Semi-Automated Guided Teleportation through Immersive Virtual Environments

Tim Weissker
RWTH Aachen University
Aachen, Germany
me@tim-weissker.de

Marius Meier-Krueger
RWTH Aachen University
Aachen, Germany
marius.meier-krueger@rwth-aachen.de

Pauline Bimberg
Trier University
Trier, Germany
bimberg@uni-trier.de

Robert W. Lindeman
University of Canterbury
Christchurch, New Zealand
rob.lindeman@canterbury.ac.nz

Torsten W. Kuhlen
RWTH Aachen University
Aachen, Germany
kuhlen@vr.rwth-aachen.de

Figure 1: We present a semi-automated teleportation technique that guides the user along a pre-defined path. *Left:* When the next teleportation target is outside of the user's view, fireflies appear to passively guide their gaze in the correct direction. *Center:* A teleportation point is visualized as a wireframe sphere. When the user looks at it, a yellow inner sphere grows continuously until its size matches the wireframe before raising the teleportation point to the user's eye height. *Right:* Once raised, this activation process is repeated before the user is teleported to the position indicated by the sphere.

ABSTRACT

Immersive knowledge spaces like museums or cultural sites are often explored by traversing pre-defined paths that are curated to unfold a specific educational narrative. To support this type of guided exploration in VR, we present a semi-automated, hands-free path traversal technique based on teleportation that features a slow-paced interaction workflow targeted at fostering knowledge acquisition and maintaining spatial awareness. In an empirical user study with 34 participants, we evaluated two variations of our technique, differing in the presence or absence of intermediate teleportation points between the main points of interest along the route. While visiting additional intermediate points was objectively less efficient, our results indicate significant benefits of this approach regarding the user's spatial awareness and perception of interface dependability. However, the user's perception of flow, presence, attractiveness, perspicuity, and stimulation did not differ significantly. The overall positive reception of our approach encourages further research into semi-automated locomotion based on teleportation and provides initial insights into the design space of successful techniques in this domain.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Interaction design**.

KEYWORDS

Virtual Reality, 3D User Interfaces, 3D Navigation, Head-Mounted Display, Teleportation, Guided Navigation, Guided Tour

ACM Reference Format:

Tim Weissker, Marius Meier-Krueger, Pauline Bimberg, Robert W. Lindeman, and Torsten W. Kuhlen. 2024. Semi-Automated Guided Teleportation through Immersive Virtual Environments. In *30th ACM Symposium on Virtual Reality Software and Technology (VRST '24), October 9–11, 2024, Trier, Germany*. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3641825.3687724

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than the author(s) must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

VRST '24, October 9–11, 2024, Trier, Germany

© 2024 Copyright held by the owner/author(s). Publication rights licensed to ACM.

ACM ISBN 979-8-4007-0535-9/24/10
https://doi.org/10.1145/3641825.3687724

1 INTRODUCTION

The increasing affordability of virtual reality (VR) hardware motivates the creation of large and feature-rich virtual environments to enable users to experience places that are remote, dangerous, or even impossible to reach. The resulting opportunities are particularly interesting for knowledge spaces like museums and historical or cultural sites, which could enrich their content with artifacts that are not available physically, attract visitors by offering novel immersive on-site experiences previously unknown to them, and make their entire exhibition available to a wider online audience [12, 54]. Navigating through these spaces in VR is different from the real world, since physical locomotion is limited by the available tracking space of the VR headset, so virtual locomotion methods like steering or teleportation [6, 44] are often offered by the system. While using these techniques and maintaining spatial awareness in the virtual environment under limited field-of-view conditions might be intuitive for tech-savvy users, they might present a challenge for inexperienced users and, as a result, negatively impact their experience.

Motivated by improving the accessibility of virtual navigation in immersive knowledge spaces, we review the prior literature on guidance techniques that assist users to complete locomotion and wayfinding tasks in VR. Based on the idea that guided tours through museums often follow specifically curated paths to visit points of interest (POIs) in a narrative order, we put a particular focus on assistive locomotion techniques that move users (semi-)automatically along pre-defined paths. We find that prior techniques almost exclusively rely on *continuous locomotion*, which has been shown to have a high risk of inducing cybersickness (e.g., [9, 15, 67]). To circumvent this issue, we propose a novel semi-automated, hands-free path traversal technique based on teleportation. Our technique subtly guides the user's attention towards the next teleportation point in the sequence and requires them to look at it for a specified amount of time in a lower and then elevated state before triggering the user's relocation (Figure 1). In an empirical user study with 34 participants, we evaluate two variations of our technique which differ in the presence or absence of intermediate waypoints between the POIs along the route.

Our empirical comparison of these two variations is motivated by the research question of how much traversing the actual route between POIs impacts the user experience of our guided teleportation technique. As teleportation inhibits the perception and acquisition of spatial information between the origin and the target position, adjusting the spacing of points in a sequence allows putting more or less emphasis on the route that the user traverses between POIs. The most efficient variation is to teleport directly from POI to POI (*Direct* condition in our study). However, we hypothesized that reducing this level of efficiency by visiting intermediate teleportation points (*Route* condition in our study) can, for example, help reduce momentary disorientation, increase presence, provide better spatial awareness, and therefore lead to a more pleasant experience for users. The results of our study partly confirm these assumptions, leading to the following scientific contributions of our work:

- The motivation and design of a semi-automated, hands-free guided teleportation technique that enables users to teleport along a series of pre-defined waypoints by only focusing on head orientation data
- The results of an empirical user study with 34 participants showing that …
  - …the addition of intermediate waypoints between the main exhibits of the traversed path reduces spatial disorientation, increases dependability ratings, and therefore results in higher user preference while, contrary to expectations, having no significant effect on perceived flow, presence, attractiveness, perspicuity, and stimulation
  - …experiencing tours with our guided teleportation technique and intermediate waypoints resulted in low sickness and an overall positive user experience, as evidenced by *excellent* UEQ ratings in terms of perspicuity and dependability, *good* ratings in terms of attractiveness, and *above-average* ratings in terms of stimulation and novelty when compared to established benchmark datasets

Our results encourage further research into automated and semi-automated locomotion based on teleportation and provide initial insights into the design space and requirements of successful techniques in this domain.

2 RELATED WORK

The work presented in this paper is inspired by a combination of prior research on techniques for locomotion guidance as well as hands-free teleportation in immersive virtual environments.

2.1 Locomotion Guidance in VR

In this paper, we classify techniques that guide the user's locomotion in virtual environments as *guidance cues* or *movement assistance. Guidance cues* leave the user in full control of their virtual viewpoint and merely support their decision-making of how to get to one of the potential next destinations. *Movement assistance*, on the other hand, constrains or even fully takes over the user's locomotion controls to guide them around the scene in a semi-automated or automated fashion.

Guidance Cues. Locomotion guidance can be achieved by deliberate architectural [61] or environmental [39] designs that facilitate wayfinding. While these design principles can also be applied to virtual environments, the fact that the system constantly keeps track of the user's current position and orientation in the environment offers the additional opportunity to display dynamically updating 3D widgets like arrows, maps, and trails to point towards the next target [21, 30, 35]. These visual helpers can also be placed by another user on demand to enable more situation-aware guidance than the system itself can offer [40, 42]. However, widgets can easily occlude relevant parts of the scene and require the user to focus parts of their attentional resources on their interpretation rather than the actual content. As a result, prior work also investigated more embedded forms of visual guidance such as the playback of a spatial recording in which another user interacts with the environment [14, 60] or the use of intelligent virtual agents that are programmed to guide the user through the virtual environment [4, 41]. In our work, we make use of guidance cues only to indicate how the user should rotate to face the correct direction, which is a mechanism often employed in cinematic virtual reality (see [51] for a survey).

