 Introduction

The interactive exploration of virtual environments that cannot be overlooked from a single vantage point requires navigation, which is a combination of the motor component *travel* and the cognitive component *wayfinding* [20]. While previous research has investigated a large number of navigation techniques for individuals (see [2, 114] for overviews), the growing popularity of multi-user virtual reality systems raises the central research question of how common single-user navigation processes can be adapted or enhanced to support the requirements of groups exploring a shared virtual space together. The most straightforward solution to multi-user navigation in these systems is to equip each member of a group with individual navigation capabilities through established single-user techniques. However, this approach can lead to several undesired side effects like non-negligible coordination overheads, the risk of losing each other, and the unnecessary allocation of attentive resources for navigation by every member of the group.

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

6.2 Group Navigation Techniques in the Literature

While the exact definition of the term *group* varies between publications, most of them emphasize some form of social relationship or interdependence between members, in which the actions and thoughts of one member can influence the others [59, chpt. 1]. Therefore, groups can be diverse with examples ranging from dyads working together over small groups exploring a museum to large crowds and audiences, where one member starting to clap might motivate the others to join. Based on Tuckman's model of small-group development [166, 167], group navigation techniques involve processes in four different phases, visualized in Figure 4.2, which can be summarized as forming navigational groups (*Forming*), distributing navigational responsibilities (*Norming*), navigating together (*Performing*), and eventually splitting up again (*Adjourning*) [175]. In multi-user virtual reality, the members of a group can be either collocated in a single workspace or distributed across multiple workspaces:

Single Workspace Members of a group meet in the same physical location to experience the virtual environment. This is usually realized by equipping each member with a head-mounted display within a common tracking space (e.g. [101, 144, 178]) or by employing multi-user projection technology (e.g. [1, 28, 96]). As a result, all participating users can have an individual perspectively-correct view onto the virtual environment.

Multiple Workspaces Members of a group are in different locations and join the virtual environment using a network connection (e.g. [8, 67, 119, 175, 177]). The absence of a shared physical space typically requires additional communication mechanisms like an audio connection via the network.

While many systems in the literature focus solely on either collocated or distributed group interaction, more advanced setups allow the collaboration of both collocated and distributed group members (e.g. [8]). As a result, group navigation in multi-user virtual reality can be classified by the number of involved distributed workspaces and the number of collocated users situated within each of these spaces (see Figure 6.1). In the following, we will apply this classification and terminology to categorize group navigation techniques presented so far and derive potentials for future research. An overview of the discussed publications with respect to their group composition and the realized mechanisms for *Forming*, *Norming*, *Performing*, and *Adjourning* is given in Figure 6.2.

6.2.1 Navigation of Collocated Dyads and Groups

Since collocated users are tracked within their common physical workspace, everybody can walk around in order to adjust their viewpoint onto the virtual content. In many systems in which the size of the virtual environment is similar to the physical workspace, this is the most prevalent method of navigation (see [1, 4, 5] for projection-based systems and [27, 39, 143, 144, 152] for head-mounted displays). If virtual navigation capabilities are provided on a per-user basis, the spatial user arrangement in the real world diverges from the arrangement of the avatars in the virtual environment, which can lead to a range of complications. For collocated users of head-mounted displays, for example, spoken words will be heard as coming from a different direction than one would expect based on the visual position of the virtual avatar. Moreover, the unawareness of another user's real-world position can easily lead to collisions during walking. Lacoche et al. coined the term *spatial desynchronization* for these situations and suggested additional visual mediators like ghost avatars and floor-projected heat maps to increase mutual awareness [101]. Other researchers focused on the almost imperceptible redirection of users during walking

Publication	Group Composition	Forming	Norming	Performing	Adjourning
Salzmann and Froehlich 2008 [149]	two collocated users (HMD)	physical	user in driver's seat is navigator	steering	physical
Salzmann et al. 2009 [150]	two collocated users (projection-based)	physical	user claiming input device is navigator	steering	physical
Kulik et al. 2011 [96]	a group of up to six collocated users (projection-based)	physical	user claiming input device is navigator	steering with virtual collision avoidance	physical
Weissker et al. 2019 [178]	two collocated users (HMD)	physical	fixed user is navigator	Multi-Ray Jumping	physical
Weissker et al. 2020 [175]	two distributed individuals (HMD)	holding controllers together	first user to activate target ray is navigator	Multi-Ray Jumping with formation adjustments	button
Weissker and Froehlich 2021 [177]	a group of up to ten distributed individuals (HMD)	not discussed	user with most expertise is navigator	Multi-Ray Jumping with preview avatars and formation adj.	not discussed
Party Portals in AltspaceVR[1], cf. Kolesnichenko et al. 2019 [92]	a group of distributed individuals (HMD)	selection of portal	portal creator initiates transition	scene transition	automatically after transition
Beck et al. 2013 [8]	two distributed groups of up to six collocated users each (projection-based)	button for linking distributed groups	input combination of both groups' navigators	steering and virtual group rearrangements	button for disconnecting distributed groups

