Bauhaus-Universität Weimar
Faculty of Media
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Navigation in Immersive Virtual Reality

The Effects of Steering and Jumping Techniques on Spatial Updating

Master's Thesis

Tim Weißker
born on 29th April 1993 in Erlangen

Matriculation number: 110940

First referee: Prof. Dr. Bernd Fröhlich
Second referee: Junior-Prof. Dr. Florian Echtler

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Declaration of Authorship

I hereby declare that I have written this thesis without the use of documents and aids other than those stated in the references, that I have mentioned all sources used and that I have cited them correctly according to established academic citation rules, and that the topic or parts of it are not already the object of any work or examination of another study programme.

Date | Tim Weißker

Abstract

The interactive exploration and understanding of large virtual environments requires techniques for navigating through the presented content. A common metaphor to do so is steering, which requires the constant input of movement direction and speed. However, the motion flow during steering seems to trigger simulator sickness for many users, especially when perceived in immersive Virtual Reality using head-mounted displays. As a result, many modern VR applications implement teleportation, which immediately moves the user to a new location. In the commonly seen jumping variant, the set of reachable targets is restricted to the scope of a pick ray in the currently visible section of the scene. Thus, in order to travel to a target further away, the user needs to perform several jumps along a route instead of direct one-time teleportation.

Other researchers have advised against the usage of one-time teleportation techniques, which is due to observed negative impacts on the formation of spatial awareness. The goal of this thesis is to extend previous research by investigating spatial awareness in immersive Virtual Reality when using active, user-initiated jumping techniques in comparison to the one obtained by traditional steering.

For this purpose, the thesis explores spatial awareness on different fidelity levels, thereby focusing on finding suitable measures for its quantification. It especially investigates the objectively measurable skill of spatial updating, an egocentric perceptual process involved in building allocentric survey knowledge. The design spaces for both steering and jumping techniques are examined in more depth, and a representative of each category is chosen for comparison. Afterwards, the design, implementation and realisation of a spatial updating user study is motivated and explained in detail. The results indicate that most participants could perform the task equally well with both techniques; however, it was observed that a non-negligible minority of users was not able to successfully use the motion cues of jumping, resulting in disorientation.

Acknowledgements

"Thank you for helping us help you help us all."
— GLaDOS, PORTAL

The Computer Science classes at school made me certain that this was the subject I am interested in for studying. However, the choice of moving to Weimar seemed rather random and when arriving here for my Bachelor studies in 2011, I was not sure if everything was going to turn out as nicely as I hoped it to be. Now, I am looking back to five and a half years of studying and know that it was a good choice. Studying in such a familial atmosphere was very inspiring, and I would like to thank every single person who motivated, encouraged and supported me during my studies.

Especially, my gratitude goes to my supervisors and friends *André Kunert* and *Dr. Alexander Kulik*. André accompanied my first steps in Virtual Reality some years ago and was always knowledgeable about questions concerning the field. Alex continuously supplemented and extended this support with creative approaches and his profound knowledge of literature. Both spent a large amount of their time discussing about my thesis despite being extremely busy with their own research. They always believed in me and backed me up during rainy days.

Furthermore, I would like to thank my primary referee *Prof. Bernd Fröhlich* for many constructive discussions that went far beyond a usual thesis supervision. He massively contributed to keeping the vast amount of ideas together, thereby helping me to not getting lost in a research field I have never touched before. My second referee *Junior-Prof. Florian Echtler* accompanied large parts of my studies by supervising three projects, so I am glad he agreed to have an eye on my thesis as well.

Another of my acknowledgements goes to *Andreas-Christoph Bernstein* for his technical support regarding our Virtual Reality framework. He has spent a lot of his time tweaking the backend and fixing bugs such that my application code could run effectively and efficiently. I would also like to honor *Stefanie Wetzel* for her helpful and constructive feedback regarding the world of statistics.

Moreover, I thank the people in the VR-Lab for all the fun we had during daytime and nighttime, on weekdays and weekends. This relaxed atmosphere made working tremendously more enjoyable. Of course, I would also like to appreciate the time and effort of my 25 user study participants. In particular, I thank *Jasmin Odenwald* for allowing me to publish some pictures of her session in this thesis. Speaking of pictures, I am glad that *Neat Corp.* and *Kubold Games* gave their permission to use screenshots of their games in Chapter 2.

As I have experienced several times, it is impossible to detect all mistakes in a text one has written. Thus, I would furthermore like to honorably mention *Veronika Haaf* and *Michael Waßner* for eliminating (hopefully all) spelling, punctuation and grammar flaws.

Finally, I must express my very profound gratitude to my mother *Tanja Weißker* and my grandparents *Helga and Herbert Wagner*. Apart from supporting my studies materially, they have always had an open ear for me and continuously expressed their interest in my doings. Because my grandparents do not speak English, I would like them to read at least one German sentence in this thesis: "Danke, Oma und Opa!". And Mum, you do speak English, so I would like to say a big thank you for being that sort of cool mother everybody wishes to have.

Contents

1 Introduction

"I am astounded by the size of this planet. We must explore vast unknown expanses as we search for edible matter."
— Captain Charlie, PIKMIN 3

This chapter leads the reader to the research question addressed in this thesis. For this purpose, Section 1.1 explains the task of *navigation* in Virtual Reality and outlines five metaphors for travelling through virtual environments. Section 1.2 depicts *teleportation*, a target-based travel technique, in more detail. Based on these illustrations, Section 1.3 highlights the goal of this thesis and explains the content of the remaining chapters.

1.1 Navigating through Virtual Environments

The interactive exploration and understanding of virtual environments requires ways of interacting with the presented content. According to Bowman et al. [1], all interaction methods belong to one of three fundamental classes: navigation, manipulation and system control. *Navigation* is described as the most prevalent interaction method in scenes which are too large to review from a single vantage point, i.e. environmental and geographical spaces according to Montello's taxonomy [2]. Conceptually, it consists of the components *travel* and *wayfinding*. While travel is solely related to the motor action of moving the group's viewpoint to another location, wayfinding involves cognitive processes of finding a suitable path to the desired target without getting lost. Ideally, wayfinding should be supported by the implemented travel technique.

Furthermore, Bowman et al. [1] subdivide travel again into five different metaphors. *Physical movement* is the most natural among them, requiring the user to walk around a tracked workspace. In order to explore larger environments than the workspace, treadmill-like devices (e.g. [3, 4]) or walking in place [5] can be used to affect virtual locomotion.

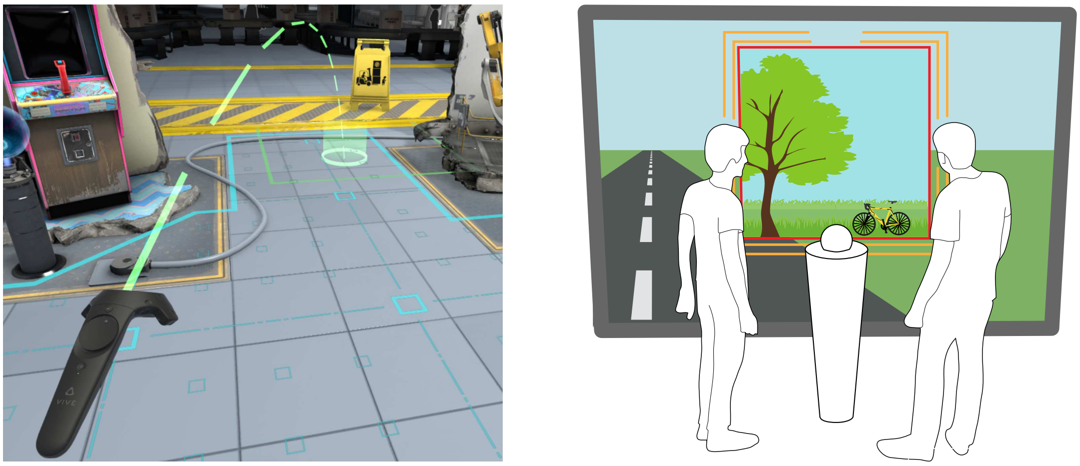
In *manual viewpoint manipulation*, the displacements of the users' hands are mapped to virtual locomotion like grabbing the air [6] or moving camera tangibles [7]. *Steering* might be the most common metaphor in traditional video games, where the user is required to continuously specify the direction and speed of motion using one or multiple input devices. *Target-based travel* techniques like Navidget [8, 9] rely on the specification of the target position and orientation in advance with the actual travel being automatically applied by the system. Similarly, *route planning* offers the input of an exact travel path through the environment beforehand using mediators like maps or World-in-Miniatures [10].