Movement Assistance. Movement assistance techniques in the literature differ in the degree to which the user's movements are induced or influenced by the system. The most basic approach in this regard is to leave the user in control of when they want to locomote but to constrain their movements to different guiding geometries [25], such as a line to reach a specific target or a surface to prevent them from moving below the ground plane. If teleportation is used as the main locomotion method, the set of admissible target points can be constrained to achieve similar effects. Habgood et al. [24] found that this approach was especially appreciated by novice users in comparison to unconstrained teleportation as it reduced the complexity of the interface. In contrast, automated approaches take full control of the user's virtual movements and move them along a previously defined path [50] or towards objects that are deemed interesting to look at based on a certain heuristic [1]. In multi-user settings, the virtual movements of all members of a group may also be controlled by an expert user to ensure that the group stays together and that the required attentional resources of the passengers are minimized [13, 62, 65]. However, for both system automation and expert leadership, losing control over their own virtual locomotion might be too invasive for certain users and use cases. For example, Li et al. compared automatic to unconstrained user-initiated steering in a virtual museum setting and found that most users preferred the exploratory freedom that active movement controls provided them with [37]. Semi-automated techniques balance the degree of system automation and the degree of user involvement during locomotion. The guided locomotion technique of Freitag et al. [20], for example, only controls the speed of steering based on the computed viewpoint quality of the user's current position. In the realm of immersive storytelling, Galyean [23] proposed using the analogy of a boat on a river, where the user is automatically moved along a pre-defined path (the river) by the system but has some individual freedom to temporarily steer to the sides in order to inspect nearby objects. However, prior work in the meantime has repeatedly shown that continuous locomotion likely increases the risk of cybersickness compared to discontinuous locomotion like teleportation (e.g., [9, 15, 46, 67]). As a result, inspired by the river analogy, our work in this paper focuses on the design and evaluation of a semi-automated guidance technique based on teleportation. To further increase the accessibility of our technique especially for novices, we decided to put a particular focus on controller-free input channels, which will be discussed in the next section.

2.2 Hands-Free Teleportation

Teleportation has become a widely popular locomotion technique in VR [44], and various implementations have been proposed that enable the user to manipulate different degrees of freedom during the process [3, 22, 63, 64]. While most prior techniques are operated with the handheld controllers that ship with modern VR headsets, a few researchers argue against the use of controllers for locomotion, as prolonged 3D interaction might lead to increased arm fatigue [38], free-hand interaction might be considered more natural and intuitive [8, 52], and handheld controllers might have to be kept free for other interaction techniques beyond locomotion [59], such as picking up or carrying virtual objects or firing virtual weapons.

Teleportation techniques consist of mechanisms for *target specification*, *pre-travel information*, the *transition*, and *post-travel feedback* [67], out of which the task of target specification is typically the only component to involve user input. Being a selection task, target specification can be further decomposed into the *indication* of a position and possibly orientation, followed by a corresponding *confirmation*, along with feedback [34, ch. 7]. Beyond controllers, prior work has proposed mechanisms for indication and confirmation based on hand-tracking [11, 52, 55], voice commands [10, 26], and eye-tracking [45, 47]. However, limitations of these approaches include that hand-tracking does not circumvent the issue of potential arm fatigue after prolonged interaction [11], that voice interaction can be considered uncomfortable when bystanders are around [48, 57], and that eye-tracking typically requires calibration and can be unstable due to involuntary eye movements [45]. More advanced mechanisms, like tracking the user's feet for indication and confirmation [58, 59], or employing mouth gestures [45] and specific EEG signals [27] for confirmation, share some of these drawbacks and require the presence of additional hardware. To circumvent these limitations, our work focuses on a simplified version of eye-tracking, in which the orientation of the VR headset is taken as an approximation of the user's gaze direction for teleportation target indication, and directional dwell is used for confirmation. This combination has already been successfully used for the unguided selection of teleportation targets, for example, as part of the jumper metaphor introduced by Bolte et al. [5]. When directly compared to conventional controller selection for teleportation, Kruse et al. [31] found a trade-off between controller selection being faster and head-dwell selection being more accurate as users took more care in performing their teleports. A similar trade-off was also observed in a more generic selection task by Esteves et al. [18], where button- and dwell-based confirmation mechanisms were generally more successful than gesture- and speech-based alternatives, but showed individual advantages in terms of efficiency and accuracy, respectively.

3 TECHNIQUE DESIGN

In contrast to exploratory scenarios where users are encouraged to get a general overview of the virtual environment, curated experiences like applications focused on storytelling, field trips, or guided tours require the user to visit a particular set of landmarks in a particular order to allow the narrative to unfold. While live tour guides in multi-user VR systems are particularly well-suited for such user guidance [2, 65], these experts might not always be available at a given time. Given that immersive knowledge spaces should be accessible to a broader audience with various technical backgrounds, employing automated or semi-automated locomotion is especially appealing as (1) they ensure that all POIs will be visited in the intended order, and (2) users can focus their attention more on the content rather than the locomotion technique. To make use of this potential, we present a novel semi-automated locomotion guidance technique that leads the user along a pre-defined route. As the reason for participating in guided tours is often to explore the environment along the route rather than traversing the route as fast as possible, our technique employs a slow-paced navigation workflow that we based on the following four design requirements:

- D_1 The technique should make use of teleportation instead of continuous virtual locomotion to reduce the risk of cybersickness for the user.
- D_2 The technique should only use the movement data of the user's VR headset so that the hands are free as input without having to engage with controllers.
- D_3 The technique should provide a relaxed and slow-paced navigation workflow suited for guided tours, allowing users some freedom for individual exploration.
- D_4 The technique should provide sufficient pre-travel information to increase the comprehensibility of the teleportation process (cf. [66]) and, therefore, to reduce spatial disorientation.

Similar to the river analogy introduced by Galyean [23], our proposed locomotion guidance is semi-automated in that the user is constrained to only teleport to the pre-defined points along the path, but has the individual freedom to look around and explore the immediate surroundings at each point by physical locomotion. In contrast to the river analogy, however, the user has to actively confirm when they want to proceed to the next teleportation point. As part of our design process, one aspect that we were uncertain about was the relevance of intermediate teleportation points along the route between the main POIs. In particular, we believe that adding these intermediate points might be beneficial for reducing spatial disorientation and increasing presence by preventing sudden long-distance teleportations. To investigate this hypothesis further in our user study, we present two variations of our technique called *Route*, which includes intermediate points, and *Direct*, which teleports the user directly from one POI to the next along the path.

3.1 Creation of Teleportation Points

The main prerequisite for our technique is a curated path that the user is intended to follow in the virtual environment. In the first step, this path has to be dissected into a discrete set of teleportation points that the user will visit in sequence (D_1). In the *Direct* variant of our technique, this set is simply given by the main POIs along the path that the user is intended to visit. For the *Route* variant of our technique, the addition of intermediate points can be performed either manually by the curator or automatically by finding the shortest collision-free path between POIs and subdividing it into teleportation points based on heuristics. While a generic algorithm that performs well in arbitrary scenes is still subject to future work, we suggest placing teleportation points at corners or other sharp turns of the path, as well as enforcing a maximum distance between teleportation points, both to ensure direct and clear visibility of the next teleportation point from the previous one, increasing comprehension (D_4). As one example of this, our *Route* variant operates by placing a new teleportation point when the accumulated turning angle since the last teleportation point exceeds a threshold of 45° and subdivides the resulting segments into multiple equally spaced teleportations to ensure that no individual teleportation point is more than $10m$ away from the previous one. This value was selected based on the literature on unconstrained teleportation,

Figure 2: When the next teleportation point is occluded by other objects, as may be the case with the *Direct* variation of our technique, we suggest rendering it on top of the occluder and highlighting it in a distinctive color (here: yellow).

where authors often report maximum distances between $6m$ and $10m$ for target selection [22, 36, 52].

