Try This for Size: Multi-Scale Teleportation in Immersive Virtual Reality

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Fig. 1: We present three novel teleportation-based travel techniques that enable users to adjust their scale in the virtual environment, thereby affecting their modeled eye distance and height. In our *Simultaneous* technique shown in this picture, the user adjusts the scale of a preview avatar while selecting its new horizontal position with a parabolic selection ray known from same-scale teleportation techniques. Upon confirmation, the user is instantaneously teleported to the indicated position and scale.

Abstract— The ability of a user to adjust their own scale while traveling through virtual environments enables them to inspect tiny features being ant-sized and to gain an overview of the surroundings as a giant. While prior work has almost exclusively focused on steering-based interfaces for multi-scale travel, we present three novel teleportation-based techniques that avoid continuous motion flow to reduce the risk of cybersickness. Our approaches build on the extension of known teleportation workflows and suggest specifying scale adjustments either simultaneously with, as a connected second step after, or separately from the user's new horizontal position. The results of a two-part user study with 30 participants indicate that the simultaneous and connected specification paradigms are both suitable candidates for effective and comfortable multi-scale teleportation with nuanced individual benefits. Scale specification as a separate mode, on the other hand, was considered less beneficial. We compare our findings to prior research and publish the executable of our user study to facilitate replication and further analyses.

Index Terms—Virtual Reality, 3D User Interfaces, 3D Navigation, Head-Mounted Display, Teleportation, Multi-Scale

1 Introduction

Travel is an essential form of interaction in immersive virtual environments that allows the user to explore an environment from various viewing perspectives. While most travel interfaces are restricted to the six degrees of freedom given by the user's position and orientation, a less commonly investigated seventh parameter is the user's scale relative to the virtual environment, which can generate the impression of miniaturized or gigantic surroundings by adjusting the modeled eye distance and user height. Prior work has shown that such scale adjustments can be beneficial for inspecting features of different spatial extent (e.g., [10, 23]), getting an overview of the environment (e.g., [29, 44]), enabling fast travel (e.g., [1, 24]), and supporting collaboration in multi-user contexts (e.g., [25, 55]). However, current realizations of multi-scale travel almost exclusively rely on continuous viewpoint transitions, thereby generating visual flow that is often associated with higher degrees of cybersickness compared to instantaneous changes (e.g., [12, 13, 21, 53]).

To overcome this issue, this paper introduces three novel multi-scale travel techniques based on short-distance teleportation (sometimes also referred to as *Point & Teleport* [8] or *Jumping* [53]). They were designed to seamlessly supplement established target specification workflows by considering the user's scale as an additional degree of freedom to be adjusted. In an empirical user study with 30 participants, we compared the use of these techniques in two different task settings and derived their advantages and disadvantages for traveling through virtual environments at different scales.

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Our work is motivated by prior research on the integration of rotation [6, 8, 17, 35, 41, 58] as well as elevation [33, 48] changes into the teleportation process. In particular, the work of Weissker et al. identified that specifying one of these additional parameters can be performed simultaneously with, as a connected second step after, or completely separate from the indicated horizontal position change [48]. As a first step to exploring the design space of multi-scale teleportation, our three techniques are derived from this tripartite division and focus on the controlled analysis of scale adjustments without introducing rotation or elevation changes beyond the modification of the user's height as a result of the scale operation. Based on this consideration, our main research question asked which of the three conceptual approaches is most effective, efficient, and user-friendly for specifying ground-based scale changes in immersive virtual environments. Our work presented in this paper makes the following scientific contributions to this question:

- The design of three teleportation-based multi-scale travel techniques based on prior research on the integration of virtual rotations and same-scale elevation changes
- Empirical insights into the effects of these techniques on travel effectiveness, efficiency, and user comfort as given by a user study with 30 participants in two different task settings
- A comparison of our findings to prior results on the integration of same-scale elevation changes into the teleportation process
- A standalone application of our user study allowing other researchers to directly replicate our experimental setup [50]

Our results encourage the combination of teleportation-based travel with scale adjustments for exploring virtual environments and provide a promising basis for future research on comfortable navigation across multiple scales.

2 Related Work

Our overview of related work begins with a summary of previous approaches to multi-scale navigation through virtual environments, which highlights an underrepresentation of research on teleportation-based interfaces in this domain (Section 2.1). We then review prior research on egocentric teleportation-based travel in immersive virtual reality and other degrees of freedom that have already been integrated into its target specification process (Section 2.2).

2.1 Multi-Scale Navigation

Use cases that benefit from the exploration of virtual environments across different scale levels have been proposed in various contexts, including astronomy [43], geography [10, 25, 34], biology [4, 23], architecture [3, 29], teleoperation [37], and storytelling [24, 32]. In 2D desktop-based systems, the same static visual impression of a virtual object can be obtained by either scaling or translation operations. The choice of an appropriate movement speed, however, differs based on the user's scale perception, which motivated several steering techniques to automatically infer suitable speed adjustments based on the immediate surroundings of the user [2, 34, 43, 46]. For stereoscopic displays, on the other hand, the modification of the user's scale relative to the virtual environment including the modeled eye distance can lead to the environment being perceived as either magnified (e.g., [4, 23]) or miniaturized (e.g., [1, 22, 24, 37]). This offers additional viewing impressions that cannot be produced by translation alone. Therefore, several prior publications suggested considering the user's scale (or the inverse scale of the environment) as a dynamic parameter of the main navigation interface or as part of a secondary view. In the following, these suggestions are summarized based on the main navigational goal they pursue.

2.1.1 Inspecting Features of Different Spatial Extent

Adjusting the user's scale relative to the environment facilitates the detailed inspection of features that would otherwise be too small or large to apprehend entirely. In the anatomic dataset of Kopper et al., for example, a magnifying glass was suggested to initiate automated continuous transitions between fixed scale levels to inspect an entire human down to the structure of individual cells [23]. This technique performed superior to a steering-based approach with automatic scale adjustments as well as manual scale adjustments by repeated button presses. Nonetheless, a drawback of the approach is its reliance on the developer's explicit prior definition of selectable regions of interest. As traveling across multiple scale levels can become disorienting for users, follow-up work by Bacim et al. in the same environment suggested the additional display of a flat hierarchical map as well as layered 3D miniature representations of the environment at different scale levels to improve spatial awareness [4]. The steering-based *GiAnt* technique by Argelaguet and Maignant automatically adjusts navigation speed and scale factor based on the distance to nearby objects and perceived optical flow, which was shown to be beneficial in providing a constant perceived navigation speed during multi-scale travel [3]. The works of Cho et al. proposed dedicated tracked "buttonball" input devices with uni- and bimanual mappings to adjust the user's scale continuously [10, 11]. While the results of the user studies showed that the proposed *Spindle+Wheel* mapping, a 3D adaptation of established 2D touchscreen gestures, was especially beneficial for multi-scale travel [11], the authors did not find systematic improvements with system-assisted over purely manual parameter adjustments [10].