Due to their proprioceptive feedback, several benefits have been shown for physical locomotion techniques over steering [11, 12, 13]. However, the size of physical tracking areas is limited and treadmill-like devices are expensive to setup and maintain. Walking in place [5], scaling [14] and resetting techniques [15] can work to some extent, but they become impractical and exhausting when the virtual environments get larger. The same is true for manual viewpoint manipulation techniques. The steering metaphor is derived from real-world tasks like driving a car and therefore considered "general and efficient" by Bowman et al. [1]. Nevertheless, steering introduces a discrepancy between the perceived motion by the visual and vestibular systems. This cue conflict is considered one among several causes for simulator sickness in Virtual Reality [16, 17]. Similar problems arise with route planning and several target-based travel techniques, where virtual motion is automatically applied by the system. Target-based travel without a continuous motion flow, also referred to as *teleportation*, avoids conflicting motion cues; however, another highly cited paper by Bowman et al. [18] advises to avoid this form of travel due to a negative impact on the users' spatial awareness and sense of presence in the virtual environment.

1.2 Jumping and One-Time Teleportation

The recent advancements in head-mounted display (HMD) technology like the Oculus Rift[1] or HTC Vive[2] have brought Virtual Reality to the consumer level, which yielded a boost of gaming-related applications designed for these devices. Since many people

1 `http://www.oculus.com/rift`
2 `http://www.vive.com/`



(a) In jumping techniques, the user is limited to the reach of the teleportation tool. A common approach is to bend a pick ray and teleport to the ray's intersection with the scene. (Picture: The Lab, Valve Corp.)

(b) Photoportals [19] show references to remote locations located anywhere in the scene. When the teleportation is initiated, the portal maximizes to the physical screen size, which yields a seamless one-time transition to the destination.

Figure 1.1: Graphical illustrations of a jumping and a one-time teleportation technique.

are affected by simulator sickness in immersive virtual environments, teleportation has been implemented as the main travel metaphor in many of these games despite the aforementioned dissuasion by Bowman et al. [18]. However, due to gameplay reasons, users are not allowed to teleport to all parts of the scene at any time; instead, they are restricted to locations within the currently reachable area of a teleportation device in the egocentric view, mostly a tracked pointer. This means that the intersection of a pointing ray with the scene exactly defines the target location. In order to reach targets farther away, the user is required to perform several jumps along a route, resulting in a discretized variant of steering rather than a one-time teleport to a remote location. In this thesis, this travel metaphor will be referred to as *jumping* through virtual environments. Figure 1.1(a) shows the egocentric target indication mechanism of the jumping technique implemented in the game *The Lab* by Valve[3].

On the other hand, unconstrained *one-time teleportation* mechanisms allow to extend the users' reach beyond vista space by offering additional mediators like target galleries [20], maps or World-in-Miniatures [21]. At our university, for example, one-time teleportation can be used for the exploration and understanding of large 3D data sets on a multi-

3 `http://store.steampowered.com/app/450390/`

user projection screen by multiple collocated users [22]. As an example of this, Figure 1.1(b) shows a graphical illustration of two users viewing potential teleportation targets using Photoportals, picture-like 3D references to locations stored in a virtual camera [19].

1.3 Goal of this Thesis

Head-mounted displays and their accompaning games become increasingly popular on the consumer market, and maintaining a high spatial awareness of large virtual worlds is crucial for scene understanding and task performance. As a result, the implemented travel techniques of an application should support and not hinder the awareness of the users' surroundings. In many conventional video games, the main travel metaphor is steering by using a keyboard or a joystick. Modern Virtual Reality games, however, increasingly replace this metaphor by jumping.

The goal of this thesis is to investigate to what extent users can maintain spatial awareness of their environment when moving by such an active, user-initiated jumping technique. Although Bowman et al. [18] advise against teleportation in general, they have only analysed the effect of passive (i.e. without user involvement) one-time teleportation in an abstract environment with unconstrained changes of 3D position and orientation. This thesis will extend this research by comparing a modern jumping technique to a common steering variant in a more realistic virtual world viewed through a head-mounted display. After a formal user study, we should be able to know if most modern games sacrifice spatial awareness during the effort of reducing simulator sickness, or if the discrete views along a route are able to deliver enough spatial information to obtain comparable performances to steering.

In order to answer this question, Chapter 2 starts by exploring the current state-of-the-art of steering and teleportation techniques and outlines the implementation of some of these techniques into our VR system. Concrete steering and jumping techniques are discussed and two of them are chosen for comparison. Chapter 3 continues by introducing the term spatial awareness in more detail, thereby focusing on a literature survey to find suitable measures for the quantification of this cognitive ability. It is motivated that this thesis will concentrate on the ability of *spatial updating*, a subskill also involved in the formation of allocentric cognitive maps. Chapter 4 describes important findings and steps towards the design of a spatial updating user study. In Chapter 5, the exact procedure of this study and the corresponding hypotheses are explained. Chapter 6 evaluates these hypotheses statistically using the data of 24 subjects and interprets the results. Finally, Chapter 7 draws conclusions from the obtained results and highlights important areas of future research.

2 Steering and Teleportation in VR

"A portal has opened here, too! If you want to breathe the air of the world of light for a moment, let me know. I'll take you there!"
— Midna, THE LEGEND OF ZELDA: TWILIGHT PRINCESS

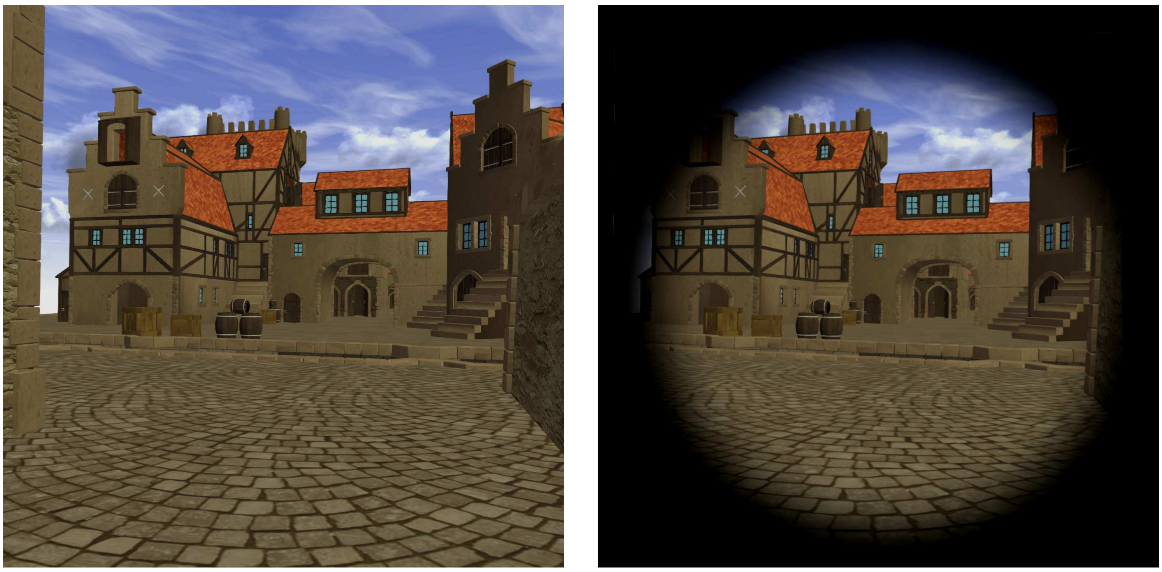
The preceding chapter introduced the topic of navigation in Virtual Reality and explained that two techniques of particular interest in the context of gaming are steering and jumping, with the latter one being a range-constrained variant of teleportation. Nevertheless, the design spaces for both steering and teleportation techniques are large, resulting in the need of finding proper representatives for further investigations. In order to perform this selection, the design space for each travel metaphor must be clear, which requires formal categorizations or taxonomies.

Thus, the goal of this chapter is to approach the current state of the art in technique design for steering and teleportation. Steering techniques have already been intensively studied and systematized by other researchers, which is briefly summarised in Section 2.1. Concerning teleportation, the aforementioned difference between one-time teleportation and jumping is just one of many orthogonal attributes to be considered. As a result, Section 2.2 broadens this view by introducing a systematic classification of the general teleportation process into four subsequent stages, which is the result of a literature and application survey. Section 2.3 continues by showing how both steering and teleportation are related to each other on a continuum. Section 2.4 then outlines implementation details of technique variants that have been integrated into our Virtual Reality Framework. Finally, Section 2.5 summarises and discusses the previous illustrations and draws conclusions on which technique representatives to compare in the user study of this thesis.

2.1 Systematic Classification of Steering

In the Virtual Reality community, Bowman and colleagues have developed highly accepted taxonomies of various interaction techniques. The high-level division of travel into five different metaphors illustrated in Section 1.1 is one example of their work. Another paper by Bowman et al. [23] shows a more fine-grained classification of first-person travel techniques in immersive head-mounted display environments using 3D input devices. According to this taxonomy, a technique can be classified by its method of *direction/target selection*, its method of *velocity/acceleration selection* and its *input conditions*.