Figure 6.2: An overview of the discussed publications on group navigation techniques for collocated dyads and groups (Section 6.2.1), distributed individuals (Section 6.2.2), and distributed dyads and groups (Section 6.2.3).

to prevent collisions [6, 49, 105, 116] or relied on users remaining mostly stationary in the physical space [22]. In multi-user projection systems, spatial desynchronization is especially disruptive since seeing the real-world bodies of other users in front of the shared projection screen(s) generates the wrong expectation that they can understand physical pointing gestures to refer to objects in the virtual environment. Nevertheless, Chen et al. argued that individual navigation in a two-user CAVE can be beneficial for loosely coupled collaboration tasks and proposed a variation of the human joystick metaphor to safely share the joint workspace while being in different locations virtually [28].

To avoid the problem of spatial desynchronization completely, group navigation techniques consider collocated users as a single entity that can only be moved as a whole by virtual navigation. Therefore, the shared workspace is often imagined as a virtual vehicle [96], conveyor [58], or magic carpet [120] that can be operated to move through the virtual environment. As a result, *Forming* and *Adjourning* are done in the real world by entering or exiting the physical space of the virtual reality system and putting the required hardware on or off. Regarding *Norming*, being on a shared vehicle usually leads to an asymmetric role distribution between the operating navigator and the passive passengers. The two-user seating buck system by Salzmann and Froehlich, for example, allowed the user in the driver's seat to steer a shared virtual car and therefore also the passenger through the environment [149]. Another system by Salzmann et al. allowed a dyad in front of a projection screen to switch between navigator and passenger roles for flying around a virtual object by passing a shared input device [150]. In the six-user projection system by Kulik et al., the shared input device was stationary within the physical workspace and could be claimed by each member of the group. During the *Performing* phase, the authors noted that the spatially consistent representation of the group can lead to uncomfortable situations when steering through doorways that are narrower than the physical workspace, where passengers collided with the adjacent virtual walls as a consequence. To address this problem, they proposed to automatically move users closer to each other in the virtual environment such that a collision-free path through the door could be guaranteed. After passing the door, users were moved back to a spatially consistent configuration. This approach was evaluated positively for providing comfortable user paths while the short moments of spatial desynchronization were not considered disrupting or nauseating [96]. In the realm of head-mounted displays, travel by steering is mostly avoided since it is often deemed a plausible cause of simulator sickness due to the resulting sensory conflict between the visual and the vestibular systems [45, 100, 136], which is especially detrimental in these setups as opposed to other display media [156]. For collocated group navigation with head-mounted displays, Weissker et al. therefore relied on teleportation-based movements for *Performing* and introduced the notion of *comprehensible group navigation*, which underlines the importance of mutual awareness and predictability of actions during the joint navigation process. To meet these quality criteria, they presented a short-distance teleportation technique for two-users called *Multi-Ray Jumping* that communicated the target position of the passenger by using a secondary target ray (see Figure 3.1). In two user studies, this additional mediation was confirmed to improve comprehensibility and reduce cognitive load without inducing higher simulator sickness for users in the passenger role [178].

6.2.2 Navigation of Distributed Individuals

Several research prototypes investigated the networked combination of single-user projection systems when collaborating users were geographically far apart or multi-user technology was not available (e.g. [67, 102, 153]). For head-mounted displays, recent technological advancements and affordable hardware have led to an increasing number of users having a personal virtual reality system, which also sparked commercial developments of networked multi-user applications for distributed individuals (see [92, 119] for an overview). Since the problem of spatial desynchronization is non-existent for purely distributed interaction, most systems provide independent virtual navigation on a per-user basis and only omit virtual navigation if the environment can be apprehended by physical locomotion only (see [4, 54, 67, 102, 153] for projection-based systems and [75, 104, 155, 159, 172] for head-mounted displays). Although the presence of others is purely virtual in these systems, it was shown that users still exhibit negative reactions to violations of their personal space, i.e., when the avatars of others approach them too closely [182]. As a result, several commercial systems implement some form of protective mechanism to increase user comfort by preventing users from entering the personal space of others or at least making intruding avatars transparent [119].