Relation to Present Work In contrast to all of the presented prior approaches, our multi-scale teleportation techniques introduced in this paper deliberately avoid continuous movements, which is an approach that was previously shown to reduce cybersickness but not yet evaluated in the context of multi-scale navigation (see Section 2.2). Our techniques give users maximal navigational freedom by having them manually select their desired scale level. To facilitate spatial orientation, our work draws inspiration from the system of Bacim et al. [4] in that it also provides a miniature representation of the user's surroundings during multi-scale travel.

2.1.2 Getting an Overview and Enabling Fast Travel

Interacting with or within a miniaturized virtual environment often serves as an intermediate step to get an overview of the environment or to enable fast travel to faraway locations. The most prominent example in the field is the work of Stoakley et al., who proposed a handheld World-in-Miniature (WIM) to facilitate object selection and user navigation [44]. For a smooth navigational transition, the authors suggested increasing the scale of the WIM continuously until the user's view is inside of the placed avatar [36]. The *Step WIM* suggested by LaViola et al. is a top-down view of the environment projected under the user's feet, which enables them to physically walk to their intended destination on the WIM before the surroundings at 1:1 scale are updated accordingly [29]. A similar approach was pursued by the *GulliVR* technique of Krekhov et al., who proposed continuous switching between a normal and a giant representation of the user to balance high interaction fidelity and fast travel capabilities [24]. This approach was shown to increase presence while maintaining low sickness levels in comparison to a standard teleportation technique without scale changes. The work of Abtahi et al. further compared the walking experience as a scaled giant (*ground-based scaling*) to two alternatives, namely the relocation of the scaled user's eyes closer to the ground (*eye-level scaling*) and the application of movement gains without rescaling (*Seven League Boots*, see [20]) [1]. While the results indicated advantages and disadvantages of all three techniques, ground-based scaling was appreciated for its visual feedback that implicitly communicates the expected speed gain, its resulting sense of embodiment, and its accuracy even at high speed gains. Most recently, the work of Lee et al. studied different automatic transition animations from and to previously defined targets at different scale levels, which revealed advantages of active user control over the animation progress in terms of spatial awareness and learning [32].

Relation to Present Work Our multi-scale teleportation techniques presented in this paper are based on the ground-based scaling approach used by *GulliVR* [24] that adjusts both the height and the distance of the user's eyes. In contrast, however, our proposals enable the user to freely specify their scale level in any direction, which allows for overviews and fast travel as well as the detailed inspection of features that are smaller than human scale. Moreover, our techniques are not limited to fixed discrete scale levels.

2.1.3 Supporting Collaboration in Multi-User Environments

Independent of the specific navigation technique, the exploration of virtual environments by multiple users at different scale levels can offer additional benefits for collaborative work. Early research in desktop-based collaborative virtual environments by Zhang and Furnas, therefore, motivated the use of individual multi-scale navigation techniques on a per-user level and discussed the associated research challenges for social interactions across multiple scales [55, 56]. Le Chénéchal et al. later suggested an asymmetric system in which a giant user collaborates with an ant-sized user to ensure precise object manipulation [30]. The *SpaceTime* system by Xia et al. uses immersive hardware for all involved users to enable collaborative scene editing at different user scales [54]. For interacting in such environments, Langbehn et al. analyzed the notion of dominant scale, concluding that the scale level of a group of avatars is likely to be considered the reference for relative spatial judgements [27]. Kulik et al. proposed a multi-scale group navigation technique for inspecting petroglyphs on a 3D projection wall, which was controlled by a stationary steering device in front of the wall and allowed for adjustments of the pivot point via raycasting from a tracked controller [25]. Photoportals [26] as well as a 3D tabletop display gave the group additional scalable views onto the environment to facilitate collaboration.

Relation to Present Work While our multi-scale teleportation techniques presented in this paper are only evaluated with individual users, they complement the presented state-of-the-art on multi-user collaboration by proposing novel navigation paradigms that can be directly used by individuals in collaborative virtual environments. Further research is required to analyze the presented navigation paradigms as part of a group navigation technique that allows the navigator to adjust the position and scale of all group members at the same time (see [47]).

2.2 Egocentric Teleportation-Based Travel

Egocentric teleportation has become a prominent travel metaphor in immersive virtual environments, requiring the user to select a target in the currently visible part of the scene before an automatic relocation towards that target is executed [38]. While several prior research efforts confirmed that this form of travel leads to reductions in cybersickness compared to continuous motion techniques for many users (e.g., [12, 13, 21, 53]), a key challenge for any form of teleportation-based travel is to prevent the user from getting disoriented as they jump through the scene [5, 7, 39]. Therefore, teleportation techniques should be designed to be *comprehensible* by enhancing awareness and making the navigational consequences predictable to the user [52], which can be achieved by adding additional visual mediators like portals, preview avatars, and Worlds-in-Miniature before the teleport [6, 15, 42, 48, 57]. Beyond the position changes that can be specified by the selection tool, several research prototypes suggested the teleportation-based adjustment of other degrees of freedom as well. A prominent example in this regard is teleportation-based virtual rotation, which can be specified either simultaneously with [8, 9, 17], as a connected second step after [6, 35], or separately from [41, 58] position changes. Recent work by Weissker et al. applied this tripartite division to the design of teleportation techniques that enable the adjustment of user elevation above the ground plane [48]. While there is currently no technique based on egocentric teleportation that enables the adjustment of the user's scale relative to the environment, the closest work in this direction was provided by Lee et al., who suggested a mechanism to easily teleport through a planetary environment by automatically computing appropriate teleportation distances based on the intended direction of travel and the surroundings of the user [31].

Relation to Present Work Our multi-scale teleportation techniques in this paper close the current research gap of interfaces that enable users to adjust their scale level as part of the teleportation process. As changes in user scale also lead to adjustments of the simulated eye height, it is reasonable to motivate our technique designs based on the tripartite division introduced by Weissker et al. [48] in the context of single-scale elevation specification. Our results, therefore, enable direct comparisons and allow for the identification of similarities and differences between same-scale teleportation with elevation changes and true multi-scale teleportation.

3 Technique Design

We designed three novel multi-scale travel techniques that build upon the commonly seen egocentric short-distance teleportation metaphor and add scale as an additional adjustable parameter. Similar to earlier work on the specification of elevation changes [48], the main difference between the suggested techniques is the degree to which scale adjustments are integrated into the basic target specification process. While our implementations and evaluations are based on using a controller from the *HTC Vive* family, the required inputs were selected to be compatible with other commonly used motion controllers that offer a joystick instead of a round touchpad. In the following, we briefly summarize the basic teleportation features without scale adjustments shared by all three techniques (Section 3.1) and describe the provided pre-travel information displayed to the user when adjusting scale with either technique (Section 3.2). We then detail our scale specification approaches that are performed simultaneously with (Section 3.3), as a connected second step after (Section 3.4), and separately from (Section 3.5) this basic process. We then conclude with a brief discussion of all techniques that motivates the deeper analysis of the presented approaches in our user study (Section 3.6).