When extracting the steering-related components from this taxonomy, it turns out that there are two major variants in terms of direction selection. In *gaze-directed steering*, the user travels in the direction they are looking. *Pointing-directed steering*, on the other hand, uses the orientation of a separate 3D input device to determine this direction. The diversities in velocity/acceleration selection and input conditions remain unchanged when focusing on steering only.



(a) When no field-of-view modifications are applied, a user perceives a strong visual flow during steering, especially in the edge regions of the screen.

(b) Dynamically and smoothly restricting the field-of-view in a radial fashion when the user steers has been shown to reduce their simulator sickness [25].

Figure 2.1: An example of dynamic field-of-view modifications during steering.

Orthogonal to this classification, each technique may offer additional mediators or visual effects to enhance travel experience and spatial awareness. An overview and analysis of different mediators during steering (like maps and trails) is given by Darken and Peterson [24]. Fernandes and Feiner [25] have proposed an example of adding a visual effect during steering. In their system, the user's field-of-view in the head-mounted display is dynamically reduced when the steering speed gets larger, which was shown to significantly reduce simulator sickness in the tested environment. Figure 2.1 illustrates one possible implementation of this effect.

2.2 Systematic Classification of Teleportation

Although the illustrated taxonomy by Bowman et al. does not exclude target-based travel techniques in principle, it does not seem appropriate for a fine-grained classification of the wide range of one-time teleportation and in particular jumping techniques which have been implemented by researchers and game designers. Since there is no such formal classification so far, an initial research on the current state of the art has been carried out. This survey focused on recent head-mounted display games on the market and was supplemented by scientific literature where pertinent and available.

The result is a systematic classification of the general teleportation process into four subsequent stages: target indication, pre-travel information, transition and post-travel feedback. Each individual teleportation technique is defined as a specific selection of

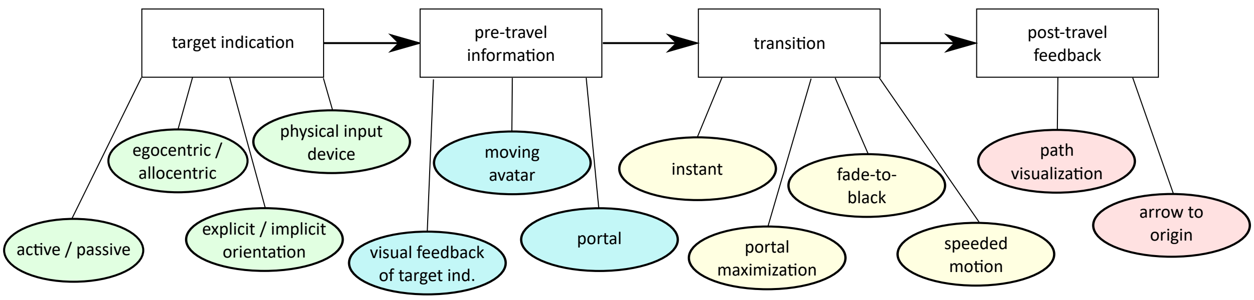


Figure 2.2: Four stages of the teleportation process with non-exhaustive examples. Each individual teleportation technique is defined by a specific selection of mechanisms for each stage.

mechanisms for each stage. It turns out that the aforementioned difference between one-time teleportation and jumping along a route is just one of several orthogonal factors in the target indication phase. The developed classification, together with some non-exhaustive examples for each stage, is shown in Figure 2.2 and is going to be further explained in the following subsections.

2.2.1 Target Indication

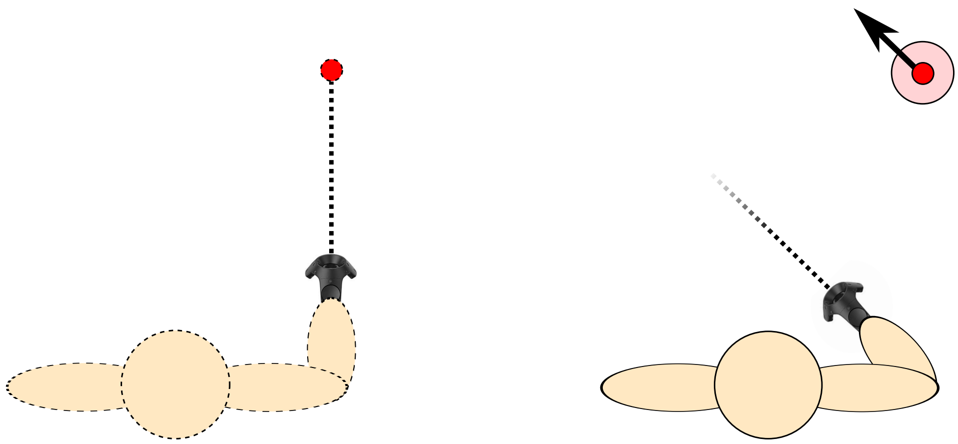
The first stage of the teleportation process is *target indication*, which is a selection of the target location and orientation after the teleport. In some user studies like [18, 26], this is a *passive* process without any user involvement at all; instead, the next targets are given by the testing protocol. However, if there is no reason to do otherwise, users should be able to *actively* explore the environment and determine teleportation targets on their own.

When target indication is active, it needs to be decided if *egocentric* or *allocentric* mechanisms should be used. This part of the taxonomy relates to the discussion of jumping and one-time teleportation in Section 1.2. If target indication is egocentric, the user is limited to the range of a teleportation tool in the currently visible portion of the scene (jumping metaphor). Allocentric target indication, on the other side, requires additional mediators to get an overview of the complete scene, thus allowing for one-time teleportations to arbitrary target locations.

The *physical input device* for target indication is a tracked pointer in the simplest case, but other selection mechanisms using gaze [27], direct walking into a gallery portal [20] or dedicated hardware [19] have been demonstrated as well.

Once the target location is specified, the determination of the target orientation may happen *explicitly* or *implicitly*. In many HMD games like *The Lab* (Valve)[1] or *Vanishing Realms* (Indimo Labs LLC)[2], the target orientation is given implicitly by the viewing direction of the user. This means that after the teleport, the user will face the same direction in the global coordinate system as before. Alternatively, when choosing a target in a gallery, the orientation is implied in the pre-defined perspective. Explicit orientation strategies

1 http://store.steampowered.com/app/450390/
2 http://store.steampowered.com/app/322770/



(a) In the first step, the user points to the position of the desired teleportation target (red circle). The selection is confirmed by a button press.

(b) Afterwards, the intended viewing direction after the teleportation can be specified by rotating the pointing device.

Figure 2.3: *The Gallery* (Cloudhead Games Ltd.) implements an explicit orientation strategy, which allows to determine both the position and the viewing direction after the teleportation.

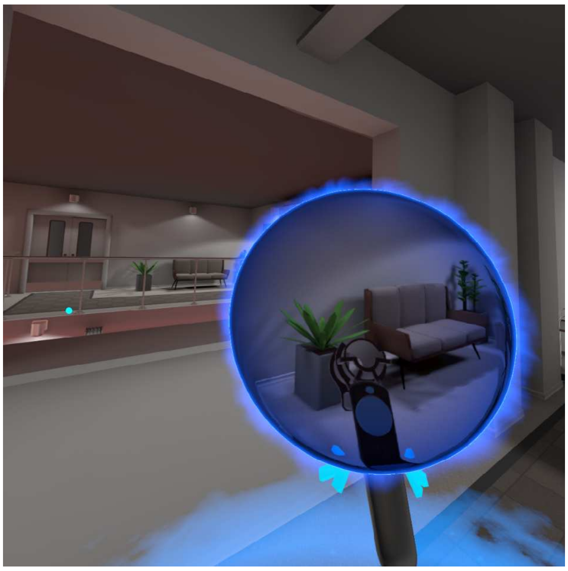
loosen this restriction. In the allocentric World-in-Miniature (WIM) approach by Pausch et al. [21], for example, the user can move and rotate a target camera widget freely in the WIM. Moreover, the game *The Gallery* (Cloudhead Games Ltd.)[3] implements an explicit orientation mechanism after pointing to the target location in the egocentric view. Figure 2.3 visualizes this twofold process for further clarification.