Recent research in larger virtual environments suggested that individually navigating users can have difficulties staying together, finding each other, or understanding spatial references [172, 175]. In that regard, the desktop-based system by Dodds and Ruddle offered additional group awareness mechanisms during individual navigation like visible connection lines between group members, direct teleportation to other group members, and sharing another person's viewpoint [47, 48]. Nevertheless, if group members should stay in close proximity to each other for exploring the same parts of the environment together, group navigation techniques can help to prevent members from having to give similar navigation inputs towards the same destination (input redundancy) and to reduce the need for coordinating where and how to get to the next destination (navigational accords) [177]. The concrete choice of how to implement *Forming* and *Adjourning* in distributed virtual environments is highly dependent on the use case and social relationships between participants. In a private classroom scenario, for example, the attendees of a tour might be inherently given while more open scenarios in public spaces would require giving explicit consent before joining a tour, for example, by moving to a meeting point within a certain time span, performing a coupling gesture, or simply pressing a dedicated button [8, 92, 175]. Similarly, a teacher might not want their students to leave the group before the end of the tour while this could be a desired feature when attendance is less strict. With respect to *Norming*, it seems reasonable to assign the main virtual group movement controls to the user with the most knowledge of the system and topic to be demonstrated. Nevertheless, this privilege might need to be passed on to a different guide when expertise is separated among multiple users. While this was mostly realized by changing the operator of a shared input device in collocated setups, distributed systems need to offer virtual mechanisms in this regard as well.

As an example for a limited form of group navigation with distributed individuals, the commercial system AltspaceVR[1] introduced the idea of *party portals* to transition from one virtual scene to another together. A party portal provided a preview of the target scene and allowed users to express their interest in joining by selecting the portal geometry. The transition was then initiated by the portal creator for all users at the same time. *Performing* group navigation within the same virtual scene for a longer period of time, however, is more challenging. Based on earlier research on collocated group navigation, it can be derived that *Performing* techniques for distributed individuals should be comprehensible for both the navigator and passengers (*Comprehensibility*), assist the group in avoiding collisions with obstacles during joint travel (*Obstacle Avoidance*), and allow the creation of meaningful spatial arrangements to observe and discuss objects of interest together (*View Optimization*) while still conforming with personal space semantics [177]. To meet these requirements, variations and extensions of Multi-Ray Jumping for two [175] and up to ten [177] distributed users were developed. In addition to default mechanisms to relocate the group in its current spatial formation, these techniques also gave the navigator the ability to generate virtual formation adjustments, i.e., rearrangements of group members to a different spatial layout without requiring individual motion (see Figure 5.1 for an example for five distributed individuals). While this would immediately lead to spatial desynchronization in collocated setups, distributed individuals appreciated this feature as it allowed for more efficient travel sequences in order to meet the requirements of *Obstacle Avoidance* and *View Optimization* while the *Comprehensibility* was not compromised due to appropriate preview mechanisms. In the implementation for up to ten users, circle and horseshoe formations helped users to focus on a common area of interest (cf. [87]) while compact grid and queue formations were convenient for moving group members through narrow passages when getting to the next destination. To minimize discomfort, the system ensured that users were never placed inside the personal space of each other or inside obstacles in the virtual environment [177].

6.2.3 Navigation of Distributed Dyads and Groups

Virtual reality systems involving multiple distributed groups of collocated users are rare up to this point. An exception is the projection-based group-to-group telepresence system by Beck et al., which enabled two groups of up to six collocated users each to meet in the virtual environment using high-fidelity video avatars [8]. To avoid spatial desynchronization, individual user movements were restricted to walking in front of the respective projection screen while virtual steering could only be applied to each group as a whole. When both groups met in the virtual environment, they could decide to link themselves by coupling their navigation systems (*Forming*). As a result, the navigator of each local group

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[1] `https://altvr.com/`

could take the remote group along for joint explorations. If both local navigators provided inputs at the same time, they were simultaneously applied to the whole group (*Norming*). Additionally, navigators could also change the spatial arrangement of both groups to a side-by-side or face-to-face arrangement, which is similar to the idea of virtual formation adjustments for distributed individuals by Weissker et al. [175, 177]. However, to maintain spatial consistency among collocated users, virtual formation adjustments were applied on a workspace level rather than on individual users. As a result, for generating a side-by-side configuration, both virtual workspace representations could be overlaid, which still required the individual users in each room to perform physical walking to line up in a "true" side-by-side arrangement. A similar situation arose for the face-to-face configuration, where only the virtual workspace representations were placed and rotated to face each other in the virtual environment.