3.1 Regular Same-Scale Teleportation

A regular teleport can be initiated with the controller's trigger button. Once pressed, it activates a parabolic selection ray with a maximum reach of $25m \cdot s_c$, where s_c is the user's current scale that is $s_c = 1.0$ for normal scale, $s_c > 1.0$ when enlarged, and $s_c < 1.0$ when miniaturized. The user can then move the controller to specify their intended position where the ray intersects the scene. A preview avatar of the user is constantly updated to be displayed above the currently indicated position, which was already suggested in prior work to improve visual saliency, enhance predictability, and thus foster comprehensibility [48, 51, 57]. Once the user is satisfied with their selection, releasing the trigger executes an instantaneous relocation that leaves their virtual rotation unchanged. As a result, the user has to physically rotate their body to change orientation when desired. Pressing one of the grip buttons on either side of the controller cancels the target specification process without executing a teleport.

3.2 Pre-Travel Information for Scale Changes

While preview avatars were shown to be beneficial for supporting the predictability of same-scale teleports in prior work [6, 15, 48, 51, 57], we argue that building a mental model of the future surroundings gets increasingly difficult when scale changes are involved. For example, while looking downwards at an ant-sized preview avatar from a human-sized perspective communicates the imminent change in size, it does not reveal details about other minuscule objects that will surround the user once the teleport is executed. Therefore, to support the planning process for all three of our proposed techniques, we display a circular cutout from a World-in-Miniature (WIM) that shows a fixed-scale copy of the preview avatar at its center and updates the visible scene to communicate the immediate surroundings at the currently selected position and scale (see Figure 2). We attach this WIM cutout to the user's second controller in the non-dominant hand, allowing them to translate and rotate it for an improved perspective.

3.3 Scale Adjustments: Simultaneous

The *Simultaneous* technique enables the user to adjust the scale of the preview avatar in parallel to selecting its position (see Figure 1). This scale adjustment is performed using the touchpad of the controller, which is located on the opposite side of the trigger and can be easily operated at the same time. While the most straightforward mapping would take the absolute vertical touch coordinate between -1 and $+1$ and induce scale adjustments of the preview avatar in the corresponding

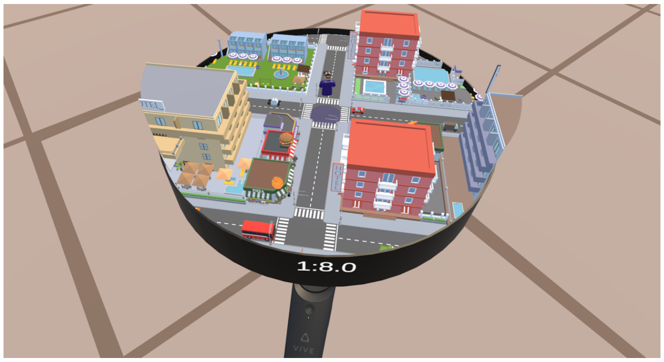


Fig. 2: When planning a teleport with scale changes, the new surroundings of the user are previewed by a circular cutout from a World-in-Miniature (WIM) attached to the user's controller in the non-dominant hand. The preview avatar has a fixed size, and the size of the surrounding objects adjusts based on the currently selected scale.

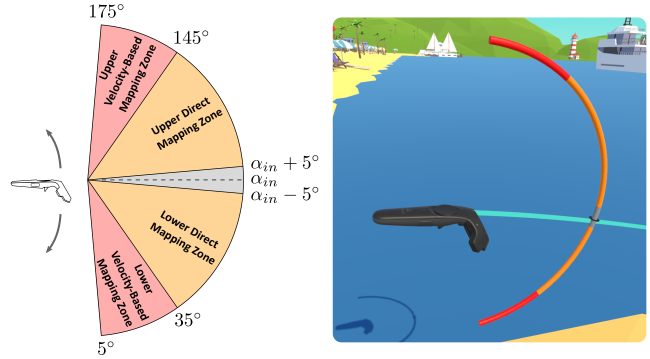


Fig. 3: The mapping of controller rotations to scale in the *Two-Step* technique is based on different zones around the initial pointing angle α_{in} at which the position is locked. Left: Exemplary illustration of zones with $\alpha_{in} = 90°$. Right: Corresponding visualization around the user's controller in the virtual environment for improved understandability.

direction and speed, a pilot run of our later presented study revealed that users had difficulties hitting the desired part of the touchpad without seeing their fingers in the virtual environment. Therefore, our proposed mapping allows users to touch down at any point and swipe up or down depending on the intended direction of scaling. The relative vertical distance to the initial touch point is then taken as the user's input i and mapped to the initial range of $[-1;+1]$.

Based on this input, the system continuously updates the scale of the preview avatar in every frame using a velocity-based transfer function. In contrast to the adjustment of other degrees of freedom in prior work like rotation or elevation, scaling follows a multiplicative instead of an additive logic with 1 instead of 0 as the neutral element. As a result, a scale difference of 0.5, for example, has vastly different consequences as an increase from 0.5 to 1.0 (doubling of the size) compared to an increase from 49.5 to 50.0 (minor increase in size). To allow for a smooth adjustment with the same perceived speed at different absolute scale values, the scale of the preview avatar in the current frame s_c is computed based on the scale factor of the last frame s_l, the user input $i \in [-1;+1]$, and the elapsed time between the last frame and the current frame Δt using the following formula:

$$s_c = s_l \cdot 2^{i \cdot \Delta t} \tag{1}$$

As a result, providing the maximum input of $+1$ or the minimum input of -1 for the duration of one second results in a doubling or halving of the scale, respectively. If desired, this adjustment speed can be varied by multiplying a global factor with the input i, which was, however, not done for the evaluations presented in this paper. By considering the elapsed time as part of the formula, this behavior is independent of the application's framerate. The selectable scale can be clamped to a convenient range depending on the use case, which includes a lower bound to avoid numeric instabilities and an upper bound to prevent the virtual environment from being too tiny to see. We also allow users to immediately reset the size of the preview avatar to 1:1 by pressing the touchpad button. When confirming the teleport by releasing the trigger, the user is teleported to match the specified position and scale of the preview avatar.

3.4 Scale Adjustments: Two-Step

The *Two-Step* technique starts with an unaltered same-scale selection of the target position using the parabolic selection ray. When the trigger is fully pressed by the user until it clicks, the specified position is locked in place, and the scale of the preview avatar can be adjusted by subsequent controller movements without requiring the additional use of the touchpad. Analogously to prior work on elevation specification [48], our mapping of controller movements to previewed scale is based on the controller's vertical pointing angle and consists of different zones around the initial pointing angle α_{in} (see Figure 3):

Deadzone First, a small deadzone within a range of $\alpha_{in} \pm 5°$ negates the influence of any minor movements that result from hand tremors or tracking instabilities.