2.2.2 Pre-Travel Information

In the second stage, the system may give the user additional information about the teleportation to be performed. First of all, the visual feedback given during the target indication stage (e.g. pointing ray, gallery preview, etc.) can already be considered pre-travel information. However, there may be additional aids after the target has been successfully selected. In the gaze indication technique by Bolte et al. [27], for instance, a visual marker is set to the indicated location, allowing the user to perform corrections. One variant by Bakker et al. [26] uses numbers to indicate the room and the orientation to which the user is about to be teleported. The game *Spell Fighter VR* (Kubold Games)[4] uses an

3 `http://store.steampowered.com/app/270130/`
4 `http://store.steampowered.com/app/455440/`

(a) In *Spell Fighter VR* (Kubold Games), an abstract avatar walks to the indicated target before the actual transition is initiated.



(b) In *Budget Cuts* (Neat Corp.), a portal is opened at the indicated travel target, in this case on the corridor behind the window (cyan circle). The user may look around at this destination by moving the pointing device before teleporting to it.

Figure 2.4: Two examples for pre-travel information given before the actual transition process.

abstract avatar walking to a target before the actual teleportation begins (see Figure 2.4(a)). Preview techniques, like the reorientation mechanism by Freitag et al. [28], Photoportals by Kunert et al. [19] or the implemented metaphor in *Budget Cuts* (Neat Corp.)[5], open a portal showing the indicated travel target. The user may look at the destination beforehand and in some cases, they are also allowed to readjust the portal view (and thus the target) if they are not yet satisfied. The technique implemented in *Budget Cuts* is illustrated in Figure 2.4(b).

2.2.3 Transition

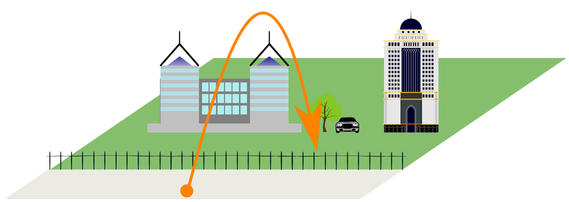
The transition stage is the core of teleportation, in which the actual travel from the origin to the target happens. The open source project *Vivecraft*[6], a Virtual Reality adaption of Minecraft, implements a simple *instant transition*, where the old view in one frame is

5 `http://store.steampowered.com/app/400940/`
6 `http://http://www.vivecraft.org/`

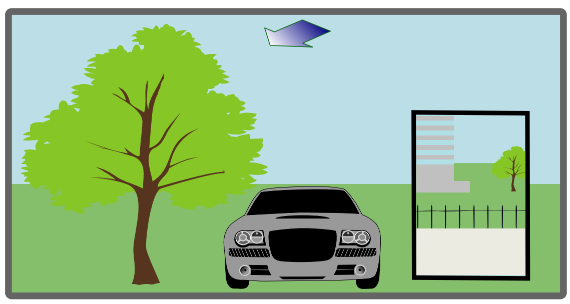
directly replaced by the new one in the next frame. Other games like *The Lab* (Valve) and *Vanishing Realms* (Indimo Labs LLC) slow the transition process down by implementing a *fade-to-black transition*, which animates the old view to a black screen, performs the teleportation jump and then fades back into the new view. When portals are used in the target indication or pre-travel information stages, a valid transition is *portal maximization*, which allows for a seamless jump into the preview window as done by Kunert et al. [19] and *Budget Cuts* (Neat Corp.). Another approach is to use *speeded motion transitions*, which move the camera from the origin to the target location very quickly. This variant is implemented in the approaches by Bolte et al. [27] and *Raw Data* (Survios)[7].

2.2.4 Post-Travel Feedback

In order to increase spatial awareness, it is possible to give additional information to the user after the transition has been performed. In the investigated games and papers, no occurrences of such post-travel feedback were observed. Nevertheless, Figure 2.5 indicates three possible methods of delivering post-travel feedback to the user. Subfigure 2.5(a) shows an additional mediator, in this case a World-in-Miniature (WIM) [10], which is used to display information about the travelled displacement in an allocentric representation of



(a) A World-in-Miniature (WIM) [10] visualizes the teleported displacement (orange arrow) in an allocentric representation of the scene. This method could also be implemented as pre-travel information.



(b) At the destination, an arrow at the top shows where the origin of the teleportation is located. An undo portal (right) can help the user to easily recover when they have lost their orientation.

Figure 2.5: Two examples on how post-travel feedback can be given to the user after the transition process.

7 `http://store.steampowered.com/app/436320/`

the scene. Subfigure 2.5(b) illustrates two egocentric widgets, namely an arrow pointing to the teleportation origin and an undo portal, which may help to recover if the user lost orientation.

2.3 The Steering-Teleportation-Continuum

Steering along a route is a commonly implemented travel metaphor in many non-immersive applications since its underlying principles are well-known from the real world. However, specifying the direction and speed of movement requires continuous attentive resources until the destination has been reached. Classic one-time teleportation without any enhancements, on the other side, requires user input only during target indication; the actual displacement to the destination is then induced by the system with virtually infinite speed by replacing the old perspective with the new one.

These two travel metaphors define the extremes of the *steering-teleportation-continuum*, which is visualized in Figure 2.6. All technique variants and modifications illustrated in Sections 2.1 and 2.2 can be located within this continuous design space. The following two subsections illustrate the transition regions between the extremes of this continuum in more detail.

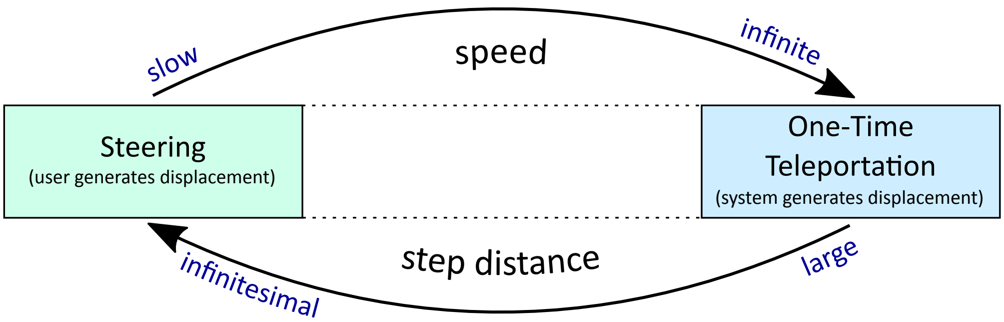


Figure 2.6: Graphical illustration of the continuum between steering and one-time teleportation. By increasing the movement speed, a steering technique gets closer to one-time teleportation. By decreasing the step distance, a one-time teleportation technique gets closer to steering.

2.3.1 From Steering to One-Time Teleportation

The minimal travel time to a destination when steering is determined by the maximal speed this technique offers. For one-time teleportation, a target must be reachable in a negligible amount of time, requiring to travel with infinite speed. Thus, when increasing the speed of a steering technique up to infinity, the difference to one-time teleportation diminishes. Of course, it will become impossible to still actively control the direction of movement with such high movement speeds, which is why one-time teleportation relies on a target indication phase with the actual displacement being applied by the system. Speeded Motion Transitions (as introduced in Subsection 2.2.3) are an intermediary technique along this axis. As part of the teleportation process, they require a target indication phase, so the actual displacement can be generated without further user involvement. Nevertheless, the travel speed is not infinite since a visual flow to the target is perceivable, which manifests this technique between the two extremes of the continuum.

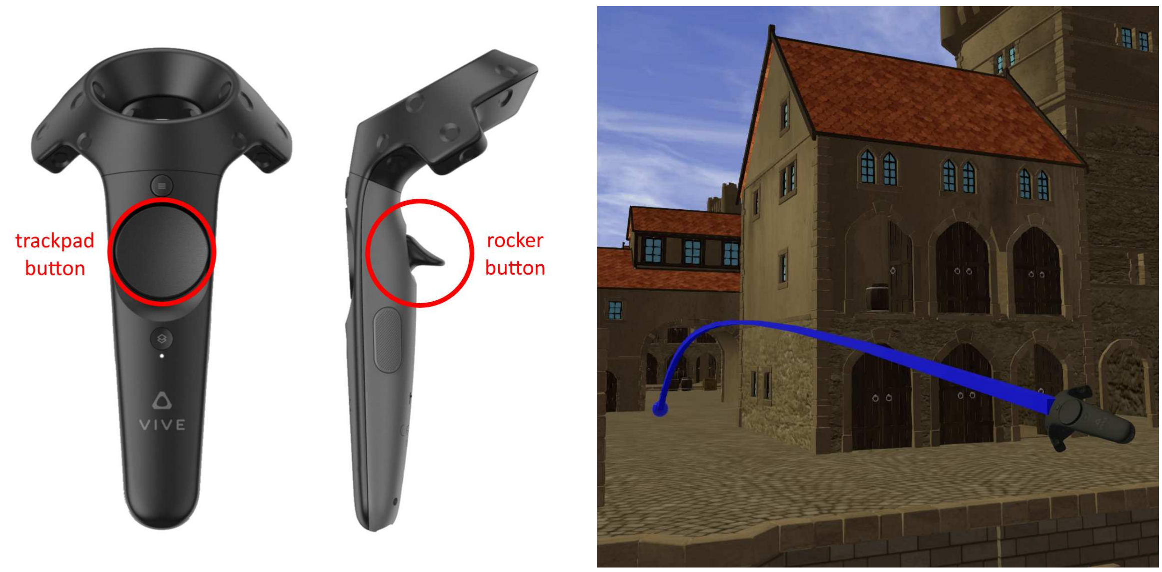
2.3.2 From One-Time Teleportation to Steering

Approaching the continuum from the other side, one-time teleportation requires just a single step to the destination after the target has been indicated. By restricting the range of the target indication tool, as it is done by choosing egocentric target indication mechanisms (see Subsection 2.2.1), the user is required to perform several steps along a route to reach their destination. Thus, all jumping techniques observed in many modern immersive video games also lie on an axis between one-time teleportation and steering. When the maximal step distance becomes infinitesimally small, the corresponding technique is identical to steering, requiring the user to continuously specify the direction and speed of travel with the teleportation pointer.