6.3 Discussion and Future Research Directions

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

Scalability Developing systematic and controlled evaluation protocols to be conducted with a large number of users per session is a challenging and laborious endeavour, which prevents the rapid acquisition of research insights. As a result, prior research mostly focused on small and therefore easily manageable group sizes. To get an initial impression on the challenges of navigating larger groups, the exploratory user study by Weissker and Froehlich [177] increased the number of participants to be navigated by adding up to seven simulated users to groups of three human participants. The results indicated that the main challenges for scalable group navigation seem to lie in assisting the group with *Obstacle Avoidance* and *View Optimization* while still conforming with personal space semantics. This means that the larger a group gets, the more challenging it is for the navigator to find suitable non-overlapping and collision-free user placements. While more spacious environments might help to reduce this problem to some extent, a large number of virtual avatars also leads to more turbulent scenes and occlusions among avatars, which might disturb the perception of the content of interest. In such cases, the group could be split into socially less-dependent sub-groups within which avatar visibility is restricted to members of the same sub-group and the navigator. This approach would allow the overlapping placement of different sub-groups without introducing additional visual disturbances, but it would also prevent all forms of social interactions between members of different sub-groups. As a result, systems following this approach should also provide options to switch between sub-groups or to become visible for everyone in order to initiate discussions. Nevertheless, allowing every user of a large group to perform actions at all times could become difficult to oversee and comprehend without any form of moderation. An additional challenge lies in finding a suitable aggregate visualization of the group for external observers [10], which allows them to get an understanding of the group activities even if the viewing positions of multiple users inside the group are overlapping.

Diversity Most of the related literature and user studies on group navigation focused on rather homogeneous scenarios regarding the physical collocation/distribution of collaborators, the use of certain types of VR hardware, and the individual capabilities of participants. While the combination of collocated and distributed users for joint navigation was initially approached by Beck et al. [8], the inherent challenges of avoiding spatial desynchronization for collocated participants while using the spatial flexibility of distributed entities for realizing *Obstacle Avoidance* and *View Optimization* (see Section 6.2.3) deserves further in-depth investigations. The combination of different hardware setups was also tackled only rudimentarily up to this point, mainly by desktop users providing verbal navigation assistance for an immersed individual [7, 126, 173]. Joint navigation of users with diverse immersive hardware, on the other hand, faces the challenge that some scenarios (like users in front of a single-screen projection system or seated users wearing head-mounted displays) require virtual rotation techniques to look around whereas other scenarios (like users surrounded by screens in a CAVE or standing users wearing head-mounted displays) enable users to perform full turns by physical rotations. The ability to rotate physically at any point in time might make it easier to maintain situational awareness, which could in turn lead to an improved *Comprehensibility* of the navigation process and therefore disadvantage other users without this ability. Finally, future studies on group navigation should also take place outside of laboratory environments to capture a more diverse audience with varying capabilities in order to validate the usability of the developed prototypes.

Social Factors While previous work confirmed initial benefits of group over individual navigation in both collocated and distributed scenarios, the underlying social factors and group processes during joint navigation are an important aspect for further investigation. Especially in distributed setups, where groups are formed only virtually, it is relevant to identify which aspects of application design are beneficial for social presence, mutual awareness, and the overall sense of belonging together during joint navigation. Based on these considerations, future evaluations could focus on the effects of individual and group navigation on more high-level goals like collaborative scene understanding, information gathering, or acquisition of spatial knowledge. The study by Buck et al. in head-mounted displays, for example, showed that dyads with individual steering capabilities could acquire better levels of survey knowledge when they were allowed to cooperate [22]. It would be interesting to see if similar results can be achieved with group navigation techniques as well and which cognitive strategies users employ to achieve the common goal.

Moreover, the study of suitable group formations for specific situations within the group navigation process is still at the beginning. Particularly, the idea of virtual formation adjustments raises questions regarding more meaningful rearrangements of users considering social relationships, common (sub-)goals, and proxemic criteria like body orientations or spatial proximity (see [69, 71] for a complete overview of proxemic dimensions).