Direct Mapping Zones Second, the deadzone is surrounded by two *direct mapping zones*, in which the controller's signed angular distance d to the deadzone in degrees directly defines the magnitude of the scale adjustment s_c to be applied to the preview avatar using the following formula:

$$s_c = 2^{0.1 \cdot d} \tag{2}$$

As a result, a pointing angle that is 10 degrees away from the deadzone leads to a doubling or halving of the preview avatar's scale depending on whether the user is pointing upwards or downwards relative to α_{in}. The factor of 0.1 multiplied with d was selected based on a pilot run of our later presented study, in which it was deemed to offer a good balance between reach and accuracy.

Velocity-Based Mapping Zones Third, absolute pointing angles greater than 145° and smaller than 35° fall into a *velocity-based mapping zone*, where the angular distance to the beginning of the zone defines the rate of a continuous in- or decrease of the preview avatar's scale. These zones extend up to 175° and down to 5°, beyond which inputs are discarded. The mapping of controller angle to velocity is governed by the formula introduced for the *Simultaneous* technique in Equation 1, with the difference that the user input i is now given by the normalized signed angular distance of the current pointing angle to the beginning of the velocity-based mapping zone. A pointing angle of 155°, for example, is $+10°$ inside of the upper zone, which leads to $i = \frac{10°}{175°-145°} = \frac{1}{3}$.

The addition of the velocity-based mapping zones enables the selection of a larger range of scales than extended direct mapping zones could provide and prevents the user from having to reach uncomfortable pointing angles above 175° and below 5°. Both zones can also be used in combination, where the velocity-based mapping zone brings the user to the approximate target range before they perform more fine-grained adjustments within this range using the direct mapping zones. To communicate to the user which zone they are currently operating in, a colored circular arc is displayed in front of the controller (see Figure 3), and changes from one zone into another are emphasized by controller vibration. Again, the touchpad button can be used to immediately set the size of the preview avatar to 1:1 (see Section 3.3).

3.5 Scale Adjustments: Separate

The *Separate* technique introduces a dedicated mode for scale adjustments that is independent of the specification of a new horizontal target position and, therefore, enables users to scale themselves on the spot.

This mode can be entered by pressing the menu button of the controller and only displays the WIM cutout as introduced in Section 3.2. The user can then adjust the scale of the WIM around the preview avatar using touchpad controls identical to the *Simultaneous* technique (Section 3.3) before pressing the trigger to execute the previewed adjustment. After that, same-scale teleports as described in Section 3.1 can be used to change the user's position. As with the other techniques, pressing the touchpad button during scale selection allows the user to immediately set the size of the preview avatar to 1:1.

3.6 Discussion

While the three presented techniques were inspired by prior work on same-scale teleports with elevation adjustments [48], multi-scale teleportation can lead to several unique situations that motivate a re-evaluation of previous findings in this new context. The *Simultaneous* approach, for example, was considered demanding but efficient for same-scale elevation changes, which might not replicate for multi-scale travel in situations where the target scale is smaller than the original scale. In this case, small hand movements already lead to large positional changes and thus impair the user's precision, potentially requiring them to perform correctional teleports more often. The *Separate* approach, on the other hand, was not appreciated for same-scale elevation changes due to the additional mode switch, which might be a less-pronounced concern for scale since it is a more distinct parameter that supplements the target position as opposed to elevation being an integral component of it. Finally, the *Two-Step* approach had high usability and induced low task load for same-scale elevation changes, but the zone-based transfer function was not yet evaluated for specifying a multiplicative parameter like scale as opposed to an additive parameter like elevation. Motivated by all of these considerations, we decided to run a user study to gain a better understanding of how the three proposed techniques for multi-scale teleportation are received by users and how these findings relate to prior results on same-scale elevation changes. This user study will be presented in the following.

4 Empiric Comparison of Scale Specification

To better understand the effectivity, efficiency, and usability of our three proposed multi-scale teleportation techniques, we conducted an empirical within-subject study in which participants evaluated the three approaches in two of the usage contexts presented in Section 2. In particular, the first part required participants to follow a pre-defined route across multiple scales to inspect features of different spatial extent as introduced in Section 2.1.1. In the subsequent second part, participants then searched for visually salient objects scattered across the environment, which required them to get an overview and perform fast travel as introduced in Section 2.1.2. As a result, the independent variables of this study were the travel technique (*Simultaneous*, *Two-Step*, or *Separate*) as well as the task (*Route Following* or *Search*).

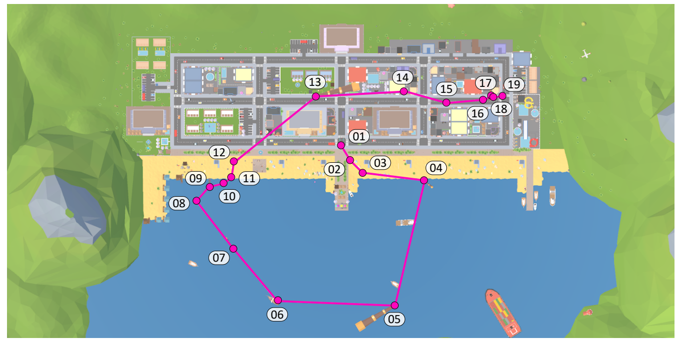
4.1 Experimental Setup

We placed tripod-mounted *HTC Vive* base stations 2.0 at three corners of a quadratic interaction space of 2m x 2m. A conventional desktop setup next to this space featured a workstation with an *NVIDIA Quadro RTX 4000* graphics card that drove an *HTC Vive Pro 2* head-mounted display. The virtual reality application was created with the *Unity* game engine and rendered the virtual environment at the native resolution (2448 x 2448 pixels per eye) and framerate (90 Hz) of the head-mounted display. Two *HTC Vive Controllers* were used for interacting with the application and operating our multi-scale travel techniques.

4.2 Experimental Tasks

We used the demo scene of the asset pack *Low Poly Tropical City* by *JustCreate* in the Unity Asset Store[1] and designed a route-following as well as a search task to be completed. Based on the characteristics of the environment, our techniques were clamped to a minimum scale of 1/40 and a maximum scale of 40.

[1] https://assetstore.unity.com/packages/3d/environments/urban/low-poly-tropical-city-226154



WP	01	02	03	04	05	06	07	08	09	10
Scale	1	1	2	8	32	1	8	2	1/8	2
Diff	-	0	+1	+2	+2	-5	+3	-2	-4	+4

WP	11	12	13	14	15	16	17	18	19
Scale	1/32	1	32	4	4	2	1/8	1/32	1
Diff	-6	+5	+5	-3	0	-1	-4	-2	+5

Fig. 4: Top: Horizontal path of the route to be traversed through the environment in the route-following task. Bottom: Overview of waypoints (WP) and their target scales (Scale) together with each exponential difference (Diff) to the previous waypoint.

4.2.1 Multi-Scale Route-Following Task

In the route-following task, participants were asked to navigate to a series of 19 pre-defined waypoints that were curated to offer interesting perspectives on the virtual environment at different scale levels. Each waypoint was marked by a virtual telescope whose size was adjusted to the desired target scale and whose vertical position above the ground was set based on the participant's calibrated eye level (see Section 4.3) to ensure that everybody could comfortably look through the telescope when standing in front of it at the correct scale level. To confirm the successful arrival at a waypoint, participants were asked to read out a letter that was visible when looking through the eyepiece of the telescope. Then, the next waypoint was activated by the experimenter. A semi-transparent red line in the virtual environment constantly guided participants to the next telescope.