3.2 Visual Guidance for Out-of-View Targets

Once a set of teleportation points has been created by the application developer, each of these points is visualized to the VR user by a wireframe sphere on the floor of the virtual environment (Figure 1, center). There are two types of situations in which the next teleportation point might not be visible to the user from the previous one. When teleportation is triggered in these situations, the user does not have a chance to predict the upcoming location change and, therefore, has a high risk of becoming spatially disoriented. To prevent this from happening (D_4), our technique employs two visual guidance mechanisms.

First, in the *Direct* variant of our technique, the next teleportation point might be far away and/or occluded by other objects in the scene like walls. In these cases, we suggest using a specific shader for the wireframe sphere that always renders it on top of occluding scene objects (Figure 2). Additionally, spheres further away from the user can be scaled up to increase their saliency.

Second, in both variants of our technique, the user might look in a different direction than towards the next teleportation point, requiring additional visual mediation to help them turn in the correct direction. While there is a multitude of options on how to realize guidance towards targets outside the user's field of view [51], we decided to use a particle system resembling fireflies that appear in front of the user and flock toward the next teleportation point when it is not directly visible (Figure 1, left). This idea was inspired by the work of Lange et al. [32], who showed that a similar form of scene-embedded guidance was beneficial for maintaining high levels of presence compared to more artificial alternatives like widgets and post-processing filters in image space.

3.3 Confirmation of the Intent to Teleport

Once the next teleportation point along the route is visible to the user, our technique features a dwell-based confirmation mechanism to indicate their desire to teleport (D_2 and D_3). To prevent accidental teleportations that might easily lead to spatial disorientation, we use a two-step activation pattern before actually relocating the user (D_3 and D_4). Our choice of a wireframe sphere to visualize teleportation points was motivated by (1) reducing occlusions during inactivity and (2) being able to visualize dwell feedback directly in-place during interaction. In particular, our activation pattern works as follows. In the first step, the user is required to direct their head to face the wireframe sphere on the floor for a duration of t_1, which is visualized using a growing yellow sphere within the wireframe (Figure 1, center). Visual highlights of an object as a feedback mechanism during dwelling were already evaluated positively in the work on decision-making in interactive storytelling by Drewes et al. [17]. After t_1, the size of the inner sphere matches the size of the wireframe. This is when the second step activates, in which the wireframe sphere is raised to the user's eye level to function as a preview geometry for the user's new head location to improve predictability of the imminent teleportation (Figure 1, right). If the user continues to look at the wireframe sphere for a duration of t_2, which is once again visualized by a growing yellow sphere within the wireframe, the teleport is executed. We decided to keep the user's global viewing orientation unchanged during the transition, given that including virtual rotation changes in the teleportation process have been shown to likely increase the risk of spatial disorientation due to the resulting visual discontinuity [7, 28, 46].

To determine whether the user is looking in the direction of the wireframe sphere, we suggest a conic activation volume starting from the user's head position with fixed horizontal and vertical opening angles of α_h and α_v, respectively, depending on the desired sensitivity. In our user study, for example, we set $\alpha_h = 10°$ and $\alpha_v = 12.5°$ to allow for a little more tolerance in the vertical direction to reduce potential neck strain. Furthermore, we set $t_1 = t_2 = 2s$, which is intentionally longer than the commonly observed dwell times of $< 1s$ in the literature on object selection [43]. Since the resulting operation in our case is a complete relocation of the user's virtual viewing position instead of the selection of an object, we aimed for higher dwell times to give users sufficient time to perceive the provided teleportation preview and, therefore, reduce the risk of spatial disorientation after the relocation.

3.4 Discussion of Interaction Design

While several prior locomotion-interface research papers pursue the objective of increasing navigation efficiency by reducing the time required to get from one location to another [55, 59, 63, 64], we argue that knowledge acquisition scenarios like guided museum tours and cultural heritage site visits benefit from a more pleasant and unhurried user experience in which more emphasis is placed on the journey rather than its completion (D_3). Therefore, while dwell times as a confirmation mechanism are often criticized in the literature for decreasing efficiency [31, 45], we believe that they are a promising interaction paradigm in slower-paced scenarios, especially since they are particularly easy to learn for novices and do not rely on additional input devices or trackers other than the VR headset itself (D_2). Moreover, requiring the user to spend some time looking at the available preview geometries before each teleportation allows them to mentally prepare for the transition, which we envision reduces spatial confusion once the transition is executed and, therefore, fosters the *comprehensibility* (cf. [66]) of the teleportation process (D_4). Therefore, we believe that further studies are required to explore the influences of alternative confirmation mechanisms like deliberate activation movements (e.g., [31]). While comprehensibility is further supported by the decision to keep the user's global viewing orientation unchanged during the transition, this also requires the selection and implementation of an additional mechanism for physical rotation guidance. While we decided on the scene-embedded option of a directed particle system, this option might not be suited for all use cases, but it can be easily replaced by one of the alternatives mentioned in the survey by Rothe et al. [51].

4 USER STUDY

We conducted an empirical user study to assess the general usability of our guided teleportation technique and to address our research question of how much traversing the route between the main POIs impacts user experience. The independent variable of the study was the technique variation, and participants tested both the *Direct* and *Route* variations as part of a within-subjects design.

4.1 Hardware and Physical Setup

Participants were equipped with an *HTC Vive Pro 2* headset that was tracked by four base stations placed around a square interaction space of approximately 2.5m x 2.5m. The headset was connected to a workstation featuring an *Intel i9-10900K* processor and a *Nvidia RTX 3080 Ti* graphics card. The VR application for the study was created with *Unreal Engine* (version 5.3) and rendered with a resolution of 2448 x 2448 pixels per eye and a framerate of 90Hz.

4.2 Environment and Task

Our study featured the scenario of visiting a cultural heritage site that informed visitors about the housing conditions of a wealthy merchant in the Middle Ages. For this purpose, we created a fictional medieval homestead using a low-poly asset pack from Unreal Engine's marketplace[1]. The homestead was divided into multiple connected areas that were set up in a symmetric fashion to allow for the creation of two comparable paths (Figure 3) for the two technique variations tested in this study. From the common starting point in the entrance corridor of the homestead, both paths featured three main points of interest that were distributed across the estate in both indoor and outdoor areas.

Participants were only given instructions to take part in two guided tours, one with each variation of our guided teleportation technique, and to report on their experiences afterwards. To create an informative scenario with more background information than the virtual objects alone, each of the three POIs per path featured an audio snippet that told a story about the different aspects of living in the Middle Ages. These audio snippets were created using

[1] https://www.unrealengine.com/marketplace/en-US/product/low-poly-medieval-interior-and-constructions

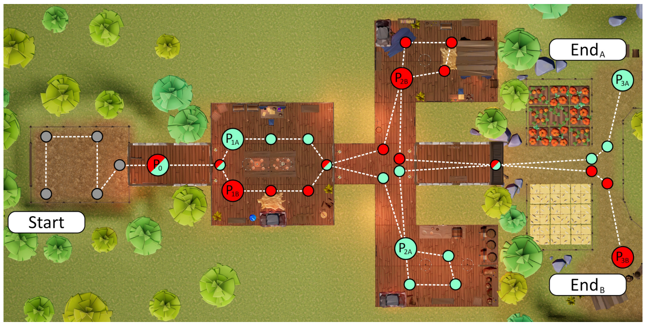

Figure 3: Overview of the virtual environment and routes to be traversed in our user study. Each larger circle labeled P_{xy} indicates one of the main POIs while smaller circles indicate the intermediate waypoints only present in the *Route* condition. Both routes (red and cyan) were set up symmetrically to create comparable experiences in both conditions. Before each route, participants completed a small tutorial route (grey waypoints) to get accustomed to the teleportation interface of the current condition.

a free text-to-speech AI model[2]. Activating the next teleportation point was disabled for the duration of the playback to prevent the participant from having to split their attention between locomotion and information acquisition.