Alternatives to Group Navigation Navigation of the entire group is a responsible task for the navigator, which should be carried out with care. While previous studies did not indicate increases in simulator sickness during passive teleportation when the navigator performed all steps at an appropriate pace [177, 178], some passengers might not be satisfied with passing control over their viewpoints to another person. Therefore, the *Norming* phase of the group navigation framework offers potentials for adjustments, e.g., by allowing passengers to notify the navigator about disagreements or to block group navigation entirely when someone feels uncomfortable. In some cases, however, the strict coupling of users to a navigational entity might not be the desired solution. It is therefore crucial to study further how users with individual navigation capabilities can stay together as a group, understand how and where to go next, and prevent colliding with each other when being physically collocated. Apart from that, prior research indicated that certain collaborative tasks benefit from a division of work rather than staying together for the whole time. In collaborative search efforts, for example, it was shown that independently navigating dyads could locate more target objects than individuals alone [84, 85]. In the desktop collaborative virtual environment of Dodds and Ruddle [47, 48], group members inspected completely different parts of the scene as part of an architectural design review, but they needed to coordinate and potentially reconvene to continue at various points throughout the study. The proposed group visualizations and navigation aids for these situations provide interesting ideas towards supporting distributed group work with individual navigation, which however still require adaptations to and evaluations in immersive virtual reality.

6.4 Conclusion

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

7

Conclusion and Future Work

This thesis presented conceptual and technical contributions to research on group navigation techniques in multi-user virtual reality as published in four peer-reviewed scientific publications. The research was guided by the four overarching research questions formulated in Section 1.2. This chapter summarizes the most relevant research insights with respect to these questions and extends the discussion in Section 6.3 by a more specific reflection of the results and the emerging challenges to be addressed in future research. To improve readability, the publications will be referred to by their short titles, namely *Multi-Ray Jumping* for Chapter 3, *Getting There Together* for Chapter 4, *Group Navigation for Guided Tours* for Chapter 5, and *An Overview of Group Navigation* for Chapter 6.

7.1 Requirements for Group Navigation Techniques

RQ_I What are the quality requirements for group navigation techniques and how can they be addressed?

Results

Our four-tier framework presented in *Getting There Together* states that group navigation techniques should provide mechanisms for users to form navigational groups (*Forming*), distribute navigational responsibilities (*Norming*), navigate together (*Performing*), and eventually split up again (*Adjourning*). At various points in *Getting There Together*, *Group Navigation for Guided Tours*, and *An Overview of Group Navigation*, we discussed that design choices in each of these phases are dependent on the targeted scenario and use case, including the involved hardware setups, group sizes, and social relationships between participants. In particular, our framework presentation in *Getting There Together* gives an overview of exemplary variations for all phases based on prior work and therefore provides structured guidance for developing novel group navigation techniques in future research.

Performing techniques allowed for the derivation of more scenario-independent requirements in our work. In *Getting There Together*, we discussed that a realization of group travel should also foster group awareness and group communication during the process. Our quality requirement of *Comprehensibility* initially formulated in *Multi-Ray Jumping* and generalized in *Getting There Together* and *Group Navigation for Guided Tours* highlights a close connection between group travel, awareness, and communication by claiming that both the navigator and all passengers in a group should be able to understand and predict what is happening to themselves and the group as a whole. In addition, *Group Navigation for Guided Tours* derived the requirements of *Obstacle Avoidance* and *View Optimization* during group travel, which emphasize the challenges of navigating through feature-rich and confined spaces as well as finding suitable group placements for the joint observation and discussion of relevant objects. We argued that the requirements of *Comprehensibility* among navigator and passengers, *Obstacle Avoidance*, and *View Optimization* are an addition to general quality requirements known from single-user navigation.

Our developments of group navigation techniques provided exemplary approaches on how the formulated requirements for *Performing* can be addressed in the realm of head-mounted displays. As the basis for our techniques, we decided to focus on the jumping metaphor with discontinuous transitions since it was previously shown to reduce the occurrence of sickness symptoms in single-user systems as opposed to steering-based approaches. Furthermore, our study in *Multi-Ray Jumping* did not provide indications for higher sickness levels when jumps were initiated by another user, which was in contrast to prior work on continuous movements [46, 142, 156, 160]. To satisfy *Comprehensibility* for group jumping, we mostly built upon enhanced *pre-travel information* to preview the consequences of the navigator's intended actions for all members of the group in order to prevent disorientation. With respect to *Obstacle Avoidance* and *View Optimization* in distributed setups, we suggested to support the rapid specification of *virtual formation adjustments* to spatially compact and/or functional formations as known from the real world while ensuring that appropriate interpersonal distances are maintained during the process. All of our implementations were based on common single-user jumping workflows to ensure easy learnability and operability.