We selected waypoints at fixed target scales given by the powers of 2 between $2^{-5} = 1/32$ and $2^5 = 32$ that required users to perform eight upward scalings, eight downward scalings, and two purely positional changes. The exact sequence of scale differences and the horizontal path of the route are shown in Figure 4. We decided to present the same route for all three tested travel techniques to offer participants a direct comparison of the three travel techniques and used counterbalancing to minimize the influence of learning effects.

4.2.2 Search Task

In the search task, participants were asked to find and move toward three ducks scattered across the virtual city. To improve their visual conspicuity from above, the ducks were situated below cyan-magenta striped umbrellas (see Figure 5) to afford the search strategy of scaling oneself up, looking for the umbrellas, moving there quickly, and then scaling oneself back down. Upon arriving at a duck, participants touched it with their controller to confirm its location, which gave it a small crown and changed the texture of the umbrella to prevent locating the same duck twice.

We designed a total of three task sets that each contained three ducks at distinct locations. As a result, each tested technique had a unique set of ducks to prevent memorization. However, to create comparable experiences, we split the virtual city into three latitudinal and three longitudinal regions and ensured that all task sets featured a single duck in each of these regions. An additional fourth duck was present at the common starting position of all task sets and triggered the activation of the task once touched.

4.3 Experimental Procedure

Participants were invited from the pool of students and academic staff at our institution as well as from their networks. When they arrived at our lab, they signed an informed consent form and were introduced to the head-mounted display and its adjustment options to ensure clear visibility (straps, display distance knob, eye distance knob). As a first task in virtual reality, participants adjusted the height of an exemplary virtual telescope, which was used to measure their eye height and to later place the telescopes of the route following task at a comfortable height to look through at their respective scale level.

Next, participants completed the route-following task described in Section 4.2.1 with each of our proposed multi-scale teleportation techniques. The order of technique presentation was counterbalanced, and all six possible combinations were covered in the study to eliminate potential order effects as much as possible. Each iteration started in a small tutorial scene, where the experimenter explained the main features of the current travel technique and asked participants to complete an unrecorded practice route of seven waypoints. After clarifying all remaining questions, participants were placed in the study environment and completed the main route. Once done, they took the head-mounted display off and completed a questionnaire consisting of:

- A one-item discomfort rating as introduced by Rebenitsch et al. to quantify overall user wellbeing: "On a scale from 0-10, 0 being how you felt coming in, 10 is that you want to stop, where are you now?" [40]
- The Raw TLX questionnaire as a simplified version of the NASA-TLX by Hart et al. to quantify task load [18, 19]
- Three custom questions on ease of learning, ease of use, and confusion
  - How difficult was it to learn the provided navigation technique? (1: very difficult, 7: very easy)
  - After the initial learning, how difficult was it to operate the provided navigation technique? (1: very difficult, 7: very easy)
  - How often were you confused about your view after a teleportation? (1: after every teleportation, 7: never)
- After seeing all three techniques, a ranking from best to worst

In the second part of the study, participants repeated this procedure with the search task described in Section 4.2.2 using the same order of techniques. The three different task sets were presented in the same order for all participants such that the counterbalancing of techniques ensured that there was no systematic correlation between technique and task set. Participants had the chance to re-familiarize themselves with each technique in the tutorial environment before they completed their search for the three ducks in the main study environment. After that, they completed a similar questionnaire to the one explained above, excluding the question on learning for this second encounter with each technique. Additionally, participants were asked to fill in a User Experience Questionnaire (UEQ) [28], in which they were asked to reflect upon their experiences with the techniques throughout the whole study. Finally, participants completed a concluding questionnaire on general demographic information before being rewarded with sweets for their participation. The entire procedure took between 60 and 90 minutes to complete.

4.4 Dependent Variables and Hypotheses

For each technique and task, our system logged all teleports, including their origin and target, the time required to specify each teleport, and the time required to complete each task. Moreover, the questionnaires yielded a discomfort score between 0 and 10, a task load score between 0 and 100, and an ease of learning, ease of use, and confusion score between 1 and 7. The UEQ conducted only once per technique resulted in scores between -3 and +3 for the six subscales representing attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. On the task level, the questionnaires further yielded a ranking of each technique between 1 and 3.

Fig. 5: In the search task, participants were asked to locate three ducks in the virtual environment, each hidden below a cyan-magenta striped umbrella. After touching a duck with the controller, the umbrella changed its texture to prevent locating the same duck twice.

Based on these dependent variables, we formulated hypotheses before running the experiment as a prerequisite for the conduction of inferential statistical tests. Since our three techniques were motivated by similar conceptual approaches in the context of same-scale teleportation with elevation changes presented in prior work [48], the results of earlier experiments could have served as the basis for directional hypotheses. However, based on our discussion in Section 3.6, the unique characteristics of scale adjustments might lead to novel and unexpected results that go beyond these predictions. To ensure that these unexpected effects can still be detected statistically, we decided to formulate undirected hypotheses and thus restrict ourselves to the less powerful two-tailed statistical tests. While this provides us with initial insights into differences in the use of the three multi-scale teleportation techniques, we explicitly encourage the reproduction of our study using directed hypotheses in future analyses.

First, we expected that the task completion time and the accumulated magnitude of scalings required in the more controlled and thus more comparable route-following task would give insights into the efficiency and accuracy of the three techniques. We further expected that these differences would also be reflected on a per-teleport level:

- The mean task completion time (H_1), mean accumulated magnitude of scalings (H_2), and mean specification time per teleport (H_3) in the route-following task will be different based on the used travel technique.

Second, we expected differences in task load based on the different interaction sequences required to operate our techniques, which we further expected to vary between both tasks as the route-following task required more accuracy. We also expected differences in usability ratings based on the users' overall judgment of the advantages and disadvantages of the techniques:

- The mean task load scores (H_4) will be different based on the used travel technique and the task.
- The mean scores of the UEQ subscales (H_5) will be different based on the used travel technique.

Third, we expected these overall usability differences to manifest themselves in the more precise questions on ease of learning, ease of use, and confusion:

- The mean ease of learning scores (H_6) will be different based on the used travel technique.
- The mean scores for ease of use (H_7), and confusion (H_8) will be different based on the used navigation technique and the task.

No hypothesis was formulated for the discomfort score, which we expected to be similarly low for all techniques due to their avoidance of continuous viewpoint movements of the user. As a result, we only performed a descriptive analysis of this variable.