4.3 Experimental Procedure

Participants arrived at our lab and signed an informed consent form. In the interest of counterbalancing the order of the two tested techniques, as well as the two paths to be traversed through the homestead, participants were then assigned to one of the four possible combinations based on their identification number. The experimenter then familiarized them with the VR headset and demonstrated its adjustment (straps, interpupillary distance knob, display distance knob) which participants could then use until it fit comfortably. Afterwards, they were placed into a small garden area in front of the homestead's entrance, during which an automated tutorial using the same voice as the main guided tours explained the different features of our guided teleportation technique to them. In the *Direct* condition, this tutorial also included a teleportation point that was occluded by another object to demonstrate the shader that renders the corresponding wireframe sphere on top of the occluder (Figure 2). Once the tutorial was completed, participants found themselves in the entrance corridor of the homestead, where the main guided tour began. After completing this tour, participants were asked to take off the VR headset and complete a questionnaire on a desktop workstation, which consisted of (in this order):

- The Fast Motion Sickness Scale (FMS) by Keshavarz and Hecht [29] to quantify the occurrence of sickness with a single question
- The User Experience Questionnaire (UEQ) by Laugwitz et al. [33] to quantify perceived attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty
- The igroup Presence Questionnaire (IPQ) based on the work of Schubert et al. [53] (revised version available online[3]) to quantify general presence, spatial presence, involvement, and experienced realism
- The English version of the Flow Short Scale (FSS) by Rheinberg [49] to quantify the perceived feeling of flow as the sum of task fluency and absorption
- Three custom questions to quantify spatial awareness and disorientation on a Likert scale:
  - Confusion: *How often were you confused by your view after a teleportation?* (1: never, 7: after every teleportation)
  - Awareness: *I was always fully aware of my virtual surroundings.* (1: fully disagree, 7: fully agree)
  - Anticipation: *I always knew where the tour guide would bring me to.* (1: never, 7: at every point in time)

Once the questionnaires were completed, participants were given a five to ten minute break before continuing with the second run of the study, in which the other technique variation was tested in combination with the other path. After filling in the technique-related questionnaires for the second time, participants were given a final questionnaire, in which they provided a preference ranking of both technique variations as well as general feedback on the study. The entire procedure took between 45 and 60 minutes to complete.

4.4 Dependent Variables and Hypotheses

The dependent variables of this user study were the subjective experience ratings from the questionnaires. These questionnaires were selected as established measures of user experience from the literature, for which we either hypothesized a difference between the two technique variations or aimed to obtain an absolute measure to quantify the general suitability of the techniques. Beyond that, interaction data from the session were only logged to ensure the validity of the experiment. As a prerequisite for conducting the inferential statistical tests, we formulated a total of five hypotheses before the experiment regarding the comparison of the *Direct* and *Route* variations of our technique:

H_1 Spatial awareness will be higher for *Route*.
H_2 FSS scores will be higher for *Route*.
H_3 IPQ scores will be higher for *Route*.
H_4 UEQ scores for *Attractiveness*, *Perspicuity*, *Dependability*, and *Stimulation* will be higher for *Route*.
H_5 UEQ scores for *Efficiency* will be higher for *Direct*.

Justification for the Hypotheses: We expected the addition of intermediate teleportation points to reduce spatial disorientation after teleportation, as each teleportation point would be in a direct line of sight from the previous one (H_1). As a consequence, we expected that participants would also rate their perception of flow (H_2) and presence (H_3) higher as they would be less frequently interrupted by having to reorient themselves. Finally, we expected that this difference would also be reflected in more general ratings of user experience as given by the UEQ, making *Route* more attractive, perspicuous, dependable, and stimulating to use than *Direct* (H_4). However, given that the addition of intermediate teleportation

[2]https://www.naturalreaders.com/online/

[3]https://www.igroup.org/pq/ipq

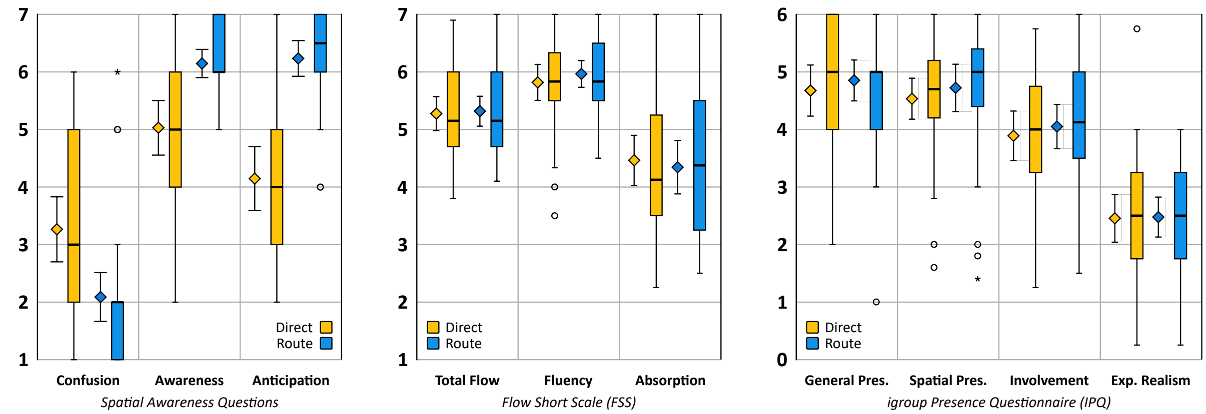

Figure 4: Boxplots illustrating the distributions of measured scores given by our three custom questions on spatial awareness (left), the Flow Short Scale (center), and the igroup Presence Questionnaire (right). The diamond next to each box indicates the mean value, with bars showing the corresponding 95% confidence interval.

points might also slow down the progress of the tour, we expected *Route* to be perceived as less efficient (H_5). No hypotheses were formulated for the FMS and the *Novelty* scale of the UEQ, as we did not expect a difference between the two technique variations based on their common reliance on teleportation-based movements and their common interaction workflow, respectively.

4.5 Participants

We followed the strategy of *convenience sampling* to recruit a total of 34 participants between 20 and 63 years of age ($M = 28.4$, $\sigma = 8.86$). Given that novice users might react differently to immersive content compared to experienced users, as outlined by Steed et al. [56], we put a particular focus on obtaining a participant sample that was spread across various levels of immersive competence to receive a mixture of both novice and expert feedback. In particular, 10 participants stated to have used VR *never* or only *once before*, 11 participants *several times before*, and 13 participants stated to be using VR *on a regular basis* or *every week*. Unfortunately, the sampling process led to a skewed gender distribution (25 male, 8 female, 1 unknown), which is a limitation of our work that we will discuss again at the end of the paper.

5 RESULTS

We evaluated our measurements with *IBM SPSS Statistics* based on our formulated hypotheses. Given our within-subjects study design involving two independent variables, the first relevant inferential test to consider for our analyses was the parametric paired-samples t-test, which requires a continuous scale of measurement, as well as an approximately normal sampling distribution. Based on our sample size of $N = 34 > 30$, we assumed a normal sampling distribution based on the central limit theorem [19, pp. 170-172] and switched to the non-parametric Wilcoxon signed-rank test for variables that were purely ordinal, i.e., raw, non-aggregated Likert scale results. To prevent an overreliance on p-values, we supplemented our results with the effect size d for t-tests and r for Wilcoxon signed-rank tests. We applied the threshold values introduced by Cohen [16] to classify these effects, with $d > 0.2, r > 0.1$ for a small effect, $d > 0.5, r > 0.3$ for a medium effect, and $d > 0.8, r > 0.5$ for a large effect.