Future Work

Future work on *Performing* implementations should investigate and compare a wide range of alternative approaches on how the formulated requirements can be realized. With respect to *Obstacle Avoidance* and *View Optimization*, for example, all our implementations relied on the navigator to select appropriate group formations and to place them in the environment while only getting visual feedback about possible collisions in *Group Navigation for Guided Tours*. A particularly fruitful area for more detailed studies therefore is the realization of system-driven suggestions for suitable group placements based on the structure of the environment, pre-defined points of interest, and social configurations in the current group arrangement.

Our studies on *Comprehensibility* demonstrated that passengers could use the provided pre-travel information to understand the navigator's intended actions and therefore prevent moments of spatial disorientation. As discussed in Section 2.2.2, this is already a relevant basis for the successful completion of any higher-level spatial task. Nevertheless, future work should put more emphasis on the explicit analysis of more complex factors of spatial cognition during group navigation like spatial updating, route knowledge, and survey knowledge. This might reveal further design recommendations for group navigation techniques in usage scenarios where the acquisition of spatial knowledge by every group member is desired.

Moreover, although jumping seems to be a viable travel metaphor for group navigation techniques, some publications report on subsets of users who still seem to prefer steering for its simplicity and the resulting experience. A few studies reported that some participants found jumping techniques more difficult to understand and use [79], that experiencing visual jumps can result in tiredness [16], that steering can result in a stronger sense of presence [37], and that individual participants expressed preferences for steering even though it elicited more sickness symptoms for them [132, 179]. Contrary to intuition, Clifton and Palmisano even observed small subsets of "telesick" users for which the occurrence of sickness symptoms during jumping was increased compared to steering [36, 37]. These results motivate further explorations on how *Performing* techniques can be realized with steering as the core travel metaphor, which leads to a variety of novel research challenges with respect to ensuring *Comprehensibility*, *Obstacle Avoidance*, and *View Optimization*.

Given all the potential alternatives, it seems relevant to derive a more formal and standardized testbed that allows for direct comparisons of different group navigation techniques across studies and publications. Furthermore, future work should put a stronger emphasis on the other stages of group navigation techniques as well. While we provided initial intuitions and design options for *Forming*, *Norming*, and *Adjourning*, these stages should be explored more systematically to derive more concrete design recommendations for particular scenarios and use cases.

7.2 Collocated and Distributed Group Navigation Techniques

RQ$_{\text{II}}$ How does the physical collocation or distribution of group members affect the process of navigating together?

Results

While it is theoretically possible to perform individual virtual navigation in collocated setups, a central challenge for user experience is the resulting spatial desynchronization between the tracked users in the real world and their avatar representations in the virtual environment. In these situations, sounds emitted by other participants come from a different direction than one would expect based on the corresponding virtual avatar, and the risk of colliding with each other during physical walking or gesturing is increased. While other researchers provided ideas to mitigate these negative effects (e.g [6, 101]), group navigation techniques can avoid spatial desynchronization completely by applying the same relative virtual travel steps to all group members simultaneously. In this case, *Forming* and *Adjourning* become real-world mechanisms that are executed by joining or leaving the VR system. However, the desire for identical user formations in the real and virtual world also restricts the available options for realizing *Obstacle Avoidance* and *View Optimization* since any form of virtual formation adjustment would immediately introduce an inconsistency with the user formation in the real world. As a result, users would need to move physically every time a change in formation is required, and individual navigation beyond physical movements is restricted to additional viewing windows like portals (e.g. [98, 99]).

For purely distributed collaboration as described in *Getting There Together* and *Group Navigation for Guided Tours*, being in separate physical workspaces allows for switching between individual and group navigation (*Forming*, *Adjourning*) as well as executing virtual formation adjustments without having to adhere to spatial constraints imposed by a formation in the real world. Our results for two spatially distributed users in *Getting There Together* indicated that the addition of virtual formation adjustments can make the group travel process considerably more efficient and therefore contribute to reductions in perceived workload, which was also confirmed by the qualitative interviews after navigating with larger groups in *Group Navigation for Guided Tours*. Furthermore, our suggested preview mechanisms were sufficient to foster *Comprehensibility* even when navigators rearranged user groups to a completely different formation.

Future Work

Since the technical developments of this thesis focused on either purely collocated or purely distributed scenarios, an emerging challenge for future work is to apply the lessons learned to the development of group navigation techniques for scenarios with both collocated and distributed participants. A key aspect in this regard is finding appropriate solutions for group travel that avoid spatial desynchronization for collocated participants while using the spatial flexibility between distributed user groups for realizing *Obstacle Avoidance* and *View Optimization*. While the work of Beck et al. provided initial ideas in this direction [8], a more systematic and exhaustive exploration of this topic is still subject to future work.