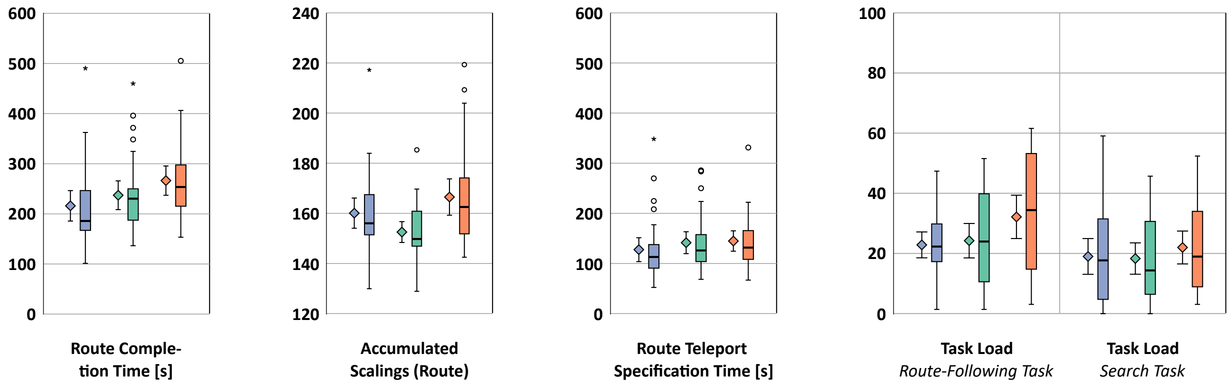


Fig. 6: Boxplots illustrating the distribution of task completion times, accumulated magnitudes of scalings, and summed teleport specification times in the route-following task as well as task loads in both tasks. Each box is complemented by a diamond representing the arithmetic mean with bars that indicate the corresponding 95% confidence interval. The colors represent *Simultaneous*, *Two-Step*, and *Separate*.

4.5 Participants

The user study was completed by 30 participants (19 male, 11 female) between 19 and 35 years of age ($M = 25.87$, $\sigma = 3.79$). While the self-reported prior experience with virtual reality spans the entire range from 1 to 4, the mean of $M = 3.13$ ($\sigma = 0.90$) indicates an overall advanced level that helps reduce a potential novelty bias in the sample and, thus, allows us to obtain sophisticated feedback on our techniques. In particular, thirteen participants identified as experts (4), nine participants as advanced users (3), seven participants as beginners (2), and one participant as novice (1).

5 Results

The evaluation of our obtained data was performed with *IBM SPSS Statistics* and guided by our formulated hypotheses. For hypotheses involving dependent variables that were captured for each technique in both the route-following and the search task, we conducted a 3x2 factorial repeated-measures ANOVA and report on the analysis of main as well as interaction effects of technique and task. These variables are marked with the icon to indicate their measurement after both tasks. For hypotheses involving dependent variables that were captured only for one task or as an overall measure, we conducted a one-way repeated-measures ANOVA and, therefore, only report on the main effect of the used technique. The icon marks these cases. We assumed a normal sampling distribution of our data based on our sample size of $N = 30$ in the context of the central limit theorem [16, pp. 170–172] and reported Greenhouse-Geisser corrected results when the requirement of sphericity was violated. Our data files are provided as supplemental material for additional clarity [49].

To prevent an overreliance on the interpretation of p-values criticized in the literature [45], we augmented our reports with the effect size η_p^2 and applied the threshold values of .01, .06, and .14 to identify small, medium, and large effects, respectively [14, pp. 285–287]. For post-hoc analyses, we solely relied on the interpretation of the effect sizes d to circumvent the risk of inflated error rates for repeated significance tests. The applied threshold values in this case were 0.2, 0.5, and 0.8 for small, medium, and large effects, respectively [14, pp. 24–26]. Our numeric reporting follows APA guidelines, particularly by dropping leading zeros for variables restricted to the range between 0 and 1.

5.1 Inferential Statistical Analyses

Boxplots illustrating the distribution of scores regarding the first four hypotheses are given in Figure 6 and complemented by inferential statistical tests in the following:

Route Completion Time (H_1) The time to complete the route-following task was significantly affected by technique, $F(2,58) = 11.302$, $p < .001$, $\eta_p^2 = .280$. Therefore, we accept H_1. Post-hoc comparisons indicated shorter completion times with *Simultaneous* compared to *Two-Step* ($d = 0.346$, small effect) and *Separate* ($d = 1.086$, large effect). Another small effect was observed regarding shorter completion times with *Two-Step* over *Separate* ($d = 0.446$).

Accumulated Scalings (H_2) The accumulated magnitude of scalings used to complete the route-following task was significantly affected by technique, $F(1.568, 45.486) = 7.142$, $p = .004$, $\eta_p^2 = .198$, Greenhouse-Geisser $\varepsilon = .784$. Therefore, we accept H_2. Post-hoc comparisons indicated a smaller magnitude for *Two-Step* compared to *Simultaneous* ($d = 0.481$, small effect) and *Separate* ($d = 0.564$, medium effect). Another small effect indicated a smaller magnitude required for *Simultaneous* over *Separate* ($d = 0.333$).

Specification Time (H_3) The total specification time for all teleports used to complete the route-following task was significantly affected by technique, $F(2,58) = 3.431$, $p = .039$, $\eta_p^2 = .106$. Therefore, we accept H_3. Post-hoc comparisons indicated shorter specification times with *Simultaneous* compared to *Two-Step* ($d = 0.346$, small effect) and *Separate* ($d = 0.511$, medium effect). The effect size for the comparison of *Two-Step* and *Separate* was below the threshold for a small effect ($d = 0.082$).

Task Load (H_4) The analysis of task load scores revealed a significant main effect of technique ($F(2,58) = 12.973$, $p < .001$, $\eta_p^2 = .309$), a significant main effect of task ($F(1,29) = 12.049$, $p = .002$, $\eta_p^2 = .294$), and a non-significant interaction effect between both factors ($F(2,58) = 2.746$, $p = .073$, $\eta_p^2 = .086$). Based on the main effects, we accept H_4. Post-hoc comparisons of the main effects indicated higher task loads using *Separate* compared to *Simultaneous* ($d = 0.837$, large effect) and *Two-Step* ($d = 0.748$, large effect). The effect size for the comparison of *Simultaneous* and *Two-Step* was below the threshold for a small effect ($d = 0.049$). The results further indicated that the route-following task imposed more task load than the search task ($d = 0.634$, medium effect).

The results of the statistical analyses conducted with the subscales of the UEQ, as well as corresponding boxplots, are given in Figure 7 and described in the following:

User Experience (H_5) All subscales were significantly affected by technique, leading us to accept H_5 with post-hoc analyses indicating consistent usability detriments of *Separate* compared to the other techniques. The comparisons between *Simultaneous* and *Two-Step* were more nuanced due to the overall high ratings, with *Simultaneous* showing a small positive effect regarding perspicuity ($d = 0.202$). *Two-Step*, on the other hand, showed a small positive effect regarding stimulation ($d = 0.255$) and a medium positive effect regarding novelty ($d = 0.569$).