2.4 Implementation of Selected Techniques

In a previous project of the VR-Systems Group at our university, the usage of several head-mounted displays has been integrated into the Virtual Reality Framework *avango*[8] using the *guacamole* rendering engine [29]. The travel techniques of this thesis were built on the basis of these contributions. They were tested and evaluated using the head-mounted display *HTC Vive*[9] with the included 3D controllers.

In terms of steering, both pointing- and gaze-directed variants have been implemented. The travel speed can be controlled using the rocker of the Vive controller (see Figure 2.7(a)). Depending on the mode, the orientation of either the controller or the headset serves as a forward vector. It is possible to enable smoothly-animated, speed-dependent field-of-view restrictions for both modes on demand.



(a) A Vive controller is used to control the implemented travel techniques. The trackpad button initiates and terminates target indication during jumping, while the rocker is mapped to the speed of steering.

(b) The target indication ray in the implemented jumping techniques has a parabolic shape. Compared to straight-line pointing, this method allows to reach some occluded destinations as well.

Figure 2.7: Button mappings and visual appearance of the implemented travel techniques.

8 https://github.com/vrsys/avango
9 http://www.vive.com/

For teleportation, the focus was on active jumping techniques using implicit orientation specification. Since it is common in many video games, the egocentric target indication ray originating from the controller was bent to have a parabolic shape, which is illustrated in Figure 2.7(b). Compared to straight-line pointing, this method allows to reach some occluded destinations as well. Moreover, it retains a higher accuracy for distant locations than the straight ray. Three transition modes to the indicated target have been implemented in an extensible fashion using the *Strategy* pattern: instant, speeded motion and fade-to-black. No additional pre- or post-travel information is given to the user.

2.5 Discussion

This chapter has illustrated the design spaces of both steering and teleportation techniques and investigated their relations to each other. For the envisioned spatial awareness study of this thesis, a representative of each category must be found to be tested. In the often mentioned spatial awareness study of Bowman et al. [18], steering and one-time teleportation were compared without any user involvement. This means that all steering movements and teleportation targets were pre-defined by the study protocol and executed by the system. In contrast, the focus of this thesis should be the active, user-initiated exploration of virtual environments since it is the more common use case also known from video gaming.

For steering, informal feedback discussions of the implemented techniques with five users (mean age: 19.7) yielded a strong preference towards the pointing-directed over the gaze-directed variant. The ability to freely look around during travel was mentioned as the main advantage of pointing-directed steering. In all cases, field-of-view restrictions during steering were rated better or equal to the unrestricted counterparts. However, as this thesis marks the first step in the analysis of spatial awareness of travel techniques at our chair, it was decided to compare only basic forms of travel techniques. Hence, pointing-directed steering without field-of-view restrictions was chosen to compete in the study.

In terms of teleportation, it seems reasonable to choose a jumping technique since the step distances of one-time teleportation can be too large to keep track of the travelled paths and distances in unknown virtual environments. Pre- and post-travel information help in this case, but the availability of additional mediators like maps and arrows also make the spatial updating task too trivial. In order to be able to detect potential technique differences at all, it is desired to keep the spread on the steering-teleportation-continuum as large as possible. As a result, it was decided to instruct users to use as large jumps as possible when completing a route, which brings the jumping technique further away from steering. Concerning the transition mode, no clear preference was visible in the informal feedback discussions. Following the argumentation above, this thesis will use instant transitions as the most basic form.

Investigating the influences of various steering and teleportation enhancements is subject to future work beyond the scope of this thesis.

3 Spatial Awareness

"Use your beacons well, and you will never fear getting lost."
— Old Impa, THE LEGEND OF ZELDA: SKYWARD SWORD

The preceding chapter investigated the design spaces of steering and teleportation techniques in detail and chose representatives of each category for a comparison in a user study focusing on spatial awareness. In the context of view navigation techniques, a seminal paper by Bowman et al. [18] defines spatial awareness as "the ability of the user to retain an awareness of her surroundings during and after travel", thus being the opposite of disorientation. The authors show an experiment, in which users were passively moved and teleported along a straight-line path in an abstract virtual environment. Despite being a complex cognitive construct, spatial awareness after travel was measured by a comparatively simple measure, namely the response time to a two-option question regarding printed letters on the environment's objects.

The goal of this chapter is to analyse the field of spatial awareness in more depth, thereby especially focusing on finding further suitable measures for its quantification. For this purpose, a literature survey yielded a non-exhaustive categorization of related work by different aspects of spatial awareness. The following sections summarise relevant papers and their findings for these respective categories.

Section 3.1 starts by introducing a tripartite high-level model for classifying spatial knowledge. It especially outlines the most profound type of spatial knowledge called *survey knowledge*, which is very challenging to obtain, especially when exposure times are short. Section 3.2 introduces an egocentric sub-skill involved in the acquisition of spatial knowledge called *spatial updating*. Section 3.3 continues by illustrating studies related to a sub-skill involved in spatial updating processes themselves, namely the judgement of distances. Section 3.4 summarises the presented works and draws conclusions on the measurements to be taken for the analysis of travel techniques in this thesis.

3.1 Landmark, Route and Survey Knowledge

In order to classify spatial knowledge, Siegel and White [30] introduced a high-level tripartite division into *landmark*, *route* and *survey knowledge*. Landmark knowledge is the simplest form and refers to the ability of knowing and recognizing salient objects in the environment. Route knowledge relates these objects to each other by knowing a sequence of travel decisions, which define how to move from one landmark to another. Finally, survey knowledge requires a cognitive map of the environment's spatial layout, including landmarks and quantitative relationships among them. According to the authors, spatial learning is assumed to be an incremental process from landmark knowledge to survey knowledge; however, further research suggests a coexistence of the different knowledge types during the learning process (e.g. [31]).

Several investigations have been carried out to find suitable aids in building all types of spatial knowledge of virtual environments. Darken and Peterson [24], for example, have written a book chapter on spatial orientation and wayfinding, outlining profound considerations and a number of experiments that led to their proposed design guidelines for navigable virtual environments. They state that spatial learning in Virtual Reality can be enhanced either by adding tools and mediators or by organizing the scene in a more logic manner. The former can be realised, for instance, by maps, movement trails and compasses while the latter refers to superimposing grids onto the scene (*explicit sectioning*) or to building scenes according to established rules in urbanism (*implicit sectioning*, see also [32]).

Landmark knowledge is very basic and does not involve spatial relationships. As a result, tests of landmark knowledge are mostly recognition-based (e.g. [33]). Route knowledge can be verified by verbal rehearsing or directly moving along the memorized path in the testing environment (e.g. [34]). Survey knowledge is the most profound type of spatial knowledge and thus considered the key to successful wayfinding in any environment by Darken and Sibert [35]. Witmer and Sadowski [36] summarise its characteristics and measures applied by other researchers in order to use them in an own spatial learning task. In particular, they name three task categories for measuring survey knowledge. The first requires subjects to draw sketch maps of the environment, which have been shown to be valid representations of cognitive maps [37]. This is a rather time-consuming process, and the evaluation of results is a highly subjective process unless well-defined criteria are specified beforehand. In a constraint version of this task, the outline of the environment and paper cutouts of landmarks are given, requiring the subject to correctly place the cutouts within the outline [38]. The second task type requires subjects to find the most direct route between two landmarks. This demands the direct application and transfer of acquired knowledge, which requires well developed spatial skills and sufficient exposure to the respective environment. Witmer et al. [34], for example, allowed training a route through a building with auxiliary material in advance and three times on-site before the inference of new routes was tested. Thirdly, subjects may be asked to state the direction and distance to landmarks from a given location within the environment, which can be easily measured in Virtual Reality using 3D input devices.