Moreover, the distinction between collocated and distributed participants also offers interesting research questions with respect to avatar design and mutual awareness during group navigation. While all of our implementations presented in this thesis worked with the same set of simplistic user avatars, future work should study the effects of avatar fidelity on presence, co-presence, and the resulting comprehensibility of group navigation techniques. This is especially relevant for distributed scenarios, where prior work indicated potential detriments in collaborative task solving as compared to the collocated case [75].

7.3 Scalability of Group Navigation Techniques

RQ$_{\text{III}}$ What are the emerging challenges for the design of scalable group navigation techniques?

Results

While *Multi-Ray Jumping* and *Getting There Together* started by exploring group navigation techniques for collocated and distributed dyads, respectively, our work in *Group Navigation for Guided Tours* focused on larger groups of spatially distributed users navigating together. In our usability evaluation, we introduced group size as an explicit independent variable by asking participants to perform guided tours for each other in groups of five and ten (partially simulated) users. While participants did not report about effects of these group sizes on *Comprehensibility* in our scenario, they mentioned a perceived increase in complexity with respect to satisfying *Obstacle Avoidance* and *View Optimization*. As a consequence, the virtual formation adjustments specified by the navigator generally resulted in smaller interpersonal distances in order to fit through narrow corridors and to ensure optimal views onto exhibits for everyone without occluding the view of others. However, our group navigation technique ensured that all adjustments kept an appropriate minimum distance between users to prevent socially uncomfortable situations as observed in the real world [56, 118] and other distributed virtual reality systems [182].

These initial results led to the hypothesis that *Obstacle Avoidance* and *View Optimization* are the key driving factors of complexity for group navigation with even larger groups. The increased preference of the *grid* over the *queue* formation in the 10-user condition of our usability evaluation underlined that the group formations to be offered by group navigation techniques should directly depend on group size. For even larger groups than in our study, for example, participants suggested “cinema seat” arrangements or circles with multiple shifted rows to reduce the occlusions introduced by other avatars. A system-driven assistance approach to provide the navigator with suggestions for suitable group placements as discussed in Section 7.1 seems to be a central building block for reducing the complexity of *Obstacle Avoidance* and *View Optimization*. Nevertheless, the increased number of avatars and the resulting complex group configurations, including the occlusions created by moving users, remain a key issue for larger groups, which in turn could also have potential implications for the *Comprehensibility* of group navigation techniques.

Future Work

Future work should build upon these initial insights and study the use of group navigation techniques for larger groups like school classes or even crowds to draw more conclusions on the scalability of mechanisms for *Comprehensibility*, *Obstacle Avoidance*, and *View Optimization*. In particular, future evaluations of group navigation techniques for larger groups should also focus on social factors during the joint navigation process by studying groups without additional simulated users. Evaluations in such settings could, for example, allow for more insights into negotiations with respect to *Norming* decisions and the emergence of closely-coupled sub-groups and social formations during *Performing*. Another interesting aspect for future research is the analysis of appropriate social conventions for enabling fluent *Forming*, *Adjourning*, and potential *Re-Forming* at a larger scale.

However, certain parts of a virtual environment or environments as a whole might simply not be spacious enough to accommodate a large number of users. As a result, there might be situations in which no solutions for *Obstacle Avoidance* and *View Optimization* also allow for keeping appropriate interpersonal distances. In these cases, future work could focus on solutions that split the group into socially less-dependent sub-groups within which avatar visibility is restricted to members of the same group and the navigator, which would allow for overlapping placements in the virtual environment. Nevertheless, as discussed in *An Overview of Group Navigation*, this approach comes with various novel research challenges regarding where these splits should be made, how users can switch between sub-groups, how users can step out of their sub-group and become visible for everyone to initiate discussions, and how the overlapping sub-groups can be comprehensibly represented for the navigator as well as for external observers.

7.4 Scenarios for Individual and Group Navigation

RQ$_{\text{IV}}$ Which situations particularly benefit from the availability of group navigation techniques, and in which situations is it more practical for group members to navigate individually?

Results

We identified two central advantages of group over individual navigation techniques in *Group Navigation for Guided Tours* by discussing the inherent reductions of input redundancy for travel and navigational accords for wayfinding. As discussed in Section 7.2, an additional advantage of group navigation techniques in collocated setups is the prevention of spatial desynchronization. Similar to being together in a real-world vehicle, these advantages make group navigation a valuable tool in a variety of collaboration scenarios. Group navigation prevents users from losing each other in the virtual environment and avoids the allocation of attentive resources for executing travel by each group member. These advantages are especially pronounced in scenarios with an asymmetric knowledge distribution between the navigator and passengers like in our expert review of *Getting There Together* and guided tour settings as in *Group Navigation for Guided Tours*. In particular, novice users of virtual reality systems especially benefit from group navigation by not having to learn the operation of a single-user navigation technique. On the other hand, users who are unfamiliar with the virtual environment mostly benefit from the provided assistance in terms of wayfinding.