5.1 Inferential Analyses

Spatial Awareness (H_1): Boxplots illustrating the distributions of scores are given in Figure 4 (left). A Wilcoxon signed-rank test revealed significantly lower spatial *Confusion* scores for *Route* over *Direct*, $z = 3.661$, $p < 0.001$, $r = 0.628$ (large effect). Similarly, the comparison of the data showed significantly higher spatial *Awareness* in the *Route* condition, $z = 3.902$, $p < 0.001$, $r = 0.669$ (large effect). This was also reflected in the results of the third question, where the comparison between both conditions also revealed significant advantages for *Route* regarding *Anticipation* of the next target, $z = 4.443$, $p < 0.001$, $r = 0.762$ (large effect).

Flow (H_2): Boxplots illustrating the distributions of scores are given in Figure 4 (center). As indicated by a paired-samples t-test, *Total* perception of flow measured by the FSS was not significantly different between both conditions, $t(33) = 0.435$, $p = 0.667$, $d = 0.075$ (negligible effect). The same was true for the two subscales of the FSS, where no significant difference in perceived *Fluency* with $t(33) = 1.189$, $p = 0.243$, $d = 0.204$ (small effect), as well as no significant difference in perceived *Absorption* with $t(33) = 1.222$, $p = 0.230$, $d = 0.210$ (small effect) could be observed.

Presence (H_3): Boxplots illustrating the distributions of presence scores are given in Figure 4 (right). A Wilcoxon signed-rank test did not detect a significant difference for the *General Presence* question of the IPQ, $z = 1.144$, $p = 0.253$, $r = 0.196$ (small effect). Further paired-samples t-tests on the aggregated subscales did also not reveal significant differences regarding the perceived *Spatial Presence*, $t(33) = 1.827$, $p = 0.077$, $d = 0.313$ (small effect), *Involvement*, $t(33) = 1.027$, $p = 0.312$, $d = 0.176$ (negligible effect), and *Experienced Realism*, $t(33) = 0.189$, $p = 0.851$, $d = 0.032$ (negligible effect).

User Experience (H_4, H_5): Figure 5 gives the results and boxplots of the UEQ, the exact numeric results of paired-samples t-tests conducted for each of the six subscales, and an absolute rating of

	Inferential Test			Benchmark	
	$t(33)$	p	d	*Direct*	*Route*
Attractiveness	1.256	0.218	0.215	abo. avg.	good
Perspicuity	1.741	0.091	0.299	excellent	excellent
Efficiency	0.550	0.586	0.094	bel. avg.	bel. avg.
Dependability	2.574	**0.015**	0.441	abo. avg.	excellent
Stimulation	0.645	0.523	0.111	abo. avg.	abo. avg.
Novelty	2.504	**0.017**	0.429	good	abo. avg.

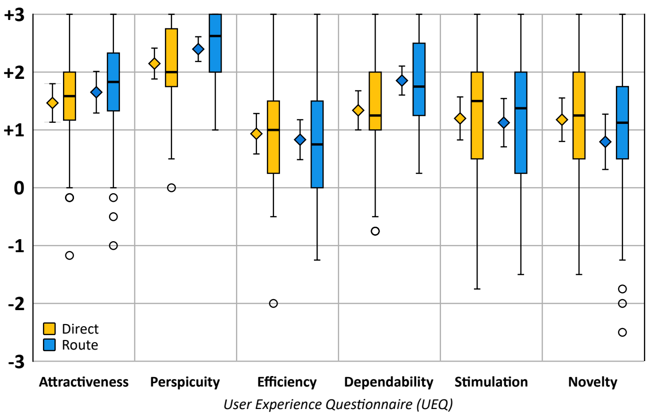

Figure 5: *Top:* Results of the inferential tests conducted on the six subscales of the User Experience Questionnaire (UEQ) and absolute classification of results in both conditions using the provided benchmark dataset (excellent, good, above average, below average, bad). *Bottom:* Boxplots illustrating the underlying distributions of scores in both conditions. The diamond next to each box indicates the mean value, with bars showing the corresponding 95% confidence intervals.

both conditions based on the official benchmark dataset. Summarizing these results, there were two significant differences indicating advantages of *Route* in terms of *Dependability* (small effect) and advantages of *Direct* in terms of *Novelty* (small effect). Non-significant small effects were further observed for *Attractiveness* and *Perspicuity*, indicating an advantageous tendency for the *Route* condition. Compared to the benchmark dataset, both *Direct* and *Route* received identical ratings for *Perspicuity* (excellent), *Efficiency* (below average), and *Stimulation* (above average). *Route* received a better absolute rating for *Attractiveness* (1-step increase) and *Dependability* (2-step increase) while receiving a poorer rating for *Novelty* (1-step decrease).

5.2 Descriptive Analyses

Tour Duration: The average time to complete the guided tour was $219.97s$ ($\sigma = 52.68s$) in the *Direct* condition and $268.97s$ ($\sigma = 48.57s$) in the *Route* condition.

Sickness: The FMS measures sickness on a Likert scale from 0 (no sickness) to 20 (frank sickness). In our study, the reported scores were overall low, with a mode score of 1 for both the *Direct* (41.2%) and the *Route* (50.0%) condition. The mean scores were 2.35 (95% CI: $[1.71, 3.00]$) for *Direct* and 2.47 (95% CI: $[1.61, 3.33]$) for *Route*, indicating similar levels of sickness in both conditions. The highest score measured during the study was a single occurrence of 11 in the *Route* condition. None of the participants decided to terminate the experiment early based on their sickness levels.

Preference: When asked for their preferred technique variation, a majority of 21 participants (61.8%) mentioned *Route* while 9 participants (26.5%) preferred the *Direct* variation. The remaining 4 participants (11.8%) did not voice a preference.

5.3 Discussion and Limitations

Our descriptive analyses of FMS scores indicated an overall low incidence of cybersickness in both conditions, which we expected based on our focus on discontinuous movements for both the *Direct* and the *Route* variation. As a result of these low scores, we conclude that our participants were in good shape to judge our techniques in the subsequent questionnaires. Regarding our hypotheses, we identified significant large effects (all $r > 0.6$) pointing towards higher spatial awareness in the *Route* than the *Direct* condition, thereby confirming H_1. This result indicates a trade-off between *Travel Efficiency* and *Spatial Disorientation*, where the less efficient addition of intermediate waypoints between the main points of interest can help create a less disorienting user experience. Contrary to H_2 and H_3, however, these advantages in terms of spatial awareness did not seem to have strongly influenced the perception of *Flow* and *Presence*. When looking at the corresponding subscales, the largest observed effect size was $d = 0.313$ for *Spatial Presence* in favor of *Route*, which did, however, not achieve statistical significance. Given that participants were teleported to completely different surroundings with the *Direct* technique, we were surprised by the high scores of *Direct* regarding general and spatial presence. Subjective comments regarding our two-step activation pattern and visualizations of dwell times were generally positive, so it might be that our preview mechanisms, in combination with the overall slow-paced interaction workflow, were sufficient to maintain a certain degree of presence that did not differ from the one offered by teleportation points in the participant's vicinity. As a result, **we advocate for more detailed future research on the influence of different kinds of target indication mechanisms and pre-travel information on presence and flow.**

Regarding the influences of our technique variations on more general facets of user experience as measured by the UEQ, our results only partially support H_4. While there was a significant small positive effect for *Route* regarding *Dependability* ($d = 0.441$), only small but non-significant effects were observed for *Attractiveness* and *Perspicuity* (both $d < 0.3$). Our results did not confirm H_5, as neither a significant difference nor a non-negligible effect size was observed on the efficiency scale. While the absence of a significant result does not automatically indicate that no effect exists at all, we were surprised that we could not capture it with the UEQ, given that our objective observations indicated more efficient tour completion times as well as fewer teleports with the *Direct* technique. A likely explanation for this is given by the comparison of the efficiency scale to the benchmark dataset, where both technique variations equally received *below average* ratings. We explain this by the overall slow-paced workflow of the task, which likely overshadowed the efficiency differences between both conditions. From the subjective statements, the most common point of criticism related to the chosen dwell duration of $t_1 = t_2 = 2s$, which was sometimes considered too high. Since we could not identify personal factors influencing this opinion (e.g., prior VR exposure), we argue that the dwell duration should likely be exposed as an adjustable parameter in the future. The remaining scales of the UEQ all yielded *above average*, *good*, and *excellent* ratings for both conditions, with minor advantages of *Route* for attractiveness and dependability and a minor advantage of *Direct* for novelty. Overall, a majority of participants (61.8%) stated to prefer *Route* over *Direct*. As a result, we conclude that **our guided teleportation technique was generally well-received and would advise using the *Direct* variation only when optimizing specifically for locomotion efficiency or for feelings of novelty**.