Acquiring advanced levels of survey knowledge of an unknown environment can be a time-consuming process. Ruddle et al. [39], for instance, have measured increased survey knowledge of a desktop virtual environment after nine sessions during the course of a week. Real-world studies by Ishikawa and Montello [31] even showed that some participants were not able to acquire passable survey knowledge at all, even after more than twelve hours of exposure.

3.2 Spatial Updating

Perfect survey knowledge allows humans to explicitly locate and orient themselves within a cognitive map of the environment. However, even when this map is not yet present, the body can use a "process that automatically keeps track of where relevant surrounding objects are while we locomote, without much cognitive effort or mental load", which is Riecke's definition of *spatial updating* [40, Section 12.2]. The term is closely related to path integration, involving studies with blindfolded subjects asked to estimate the relative location of important points in the scene after a series of active or passive body movements (e.g. [41, 42, 43]). This ability can be tested by pointing towards previously seen objects, by naming those objects that are currently at a specific orientation with respect to the own body, or by completing face-origin or straight-line return-to-origin tasks [40, Section 12.2]. It has been shown that accurate spatial updating requires high degrees of spatial presence and immersion [40, Section 16.3].

In the literature, there are two main types of spatial updating studies conducted in virtual environments. The first one requires learning the spatial layout of the environment in advance before being moved and tested. In some cases, the scene is kept deliberately simple to speed up this process (e.g. [44, 45]). Other studies, however, seem to go far beyond the working memory's capacity, for example by asking subjects to memorize 15 objects in three different rooms [26] or 22 landmarks on a marketplace [40, Chapter 14]. This experimental approach requires to verify the successful memorization and localization of all objects before the actual spatial updating study begins.

A second type of studies requires no prior learning phase; subjects are supposed to gather knowledge of their environment during the actual motion phase. Chance et al. [46] and Bowman et al. [47], for instance, made subjects move through a linear maze and asked them to point to encountered objects at the terminal location. Similarly, a study by Napieralski et al. [48] involved travelling a pre-defined route through a city model with highlighted landmarks of interest, which were asked to be pointed to at multiple checkpoints along the way. A face-origin and a return-to-origin task in unknown virtual environments have been used by Klatzky et al. [49] and May and Klatzky [50, Exp. 4], respectively. For an overview of several further spatial updating experiments in real and virtual environments and the measured average absolute pointing errors thereof, the reader is referred to the PhD thesis of Vuong [51, Section 1.3].

In the PhD thesis of Riecke [40], a series of experiments was conducted in order to investigate the influence of various cues in projection-based Virtual Reality systems on the ability of spatial updating. For the scope of this thesis, there are two major findings. First of all, the absence of proprioceptive and vestibular cues while moving through a virtual environment did not have an effect on the homing performance in a triangle completion task [40, Section 11.2]. Thus, proper spatial updating seems to be possible when only visual motion can be perceived. Secondly, alongside the *continuous spatial updating* process during self-motion, a complementary process called *instantaneous spatial updating* exists [40, Section 16.2]. This process relies on the recognition of salient features in the environment and is able to update a person's current reference frame accordingly. When the scene is well-known or heavily trained in advance, people seem to be able to reorient themselves instantaneously, even after discontinuous viewpoint changes as in teleportation [40, Chapter 14]. As a result, the absent continuous spatial updating process can be compensated by instantaneous spatial updating in these situations.

3.3 Distance Judgements

Proper spatial updating requires constantly relocating one's egocentric reference frame while moving through space. A key component is the ability of estimating and judging travelled distances. In 1997, Daniel Montello [52] has published a literature survey on information sources used for the perception of distances in real environments. It turned out that the *number of environmental features*, the *travel time* and the *travel effort* are three main complementary cues, with the number of environmental features having received the strongest empirical support.

In a desktop virtual environment, Bremmer and Lappe [53] have shown that the perception of only passive visual motion can be used for discriminating and reproducing travel distances. In their first experiment, subjects viewed two displacements and were asked to *compare* which of them was the longer one. Their second experiment included an active component, requiring the participants to *reproduce* a previously seen displacement. Both the comparison and the reproduction task could be completed with high accuracies. Redlick et al. [54] extended these findings by showing that strong passive visual motion in a head-mounted display environment was sufficient to *estimate* when a participant has reached a previously seen, currently invisible target along a corridor. Further exemplary measures of distance judgements include numeric *quantification* on an absolute scale [55] and line *sketches* of traversed paths [56].

Since the focus of this thesis is on head-mounted displays, the findings of Redlick et al. seem especially promising. On the other hand, however, several researchers have observed a general tendency to underestimate distances in these immersive virtual environments, which could have a negative influence on the overlying spatial updating process. The task which is commonly used in this context is similar to the one of Redlick et al.; the main difference is given by asking participants to *physically walk* to the previously seen target. A paper by Willemsen et al. [57] is one example of such a study, where mechanical aspects of head-mounted displays and their effects on distance compression were analysed in more depth. A broader overview over research on distance compression in immersive Virtual Reality is given by Interrante et al. [58], who have also found out that the compression effect decreases when the virtual environments are realistic replicas of their physical counterparts.

3.4 Discussion

Spatial awareness is a complex cognitive ability that prevents humans from getting lost during locomotion in real and virtual environments. This chapter has outlined different aspects of spatial awareness and summarised relevant measurement methods and findings for each category. Figure 3.1 recapitulates this literature survey by illustrating the relationships between the presented types of spatial awareness among each other.

Although initially assumed to grow sequentially, is has been shown that the three high-level types of spatial knowledge emerge concurrently during the spatial learning process. The most profound type of spatial awareness is survey knowledge, an allocentric and quantitative cognitive map of the environment. Spatial updating, on the other hand, is purely egocentric, requiring the user to constantly update the location of objects with

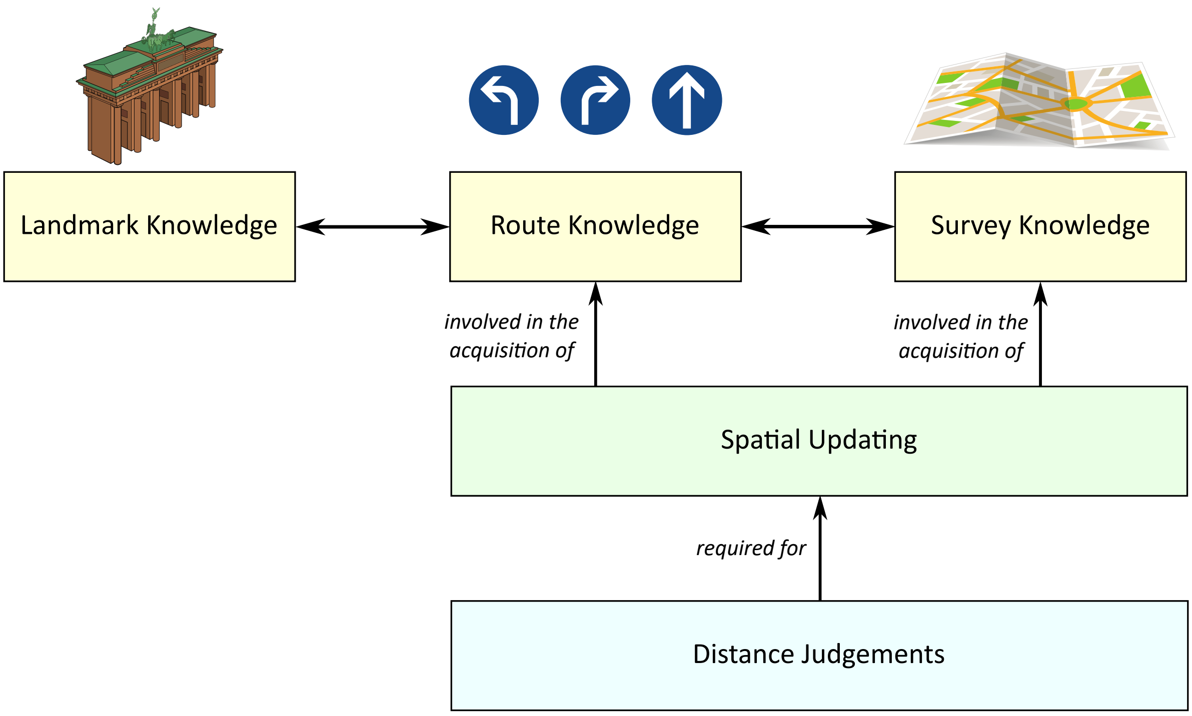


Figure 3.1: Different aspects of spatial awareness. The yellow boxes represent the high-level tripartite division of Siegel and White [30]. Spatial updating contributes to the acquisition of route and survey knowledge, and correct distance judgements are the prerequisite for accurate spatial updating.

respect to their current reference frame. Pointing towards previously seen objects is a commonly implemented task in spatial updating tests, but it was also listed as one of the three task categories for measuring survey knowledge. Thus, both abilities are closely related, with spatial updating being an egocentric sub-skill of acquiring allocentric survey knowledge. Moreover, it can also contribute to the development of route knowledge when routes are learned from direct experience. Since landmark knowledge is purely recognition-based, spatial processes are not involved in its formation. Another level deeper, correct distance judgements are a prerequisite for accurate spatial updating.