Individual virtual navigation capabilities are more suitable for scenarios with only loose collaboration among participants, where staying together is less relevant or even not desired. These particularly include parallelizable tasks like the naïve search for specific target items scattered across the virtual environment [84, 85] or design flaws in urban planning [47, 48]. While individual virtual navigation immediately leads to spatial desynchronization in collocated setups, prior work provided several approaches to at least mitigate the resulting side effects by displaying additional warning geometries [101] or redirecting users around each other [6]. In general, however, the possibility to avoid spatial desynchronization completely makes group navigation techniques a particularly viable solution for collocated setups, where individual navigation capabilities for loose collaboration can still be provided by additional viewing windows if they are required [98, 99].

Finally, our expert review in *Getting There Together* also revealed interesting strategies for cooperative task solving based on combinations of both individual and group navigation, which is in line with the observed phases of loose and tight collaboration in other forms of multi-user tasks in the literature (e.g. [50, 78, 80]). As a result, we concluded that systems should offer both navigation paradigms and allow for fluent transitions between phases of individual navigation for loose and group navigation for tight collaboration.

Future Work

Future work should study appropriate ways of supporting phases of loose collaboration in which group members are located at different places in the virtual environment. The work of Dodds and Ruddle in the realm of desktop-based collaborative virtual environments, for example, already provided interesting approaches in this regard, ranging from visual highlights of other group members over portals showing the views of others up to instantaneous travel options for subsequent tightly-coupled activities [47, 48]. With respect to the discussed transitions between individual and group navigation techniques, these and similar features would fill the gap between *Adjourning* and *(Re-)Forming*, regarding which participants in our expert review of *Getting There Together* still had to verbally agree on where to meet for subsequent group navigation. However, some of the presented approaches from desktop-based systems do not seem to be directly applicable to immersive virtual reality, which motivates the study of suitable adaptations and alternatives for these setups.

With respect to fostering tight collaboration, the work presented in this thesis was motivated by the overarching idea of assisting groups with getting to new destinations together. While we have contrasted fully-individual navigation techniques as known from single-user systems to fully-coupled group navigation techniques that move all group members simultaneously, these two mark the extreme points of a continuum with several potential design options in between to be explored further in future work. Starting from individual navigation, for example, several visual enhancements like breadcrumbs or beacons could help group members to locate and follow the guide. Starting from fully-coupled group navigation techniques, on the other hand, less rigid approaches could only apply passive virtual movements to assist participants with catching up if a guide accidentally went too far away from the group. The systematic exploration, comparison, and evaluation of these and other approaches remains an important aspect for future research.

7.5 Concluding Remarks

The increasing affordability of head-mounted displays as well as the ubiquitous availability and variety of software systems for immersive collaboration are making multi-user virtual reality accessible to a fast-growing audience. Among a large variety of potential use cases, some experts even predict a shift from conventional social networking applications to *virtual reality social networks*, in which a large fraction of the population will participate to meet and interact with each other in immersive virtual reality [128]. The development and study of multi-user interactions in virtual environments is therefore a vibrant area of research, to which this thesis makes the following major contributions:

- the framing of group navigation as a specific instance of Tuckman's model of small-group development
- the derivation of central requirements for effective group navigation techniques beyond common quality factors known from single-user navigation
- the introduction of virtual formation adjustments during group navigation and their integration into concrete group navigation techniques
- evidence that appropriate pre-travel information and virtual formation adjustments lead to more efficient travel sequences for groups and lower workloads for both navigators and passengers

While this work has begun to explore the extensive field of group navigation, there are still many exciting challenges ahead, including the exploration of steering-based group navigation, the investigation of the effects of group navigation on passengers' spatial cognition, the development of algorithms for maintaining social sub-group formations during group navigation with virtual formation adjustments, and the design of effective group navigation techniques for larger audiences.

In summary, the results of this thesis suggest that group navigation techniques are a valuable addition to the portfolio of interaction techniques in multi-user virtual reality and provide effective guidance for application developers as well as inform future research in this area. We believe that effective and efficient group navigation techniques will eventually become a ubiquitous standard in collaborative virtual environments.

A

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