Limitations. While we strived for a mixture of participants with different prior exposure to VR systems, one of the most notable limitations of our sampling process is the resulting over-representation of male participants (see Section 4.5). Furthermore, as illustrated in Section 3.4, our final technique design represents just one of several potential alternatives regarding possible visualizations, confirmation mechanisms, and attention-guiding features. Finally, our user study featured only a single scenario with routes that could be completed in less than five minutes each. While all of these factors influence the final results, we believe that our main findings regarding the advantages of *Route* over *Direct* as well as the overall positive user experience of our technique stand up to further scrutiny. Therefore, we explicitly encourage other researchers to replicate and extend our work to gain further insights into the design of effective guidance techniques in immersive virtual environments.

6 CONCLUSION

We presented a semi-automated guidance technique based on teleportation that enables curators of immersive knowledge spaces to prepare accessible guided tours for audiences with different technical backgrounds. We focused on a slow-paced interaction workflow that keeps the user's hands free and gives them sufficient time to prepare for a teleport. Based on prior research, we believe that this interaction paradigm reduces the risk of cybersickness compared to continuous locomotion techniques while attempting to address the prevalent concerns regarding spatial disorientation after teleportation. In an empirical user study, we asked the research question of how much traversing the actual route between POIs impacts the user experience and compared the use of our technique with (*Route* condition) and without (*Direct* condition) intermediate waypoints. Our results indicate a generally positive reception of our interaction workflow, with the predominantly preferred *Route* variation (placing teleportation points at sharp corners and maximally $10m$ apart from each other) significantly reducing spatial disorientation and increasing perceived dependability. Therefore, we generally advise including intermediate waypoints and ensuring that the next waypoint is always in direct line of sight from the previous one. However, omitting intermediate waypoints did not lead to as many negative effects as expected, given that no significant differences in perceived flow, presence, attractiveness, perspicuity, and stimulation were observed. As a result, the *Direct* variation might be an option to consider in scenarios for which visiting intermediate waypoints is considered too exhausting, for example, when distances between POIs are large.

Future work should evaluate alternative mechanisms for realizing guided teleportation, including the choice of shorter dwell times, as well as non-dwell-based confirmation gestures. In addition, evaluating different forms of attention-guiding techniques when the next teleportation point is outside the user's field of view is an interesting focus of further studies. Furthermore, deriving a more formal algorithm for automatically placing suitable intermediate waypoints based on the particulars of the virtual environment is still subject to future work, as our initial heuristics presented in this paper were not comprehensively evaluated in a multitude of different environmental contexts. Future work also includes the identification of threshold values with respect to what users consider *too few* or *too many* teleportation points along a route. Finally, while our focus on teleportation-based movements was motivated by the literature on cybersickness, our guided teleportation techniques should be compared to the established steering-based counterparts to gain further insights into the benefits and drawbacks of each paradigm. We believe that further research in this domain is necessary to increase the accessibility of virtual reality systems for novices and, therefore, enable virtual knowledge spaces like museums to reach a broader and more diverse audience.

ACKNOWLEDGMENTS

This work has received funding from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under grant *528403131* (Project "Put me There").

REFERENCES

[1] Steffi Beckhaus, Felix Ritter, and Thomas Strothotte. 2001. Guided Exploration with Dynamic Potential Fields: the Cubical Path System. *Computer Graphics Forum* 20, 4 (2001), 201–211. https://doi.org/10.1111/1467-8659.00549

[2] Katie Best. 2012. Making museum tours better: understanding what a guided tour really is and what a tour guide really does. *Museum Management and Curatorship* 27, 1 (2012), 35–52. https://doi.org/10.1080/09647775.2012.644695

[3] Pauline Bimberg, Tim Weissker, Alexander Kulik, and Bernd Froehlich. 2021. Virtual Rotations for Maneuvering in Immersive Virtual Environments. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology (VRST '21)*. Association for Computing Machinery, New York, NY, USA, Article 21, 10 pages. https://doi.org/10.1145/3489849.3489893

[4] Andrea Boensch, Jonathan Ehret, Daniel Rupp, and Torsten W. Kuhlen. 2024. Wayfinding in immersive virtual environments as social activity supported by virtual agents. *Frontiers in Virtual Reality* 4 (2024), 1–21. https://doi.org/10.3389/frvir.2023.1334795

[5] Benjamin Bolte, Frank Steinicke, and Gerd Bruder. 2011. The Jumper Metaphor: An Effective Navigation Technique for Immersive Display Setups. In *Proceedings of Virtual Reality International Conference*. Laval Virtual, Laval, France, 1–7.

[6] Doug A Bowman, Ernst Kruijff, Joseph J LaViola, and Ivan Poupyrev. 2001. An Introduction to 3-D User Interface Design. *Presence* 10, 1 (2001), 96–108.

[7] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. Association for Computing Machinery, New York, NY, USA, 205–216. https://doi.org/10.1145/2967934.2968105

[8] Gavin Buckingham. 2021. Hand Tracking for Immersive Virtual Reality: Opportunities and Challenges. *Frontiers in Virtual Reality* 2 (2021), 6 pages. https://doi.org/10.3389/frvir.2021.728461

[9] Fabio Buttussi and Luca Chittaro. 2019. Locomotion in Place in Virtual Reality: A Comparative Evaluation of Joystick, Teleport, and Leaning. *IEEE Transactions on Visualization and Computer Graphics* 27, 1 (2019), 125–136. https://doi.org/10.1109/TVCG.2019.2928304

[10] Davide Calandra, Filippo Gabriele Pratticò, and Fabrizio Lamberti. 2022. Comparison of Hands-Free Speech-Based Navigation Techniques for Virtual Reality Training. In *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*. IEEE, USA, 85–90. https://doi.org/10.1109/MELECON53508.2022.9842994

[11] Jorge C. S. Cardoso. 2016. Comparison of Gesture, Gamepad, and Gaze-based Locomotion for VR Worlds. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*. Association for Computing Machinery, New York, NY, USA, 319–320. https://doi.org/10.1145/2993369.2996327

[12] Marcello Carrozzino and Massimo Bergamasco. 2010. Beyond virtual museums: Experiencing immersive virtual reality in real museums. *Journal of Cultural Heritage* 11, 4 (2010), 452–458. https://doi.org/10.1016/j.culher.2010.04.001

[13] Vuthea Chheang, Florian Heinrich, Fabian Joeres, Patrick Saalfeld, Roghayeh Barmaki, Bernhard Preim, and Christian Hansen. 2022. WiM-Based Group Navigation for Collaborative Virtual Reality. In *2022 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, USA, 82–92. https://doi.org/10.1109/AIVR56993.2022.00018

[14] Kevin Chow, Caitlin Coyiuto, Cuong Nguyen, and Dongwook Yoon. 2019. Challenges and Design Considerations for Multimodal Asynchronous Collaboration in VR. *Proceedings of the ACM on Human-Computer Interaction* 3, CSCW, Article 40 (2019), 24 pages. https://doi.org/10.1145/3359142