Finally, a descriptive overview of the ordinal data acquired from our custom questions on technique usage is provided in Figure 8 and supplemented with inferential analyses in the following:

	Overall Test			Post-Hoc Tests		
	F	p	η_p^2	d(■■)	d(■■)	d(■■)
Attractiveness	27.535	<.001	.487	-0.017	1.151	1.130
Perspicuity	4.737	.012	.140	0.202	0.349	0.529
Efficiency	28.263	<.001	.494	0.149	1.238	1.221
Dependability	4.772	.012	.141	-0.052	0.542	0.446
Stimulation	25.632	<.001	.469	-0.255	1.232	0.952
Novelty	28.664	<.001	.497	-0.569	1.379	0.768

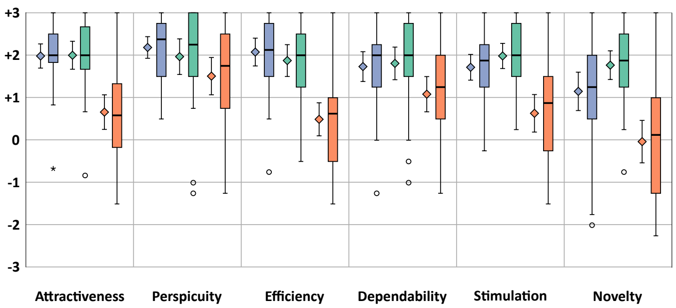


Fig. 7: Top: Results of the statistical tests conducted on the six subscales of the User Experience Questionnaire (UEQ). Bottom: Boxplots illustrating the score distributions of the six subscales separated by technique. Each box is complemented by a diamond representing the arithmetic mean with bars that indicate the corresponding 95% confidence interval. The colors represent ■ *Simultaneous*, ■ *Two-Step*, and ■ *Separate*.

Ease of Learning (H_6) The ease of learning score measured after the first encounter of each technique differed significantly between techniques, $F(2,58) = 8.269$, $p = .001$, $\eta_p^2 = .222$. Therefore, we accept H_6. Post-hoc analyses indicated poorer scores with *Separate* compared to *Simultaneous* ($d = 0.910$, large effect) and *Two-Step* ($d = 0.512$, medium effect). The effect size for the comparison of *Simultaneous* and *Two-Step* was below the threshold for a small effect ($d = 0.157$).

Ease of Use (H_7) The analysis of ease of use scores revealed a significant main effect of technique ($F(2,58) = 8.526$, $p = .001$, $\eta_p^2 = .227$), a significant main effect of task ($F(1,29) = 25.106$, $p < .001$, $\eta_p^2 = .464$), and a non-significant interaction effect between both factors ($F(2,58) = 1.994$, $p = .145$, $\eta_p^2 = .064$). Based on the main effects, we accept H_7. Post-hoc comparisons of the main effects indicated lower scores using *Separate* compared to *Simultaneous* ($d = 0.591$, medium effect) and *Two-Step* ($d = 0.785$, medium effect). The effect size for the comparison of *Simultaneous* and *Two-Step* was below the threshold for a small effect ($d = 0.081$). The results further indicated that technique usage was more challenging in the route-following task ($d = 0.915$, large effect).

Confusion (H_8) The analysis of confusion scores revealed a significant main effect of technique ($F(2,58) = 3.528$, $p = .036$, $\eta_p^2 = .108$), a significant main effect of task ($F(1,29) = 9.513$, $p = .004$, $\eta_p^2 = .247$), and a non-significant interaction effect between both factors ($F(2,58) = 0.381$, $p = .685$, $\eta_p^2 = .013$). Based on the main effects, we accept H_8. Post-hoc comparisons of the main effects indicated poorer results using *Separate* compared to *Simultaneous* ($d = 0.447$, small effect) and *Two-Step* ($d = 0.266$, small effect). Another small effect was observed regarding poorer results of *Two-Step* compared to *Simultaneous* ($d = 0.238$). The results further indicated more confusion in the route-following compared to the search task ($d = 0.563$, medium effect).

5.2 Descriptive Analyses

Discomfort/Sickness The discomfort scores captured across the study were overall low, with the medians for all techniques and tasks being 1 except for the *Simultaneous* technique in the route-following task ($Mdn = 0$). 95.0% of responses were between 0 and 3, with 43.9% being a score of 0. The remaining scores were 4 in 4.4% of the cases as well as a single outlier at 9.

		■ Simultaneous		■ Two-Step		■ Separate	
		M	σ	M	σ	M	σ
Ease of Learning 1 very difficult – 7 very easy		5.87	1.28	5.60	1.45	4.80	1.58
Ease of Use 1 very difficult – 7 very easy	R	5.50	1.43	5.87	1.22	4.93	1.51
	S	6.53	0.86	6.37	1.03	5.73	1.20
Confusion 1 after every teleport – 7 never	R	5.93	1.29	5.80	1.22	5.63	1.30
	S	6.40	1.07	6.20	1.10	5.90	1.32

Fig. 8: Means (M) and standard deviations (σ) of responses given to the single-item questions on ease of learning, ease of use, and confusion. Where applicable, results are divided into the route-following task (R) and the search task (S).

Preference The preference rankings submitted by participants are visualized in Figure 9. The overall trends are similar for the route-following and the search task, showing split preferences between *Simultaneous* and *Two-Step* while *Separate* was mostly disfavored. In the search task, *Simultaneous* was slightly more preferred over *Two-Step*, and a few additional participants rated *Separate* second instead of last.

5.3 Discussion

All participants were able to solve the presented tasks with all three techniques, which would not have been possible with same-scale teleportation techniques in the route-following task and would have taken substantially more travel efforts in the search task. However, the results paint the unanimous picture that the separation of horizontal target and scale selection into two distinct mechanisms did not provide clear advantages over the other two approaches. Instead, *Separate* led to longer route completion times (medium/large effects), imposed higher task loads (large effects), and therefore resulted in poorer usability ratings including user experience (small/medium/large effects), ease of learning (medium/large effects), ease of use (medium effects), and confusion (small effects). It is interesting to observe that the overall differences in route completion time were, only for the *Separate* technique, not reflected in the accumulated specification times of the individual teleports, where the effect sizes went down from $d = 0.446$ to $d = 0.082$ for *Separate* compared to *Simultaneous* and from $d = 1.086$ to $d = 0.511$ for *Separate* compared to *Two-Step*. This shows that participants spent more time between teleports with *Separate*, which indicates that this technique required more reorientation and planning efforts than others.

The findings comparing *Simultaneous* and *Two-Step* were more nuanced, with both achieving overall highly positive results. While the analysis on accumulated scalings indicated that participants were slightly more precise with *Two-Step* (small effect), participants also needed slightly more time to complete the route with this technique (small effect). This difference was not reflected in the inferential analyses of task load, where we did neither observe an overall effect between Two-Step and Simultaneous ($d = 0.049$) nor an interaction effect between technique and task ($p = 0.073$). However, the interquartile range of scores with *Two-Step* in the route-following task of 29.58 was more than twice the size of the one for *Simultaneous* with 13.13 – a trend not present in the search task (*Two-Step*: 25.21, *Simultaneous*: 27.08). This indicates a larger spread of scores for *Two-Step* in the route-following task, which could indicate that the pointing-based transfer function was more convenient to use for some users but also more cumbersome for others. Informal discussions with participants also revealed that the precision of a single teleport was not always considered the most important requirement given the option of performing follow-up correctional teleports as a viable travel strategy. On the usability scales, the most notable difference between *Simultaneous* and *Two-Step* was the increased novelty of *Two-Step* (medium effect). Another small positive effect of *Two-Step* was observed for stimulation while *Separate* showed a small advantage in terms of perspicuity. There was also a small effect indicating less confusion when using *Separate* over *Two-Step*.