In order to maximize task performance and scene understanding in virtual environments, travel techniques should support the formation of sophisticated survey knowledge. However, creating and measuring advancements in this type of knowledge is resource-consuming and may not be accomplished at all for some people [31]. As a result, this thesis aims at investigating the underlying process of spatial updating in more detail. For this purpose, pointing towards previously seen objects is an interesting task; it is a classic spatial updating measure which is also used to quantify one aspect of survey knowledge. In order to keep the working memory's load low, it has been decided to require the update of one target only, namely the origin of a route. Thus, users will be asked to follow a route using a specific travel technique until being asked to point the straight-line path to where they came from.

Riecke's experiment [40, Chapter 14] demonstrated that once a scene is perfectly known, even the simplest form of passive teleportation triggers correct spatial updating. This finding makes teleportation studies based on pre-learning the environment impracticable since equal results can be expected for teleportation and continuous motion techniques. As a consequence, the user study conducted in this thesis will compare travel techniques in unknown virtual environments only.

The steps towards the design of the user study will be detailed in the upcoming chapter.

4 Designing a Spatial Updating Study

"If you go into this blizzard without a plan, you'll get lost... and that'll only lead to disaster, trust me."
— Ashei, THE LEGEND OF ZELDA: TWILIGHT PRINCESS

The last chapter described different facets of spatial awareness and suggested spatial updating as the ability to be tested with different travel techniques in the envisioned user study of this thesis. Pointing to the origin of a route was identified as a useful measure to be investigated. In order to choose concrete technique instances to be compared, Chapter 2 introduced the design spaces of both steering and teleportation. It was decided that basic implementations of pointing-directed steering and user-initiated jumping with instant transitions should be compared to each other.

The goal of this chapter is to describe the development process of a spatial updating in immersive head-mounted display environments and justify the involved decisions. While the concrete study protocol will be given in Chapter 5, this chapter provides the necessary background information on the implemented spatial updating task. For this purpose, Section 4.1 describes an error model for this type of tasks and discusses the influences of different travel techniques on it. Section 4.2 continues by making informed decisions on route layouts to be travelled by the participants. Section 4.3 explains how these abstract route descriptions are transformed into explorable virtual environments. Finally, Section 4.4 discusses the design of a distractor task, which can be used to draw the user's attention away from their primary goal of spatial updating in order to control the effects of task solving strategies.

4.1 The Encoding-Error Model

Triangle completion tasks are commonly used in traditional, real world spatial updating experiments (e.g. [59, 60]). In these studies, blindfolded participants are led along two edges of a triangle and are then asked to point along or actively walk the straight-line path to the origin. Fujita et al. [61] have developed an error model for these task setups, which distinguishes three consecutive phases that are potentially prone to errors. This model is illustrated in Figure 4.1. First, during the *encoding phase*, the subject accumulates all motion perceptions into a mental model of the travelled route. At the end of the second triangle edge, *mental spatial reasoning* follows, in which the subject computes the path needed to travel back to the origin. Finally, in the *execution* phase, this computed path is walked or indicated by pointing. The authors furthermore hypothesised a model, the *encoding-error model*, which attributes all systematic errors to the encoding phase only and found support in the results of triangle completion tasks. Péruch et al. [62] have shown that this assumption is also met for purely visual path integration in a desktop virtual environment. However, Fujita et al. state that this model is not true anymore for more complex routes, which is supported by further research underlining that mental spatial reasoning can also be a non-negligible error source (e.g. [63]).

A similar three-stage model can be applied to the planned spatial updating user study of this thesis. In the encoding phase, subjects accumulate the visual distance cues offered by each travel technique and derive a mental model of the travelled route. Steering offers

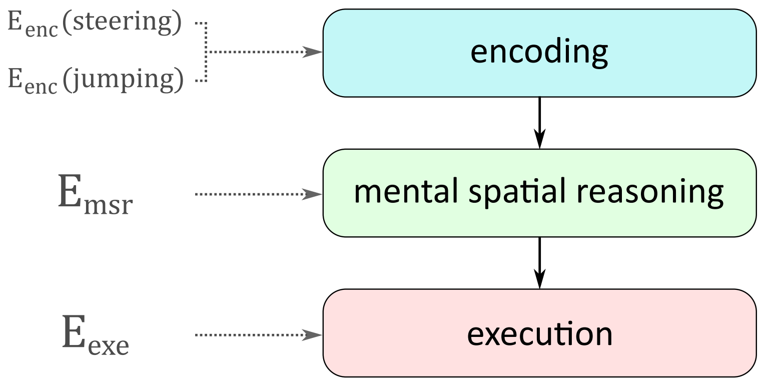


Figure 4.1: The three stages used in the encoding-error model by Fujita et al. [61]. Errors may potentially occur in each of the phases (indicated by the *E*-terms in grey). Choosing a different travel technique is equivalent to exchanging the available cues used in the encoding phase.

the perception of a motion flow for a specific amount of time whereas jumping gives hints about countable steps of certain lengths. In both cases, however, distances can be estimated while not moving at all by investigating environmental features. Furthermore, the turns are perceived identically for both techniques by physical rotation at the corner points. At the terminal location, mental spatial reasoning is used to compute a pointing direction to the start from the encoded segment lengths. Finally, in the execution phase, the subjects point to the computed direction using a tracked input device. The planned user study aims at analysing the effects of different perceptual inputs during the encoding phase on the accuracy of spatial updating. In other words, it focuses on the analysis of $E_{enc}(steering)$ and $E_{enc}(jumping)$ as visualised in Figure 4.1.

When using pointing to the origin, only a small and constant errors are expected in the execution phase that may result from hand tremor and tracking noise. Thus, observed spatial updating errors can be fully attributed to encoding and mental spatial reasoning. The distinction between effects of these two subprocesses, however, is not so clear. In order to find an answer to this question, Riecke et al. [64] compared spatial updating performances of individuals with more general tests on their spatial reasoning abilities. They found correlations between both measures and argue that in their experimental setup, this shows that "the mental determination of the homeward trajectory was not void of systematic errors". Thus, for the envisioned spatial updating study of this thesis, it seems useful to perform similar spatial ability pre-tests in order to be able to attribute errors to mental spatial reasoning instead of encoding if necessary.

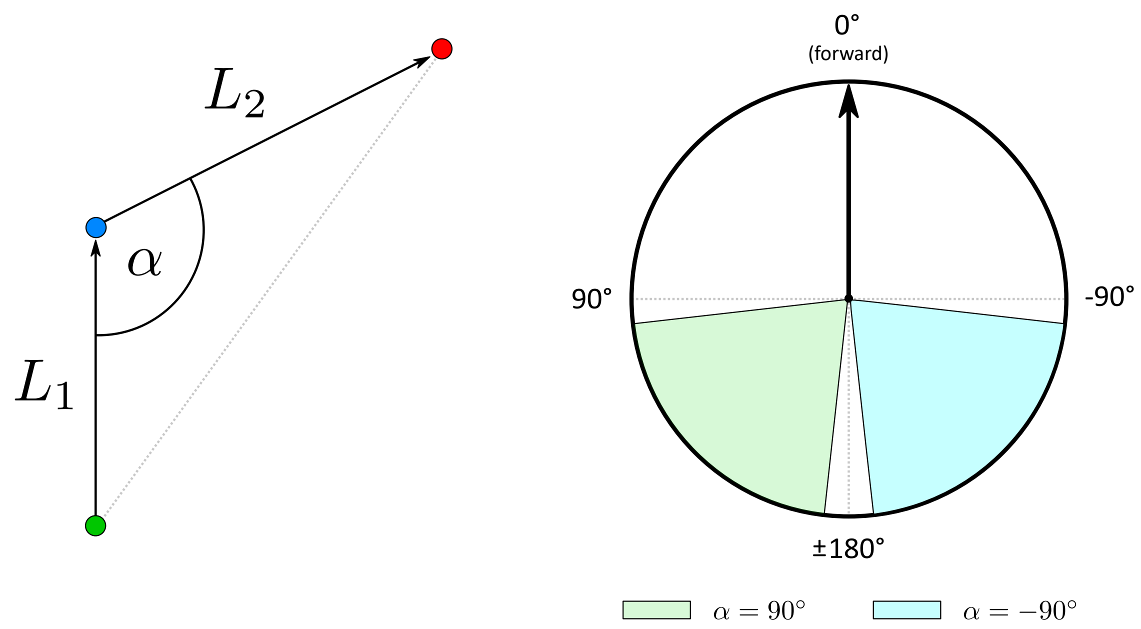
4.2 Spatial Updating Route Design

Section 3.4 motivated an experimental task for studies on spatial updating. Participants will be asked to follow a given route and point back to its origin after reaching the end. However, the shape, complexity and length of these routes are further parameters that need to be carefully controlled. Presumably, they strongly affect the involved perception and memorization process. In terms of complexity, there are two extremes in route design. The easiest non-trivial layout is given by triangular routes as described in the previous section together with the original encoding-error model. On the other end of the spectrum, there are long organic routes with curved segments as they can be found, for example, in some European cities.