[15] Chris G. Christou and Poppy Aristidou. 2017. Steering versus Teleport Locomotion for Head Mounted Displays. In *Augmented Reality, Virtual Reality, and Computer Graphics*, Lucio Tommaso De Paolis, Patrick Bourdot, and Antonio Mongelli (Eds.). Springer, Cham, Switzerland, 431–446. https://doi.org/10.1007/978-3-319-60928-7_37

[16] Jacob Cohen. 1992. A Power Primer. *Psychological Bulletin* 112, 1 (1992), 155–159. https://doi.org/10.1037/0033-2909.112.1.155

[17] Heiko Drewes, Evelyn Müller, Sylvia Rothe, and Heinrich Hussmann. 2021. Gaze-Based Interaction for Interactive Storytelling in VR. In *Augmented Reality, Virtual Reality, and Computer Graphics*, Lucio Tommaso De Paolis, Pasquale Arpaia, and Patrick Bourdot (Eds.). Springer International Publishing, Cham, 91–108. https://doi.org/10.1007/978-3-030-87595-4_8

[18] Augusto Esteves, Yonghwan Shin, and Ian Oakley. 2020. Comparing selection mechanisms for gaze input techniques in head-mounted displays. *International Journal of Human-Computer Studies* 139 (2020), 102414. https://doi.org/10.1016/j.ijhcs.2020.102414

[19] Andy Field. 2013. *Discovering Statistics Using IBM SPSS Statistics*. Sage Publications, Thousand Oaks, CA, USA.

[20] Sebastian Freitag, Benjamin Weyers, and Torsten W. Kuhlen. 2016. Automatic Speed Adjustment for Travel through Immersive Virtual Environments based on Viewpoint Quality. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, USA, 67–70. https://doi.org/10.1109/3DUI.2016.7460033

[21] Sebastian Freitag, Benjamin Weyers, and Torsten W. Kuhlen. 2018. Interactive Exploration Assistance for Immersive Virtual Environments Based on Object Visibility and Viewpoint Quality. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 355–362. https://doi.org/10.1109/VR.2018.8447553

[22] Markus Funk, Florian Müller, Marco Fendrich, Megan Shene, Moritz Kolvenbach, Niclas Dobbertin, Sebastian Günther, and Max Mühlhäuser. 2019. Assessing the Accuracy of Point & Teleport Locomotion with Orientation Indication for Virtual Reality using Curved Trajectories. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300377

[23] Tinsley A. Galyean. 1995. Guided Navigation of Virtual Environments. In *Proceedings of the 1995 Symposium on Interactive 3D Graphics* (Monterey, California, USA) *(I3D '95)*. Association for Computing Machinery, New York, NY, USA, 103–104. https://doi.org/10.1145/199404.199421

[24] Jacob M. P. Habgood, David Moore, David Wilson, and Sergio Alapont. 2018. Rapid, Continuous Movement Between Nodes as an Accessible Virtual Reality Locomotion Technique. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 371–378. https://doi.org/10.1109/VR.2018.8446130

[25] Andrew J. Hanson and Eric A. Wernert. 1998. Constrained Navigation in Immersive Virtual Reality. In *Proceedings of IEEE VRAIS 1998*. Indiana University, Bloomington, IN, USA, 6 pages.

[26] Jan Hombeck, Henrik Voigt, Timo Heggemann, Rabi R. Datta, and Kai Lawonn. 2023. Tell Me Where To Go: Voice-Controlled Hands-Free Locomotion for Virtual Reality Systems. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 123–134. https://doi.org/10.1109/VR55154.2023.00028

[27] Dooyoung Kim Jinwook Kim, Hyunyoung Jang and Jeongmi Lee. 2023. Exploration of the Virtual Reality Teleportation Methods Using Hand-Tracking, Eye-Tracking, and EEG. *International Journal of Human–Computer Interaction* 39, 20 (2023), 4112–4125. https://doi.org/10.1080/10447318.2022.2109248

[28] Jonathan W. Kelly, Alec G. Ostrander, Alex F. Lim, Lucia A. Cherep, and Stephen B. Gilbert. 2020. Teleporting through virtual environments: Effects of path scale and environment scale on spatial updating. *IEEE Transactions on Visualization and Computer Graphics* 26, 5 (2020), 1841–1850. https://doi.org/10.1109/TVCG.2020.2973051

[29] Behrang Keshavarz and Heiko Hecht. 2011. Validating an Efficient Method to Quantify Motion Sickness. *Human Factors* 53, 4 (2011), 415–426. https://doi.org/10.1177/0018720811403736

[30] Matthias Kraus, Hanna Schäfer, Philipp Meschenmoser, Daniel Schweitzer, Daniel A. Keim, Michael Sedlmair, and Johannes Fuchs. 2020. A Comparative Study of Orientation Support Tools in Virtual Reality Environments with Virtual Teleportation. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, USA, 227–238. https://doi.org/10.1109/ISMAR50242.2020.00046

[31] Lucie Kruse, Sungchul Jung, Richard Li, and Robert Lindeman. 2020. On the Use of Jumping Gestures for Immersive Teleportation in VR. In *ICAT-EGVE 2020 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*, Ferran Argelaguet, Ryan McMahan, and Maki Sugimoto (Eds.). The Eurographics Association, Eindhoven, The Netherlands, 113–120. https://doi.org/10.2312/egve.20201265

[32] Daniel Lange, Tim Claudius Stratmann, Uwe Gruenefeld, and Susanne Boll. 2020. HiveFive: Immersion Preserving Attention Guidance in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376803

[33] Bettina Laugwitz, Theo Held, and Martin Schrepp. 2008. Construction and Evaluation of a User Experience Questionnaire. In *HCI and Usability for Education and Work*, Andreas Holzinger (Ed.). Springer, Berlin, Heidelberg, 63–76.

[34] Joseph J. LaViola Jr, Ernst Kruijff, Ryan P. McMahan, Doug Bowman, and Ivan P. Poupyrev. 2017. *3D User Interfaces: Theory and Practice*. Addison-Wesley Professional, Glenview, IL, USA.

[35] Jaewook Lee, Fanjie Jin, Younsoo Kim, and David Lindlbauer. 2022. User Preference for Navigation Instructions in Mixed Reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 802–811. https://doi.org/10.1109/VR51125.2022.00102

[36] Nianlong Li, Zhengquan Zhang, Can Liu, Zengyao Yang, Yinan Fu, Feng Tian, Teng Han, and Mingming Fan. 2021. VMirror: Enhancing the Interaction with Occluded or Distant Objects in VR with Virtual Mirrors. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Article 132, 11 pages. https://doi.org/10.1145/3411764.3445537

[37] Yue Li, Paul Tennent, and Sue Cobb. 2019. Appropriate Control Methods for Mobile Virtual Exhibitions. In *First International Conference on VR Technologies in Cultural Heritage*. Springer, Cham, 165–183.

[38] Xiaolong Lou, Xiangdong Li, Preben Hansen, and Zhipeng Feng. 2020. An Empirical Evaluation on Arm Fatigue in Free Hand Interaction and Guidelines for Designing Natural User Interfaces in VR. In *Virtual, Augmented and Mixed Reality. Design and Interaction*, Jessie Y. C. Chen and Gino Fragomeni (Eds.). Springer International Publishing, Cham, 313–324. https://doi.org/10.1007/978-3-030-49695-1_21

[39] Kevin Lynch. 1964. *The Image of the City*. MIT Press, Cambridge, MA, USA.