In summary, our results encourage the integration of scale changes into the teleportation process instead of separating them into a distinct mechanism. The decision between *Simultaneous* and *Two-Step* is more

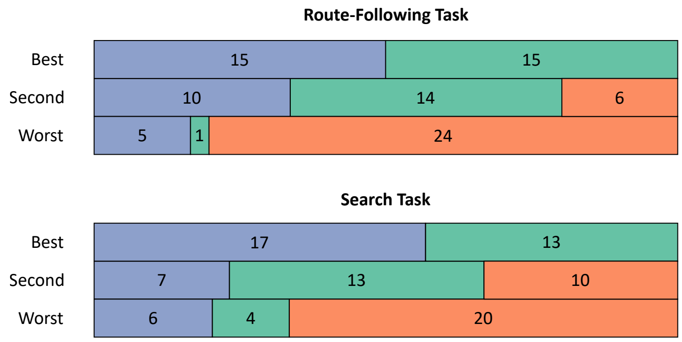


Fig. 9: Overview of preference rankings submitted by participants after the completion of each task with all three techniques. The colors represent ■ *Simultaneous*, ■ *Two-Step*, and ■ *Separate*.

a matter of personal preference, and we would recommend offering *Simultaneous* by default and *Two-Step* as an alternative if users are dissatisfied with the simultaneous operation of an additional input channel. Further research is required to investigate the operation of *Simultaneous* with a different controller using a joystick instead of a touchpad, which would allow drawing clearer conclusions on the use of additional input channels with *Simultaneous* over the *Two-Step* technique that works solely based on controller movements.

5.3.1 Comparison to Related Work

As the design of our three multi-scale teleportation techniques was motivated by the tripartite division introduced by Weissker et al. in the context of same-scale teleportation with elevation changes [48], it is sensible to compare our findings to the ones presented in their paper. On an overall level, our study replicated their previous findings in that the separation of the additional parameter to be specified was not considered beneficial while there was a close competition between the *Simultaneous* and *Two-Step* specification paradigms. However, our findings differed in the specific comparison of *Simultaneous* and *Two-Step*, where Weissker et al. observed higher specification accuracy with the *Simultaneous* paradigm that also came with a higher task load. In contrast, small accuracy benefits and a larger spread of task load scores were observed for *Two-Step* in our work, for which we see two potential reasons. First, as described in Section 3.3, we employed a refined touchpad mapping that was operated with relative finger movements instead of absolute touch locations, which could be a reason for the lower task loads of *Simultaneous* in our work. Second, also described in Section 3.3, user scaling is a multiplicative instead of an additive parameter, whose specification using the zone-based transfer function might have been slightly less intuitive and therefore more challenging to operate in our user study as opposed to the study on same-scale elevation changes. A more thorough investigation of the direct manipulation of different parameters based on controller movements is, therefore, still subject to future work.

5.3.2 Limitations

To put our presented results into context, we would like to discuss three limitations related to our experimental analysis.

First, our route-following task was designed to require a large number of different scale changes in a rather short amount of time. While we embedded these changes into the context of exploring the virtual city such that every required change resulted in a meaningful viewing position on an object of the scene, use cases beyond our experiment might require less drastic scale changes in quick succession. Meaningful transitions within the employed city environment also resulted in only covering scale changes from 2^{-5} to 2^{5}. As a result, our experimental setup did not allow for investigating transitions to molecular and astronomical scale levels as done in a few prior publications on multi-scale navigation in virtual reality.

Second, our employed sampling strategy resulted in a large number of participants who rated themselves as either advanced or expert users of virtual reality (22 of 30). While this reduced a potential novelty bias in our data and gave us competent feedback on our techniques, the results might differ when repeating the study with a pure sample of novices. In particular, we speculate that the more complex interfaces *Simultaneous* and *Two-Step* might receive less positive feedback while *Separate* could be favored more due to its simplicity resulting from the isolation of scale adjustments into a distinct mode. Studying the effects of different levels of expertise on multi-scale teleportation is, therefore, a relevant aspect of future work.

Third, while we counterbalanced the appearance of techniques across participants, the route-following and search tasks were always completed in the same order. Even though participants had sufficient time to familiarize themselves with the techniques in the tutorial phase, the results of the search task might be influenced by the additional training time participants had when completing the route-following task. However, due to the constrained nature of the route-following task that required considerably more precise movements than the search task, we believe that the identified negative main effects of the route-following task on task load, ease of use, and confusion would still hold if the tasks had been counterbalanced as well.

6 Conclusion and Future Work

Multi-scale travel techniques assist users with specific navigational requirements that become particularly relevant in large virtual environments with various features of different spatial extents. Our work presents the first purely teleportation-based multi-scale travel techniques, which were designed to seamlessly extend established same-scale teleportation workflows for improved learnability. Regarding our research question in the introduction, we conclude that integrating scale adjustments as an additional parameter into the existing same-scale target selection process is beneficial over outsourcing them to a separate mode. However, the preferred degree of integration seems to be more a matter of individual preference, with the *Simultaneous* technique showing slight advantages in terms of efficiency and task load. The *Two-Step* technique, on the other hand, prevented users from operating an additional input channel and showed slight advantages in terms of selection precision. In absolute terms, both paradigms appear suitable for multi-scale teleportation through immersive virtual environments.

Our work in this paper was focused on the design of teleportation-based techniques since related work pointed towards reduced sickness symptoms with teleportation compared to steering for same-scale travel. While the results of our study indeed indicated an overall low level of sickness symptoms, it is still subject to future work to formally confirm if teleportation results in lower sickness symptoms than steering for scale adjustments. As a result, future work will investigate alternative methods for realizing our techniques and empirically compare the most promising multi-scale teleportation techniques against the established steering-based approaches introduced in Section 2.1. Beyond sickness, such a comparison promises to yield further comparative insights into the benefits and drawbacks of both steering- and teleportation-based interfaces for multi-scale travel. Furthermore, the application of multi-scale teleportation techniques in multi-user contexts is an interesting aspect of future work that gives rise to novel research challenges including the effective communication of a user's planned relocation and scale adjustment to observers. Finally, future work will focus on the synthesis of expert teleportation interfaces that allow operators to adjust their horizontal position, rotation, scale, and elevation above ground level with a single mechanism if required – potentially assisted by system-driven suggestions based on the current surroundings. We hope that these steps will eventually lead to expressive teleportation interfaces that present viable sickness-reducing alternatives to their steering-based counterparts.

Acknowledgments

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