[40] Marina L. Medeiros, Bettina Schlager, Katharina Krösl, and Anton Fuhrmann. 2022. The Potential of VR-based Tactical Resource Planning on Spatial Data. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 176–185. https://doi.org/10.1109/VR51125.2022.00036

[41] Anh Nguyen, Pascal Wüest, and Andreas Kunz. 2020. Human Following Behavior In Virtual Reality. In *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 57, 3 pages. https://doi.org/10.1145/3385956.3422099

[42] Thi Thuong Huyen Nguyen, Thierry Duval, and Cédric Fleury. 2013. Guiding Techniques for Collaborative Exploration in Multi-Scale Shared Virtual Environments. In *GRAPP International Conference on Computer Graphics Theory and Applications*. SCITEPRESS, Setúbal, Portugal, 327–336.

[43] Thammathip Piumsomboon, Gun Lee, Robert W. Lindeman, and Mark Billinghurst. 2017. Exploring Natural Eye-Gaze-Based Interaction for Immersive Virtual Reality. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, USA, 36–39. https://doi.org/10.1109/3DUI.2017.7893315

[44] Aniruddha Prithul, Isayas Berhe Adhanom, and Eelke Folmer. 2021. Teleportation in Virtual Reality; A Mini-Review. *Frontiers in Virtual Reality* 2 (2021), 7 pages. https://doi.org/10.3389/frvir.2021.730792

[45] Aniruddha Prithul, Jiwan Bhandari, Walker Spurgeon, and Eelke Folmer. 2022. Evaluation of Hands-free Teleportation in VR. In *Proceedings of the 2022 ACM Symposium on Spatial User Interaction (SUI '22)*. Association for Computing Machinery, New York, NY, USA, Article 5, 6 pages. https://doi.org/10.1145/3565970.3567683

[46] Kasra Rahimi, Colin Banigan, and Eric D. Ragan. 2020. Scene Transitions and Teleportation in Virtual Reality and the Implications for Spatial Awareness and Sickness. *IEEE Transactions on Visualization and Computer Graphics* 26, 6 (2020), 2273–2287. https://doi.org/10.1109/TVCG.2018.2884468

[47] Mikkel Rosholm Rebsdorf, Theo Khumsan, Jonas Valvik, Niels Christian Nilsson, and Ali Adjorlu. 2023. Blink Don't Wink: Exploring Blinks as Input for VR Games. In *Proceedings of the 2023 ACM Symposium on Spatial User Interaction* (Sydney,

NSW, Australia) *(SUI '23)*. Association for Computing Machinery, New York, NY, USA, Article 3, 8 pages. https://doi.org/10.1145/3607822.3614527
[48] Maximilian Rettinger, Christoph Schmaderer, and Gerhard Rigoll. 2022. Do You Notice Me? How Bystanders Affect the Cognitive Load in Virtual Reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 77–82. https://doi.org/10.1109/VR51125.2022.00025
[49] Falko Rheinberg. 2015. *Die Flow-Kurzskala (FKS) übersetzt in verschiedene Sprachen - The Flow-Short-Scale (FSS) translated into various languages*. Technical Report. ResearchGate. https://doi.org/10.13140/RG.2.1.4417.2243
[50] Timo Ropinski, Frank Steinicke, and Klaus Hinrichs. 2005. A Constrained Road-Based VR Navigation Technique for Travelling in 3D City Models. In *Proceedings of the 2005 International Conference on Augmented Tele-Existence* (Christchurch, New Zealand) *(ICAT '05)*. Association for Computing Machinery, New York, NY, USA, 228–235. https://doi.org/10.1145/1152399.1152441
[51] Sylvia Rothe, Daniel Buschek, and Heinrich Hußmann. 2019. Guidance in Cinematic Virtual Reality-Taxonomy, Research Status and Challenges. *Multimodal Technologies and Interaction* 3, 1 (2019), 23 pages. https://doi.org/10.3390/mti3010019
[52] Alexander Schaefer, Gerd Reis, and Didier Stricker. 2021. Controlling Teleportation-Based Locomotion in Virtual Reality with Hand Gestures: A Comparative Evaluation of Two-Handed and One-Handed Techniques. *Electronics* 10, 6 (2021), 21 pages. https://doi.org/10.3390/electronics10060715
[53] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments* 10, 3 (2001), 266–281. https://doi.org/10.1162/105474601300343603
[54] Werner Schweibenz. 2019. The virtual museum: an overview of its origins, concepts, and terminology. *The Museum Review* 4, 1 (2019), 1–29.
[55] Siddhanth Raja Sindhupathiraja, A K M Amanat Ullah, William Delamare, and Khalad Hasan. 2024. Exploring Bi-Manual Teleportation in Virtual Reality. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, USA, 754–764. https://doi.org/10.1109/VR58804.2024.00095
[56] Anthony Steed, Dan Archer, Lisa Izzouzi, Nels Numan, Kalila Shapiro, David Swapp, Dinah Lammiman, and Robert W. Lindeman. 2024. Immersive competence and immersive literacy: Exploring how users learn about immersive experiences. *Frontiers in Virtual Reality* 4, 1129242 (2024), 1–14. https://doi.org/10.3389/frvir.2023.1129242
[57] Kenji Tsukamoto, Tatsuo Nakajima, and Kota Gushima. 2021. Investigating a Method to Reduce Japanese People's Embarrassment in Using Voice Inputs. In *2021 IEEE 3rd Global Conference on Life Sciences and Technologies (LifeTech)*. IEEE, USA, 166–170. https://doi.org/10.1109/LifeTech52111.2021.9391937
[58] Julius von Willich, Martin Schmitz, Florian Müller, Daniel Schmitt, and Max Mühlhäuser. 2020. Podoportation: Foot-Based Locomotion in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376626
[59] Dayu Wan, Xiaolei Guo, Jiahui Dong, Christos Mousas, and Yingjie Chen. 2023. ManiLoco: A VR-Based Locomotion Method for Concurrent Object Manipulation. *Proceedings of the ACM on Computer Graphics and Interactive Techniques* 6, 1, Article 7 (may 2023), 20 pages. https://doi.org/10.1145/3585502
[60] Cheng Yao Wang, Mose Sakashita, Upol Ehsan, Jingjin Li, and Andrea Stevenson Won. 2020. Again, Together: Socially Reliving Virtual Reality Experiences When Separated. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA,) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376642
[61] Jerry Weisman. 1981. Evaluating Architectural Legibility: Way-Finding in the Built Environment. *Environment and Behavior* 13, 2 (1981), 189–204. https://doi.org/10.1177/0013916581132004
[62] Tim Weissker, Pauline Bimberg, and Bernd Froehlich. 2021. 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)*. IEEE, USA, 363–369. https://doi.org/10.1109/VRW52623.2021.00073
[63] Tim Weissker, Pauline Bimberg, Aalok Shashidhar Gokhale, Torsten Kuhlen, and Bernd Froehlich. 2023. Gaining the High Ground: Teleportation to Mid-Air Targets in Immersive Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2467–2477. https://doi.org/10.1109/TVCG.2023.3247114
[64] Tim Weissker, Matthis Franzgrote, and Torsten Kuhlen. 2024. Try This for Size: Multi-Scale Teleportation in Immersive Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 30, 5 (2024), 2298–2308. https://doi.org/10.1109/TVCG.2024.3372043
[65] Tim Weissker and Bernd Froehlich. 2021. Group Navigation for Guided Tours in Distributed Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 27, 5 (2021), 2524–2534. https://doi.org/10.1109/TVCG.2021.3067756
[66] Tim Weissker, Alexander Kulik, and Bernd Froehlich. 2019. 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)*. IEEE, USA, 136–144. https://doi.org/10.1109/VR.2019.8797807
[67] Tim Weissker, Andre Kunert, Bernd Froehlich, and Alexander Kulik. 2018. 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)*. IEEE, USA, 97–104. https://doi.org/10.1109/VR.2018.8446620

Received 17 June 2024; revised 12 August 2024; accepted 16 August 2024