4.2.1 Triangular Routes

In order to keep the parameter space manageable, triangular routes seem especially promising at first sight. Figure 4.2(a) illustrates an exemplary route layout of this type. Adjustable parameters are the lengths L_1, L_2 of the two segments to be travelled and the enclosed angle α. Because the rotation encodings for both travel techniques to be compared are the same (see Section 4.1), it seems reasonable to keep α simple and constant. As we want to enable turning to both left and right, it has thus been decided to only consider routes with $\alpha = \pm 90°$.

A simulation of different (L_1, L_2) combinations was run to get an impression of the solution space resulting from the spatial updating task. For this purpose, $L_1 \in [0.1; 0.9]$ was chosen at random, and $L_2 = 1.0 - L_1$ was set. Afterwards, the correct response angle of the spatial updating task was computed. Figure 4.2(b) shows the distribution of this angle for



(a) Exemplary layout of a triangular route used in triangle completion tasks. The green, blue and red circles mark the start, checkpoint and end positions, respectively. Adjustable parameters are the lengths of the two segments L_1, L_2 to be travelled and the enclosed angle α.

(b) Correct response angle distribution of the spatial updating task for triangular routes with $L_1 \in [0.1; 0.9]$ and $L_2 = 1.0 - L_1$. The green and blue areas correspond to correct response angles after left and right turns, respectively. They range from $\pm 96°$ to $\pm 174°$.

Figure 4.2: Analysis of triangular routes for the spatial updating task.

multiple simulation runs depending on the turn direction at the checkpoint. It is visible that once the turn direction is known, the solution space reduces to a range smaller than 90°. Hence, even when a user always guesses by pointing to ±135°, their maximum error will still be smaller than 45°.

4.2.2 Rectangular Routes

The response angle spread and the resulting small guessing error of triangular routes are undesired properties for the envisioned user study, which means that the route complexity needs to be increased. The next level of difficulty is given by adding a third segment to a triangular route layout, which results in two turns to be performed by the user. Sticking to the aforementioned angle constraints, both turns can be either left (L) or right (R), which yields four possible turn combinations: LL, LR, RL and RR. Figure 4.3 visualizes these four path layouts for a fixed set of segment lengths L_1, L_2 and L_3.

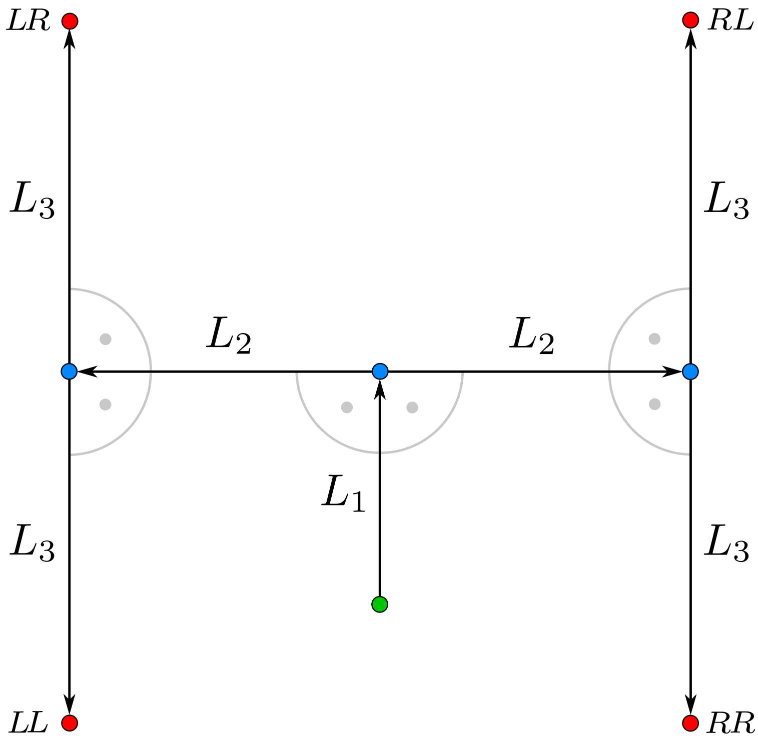
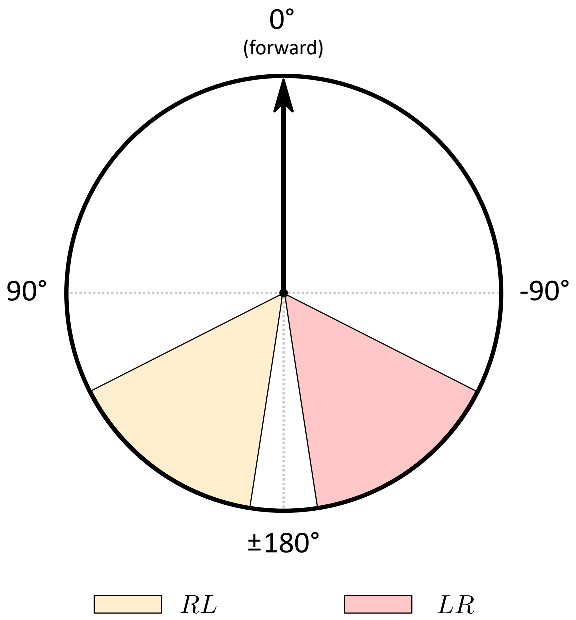
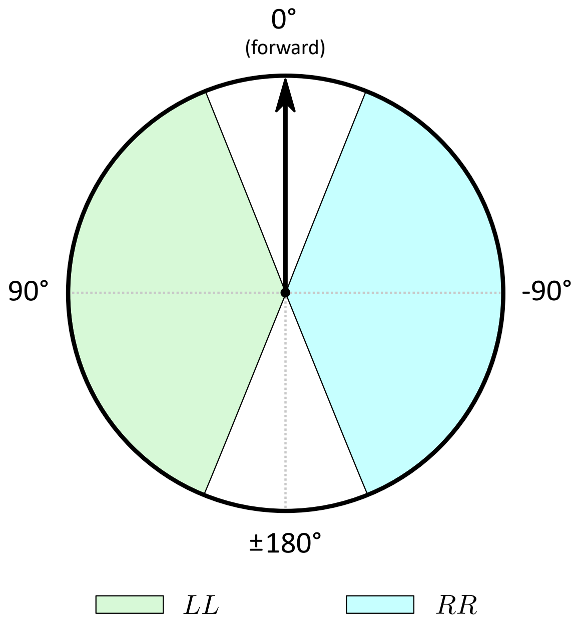


Figure 4.3: Adding a third segment to a triangular route results in two turns to be executed by the user. As both turns can be either left or right, four possible endpoints emerge. This illustration visualizes the corresponding paths with the green, blue and red circles marking start, checkpoint and end positions, respectively.



(a) When considering the correct response angles of all RL and LR routes, it turns out that the distributions are even smaller than the ones of triangular routes. They range from ±124° to ±171°. This makes RL and LR routes impractical for the user study.



(b) LL and RR routes offer a much wider spectrum of correct response angles from ±22° to ±158°. The length of the third segment in relation to the first one determines whether the user stops in front of, at the same height or behind the start position.

Figure 4.4: Correct response angle distributions of the spatial updating task for rectangular routes with the described segment length choices.

For the simulation of the correct response angle spreads of the spatial updating task, it was decided that the three segments should be initially different in their lengths. Hence, there is a short, a middle and a long segment of lengths $\frac{1}{6}$, $\frac{2}{6}$ and $\frac{3}{6}$, respectively. However, this discrete choice would lead to a total of six combinations only. As a result, a jitter algorithm was applied, which chooses two segments i and j and modifies their lengths by randomly chosen factors $\lambda_i, \lambda_j \in [0.8; 1.2]$. The remaining segment k is set to have length $L_k = 1.0 - L_i - L_j$ in order to obtain routes of same length.

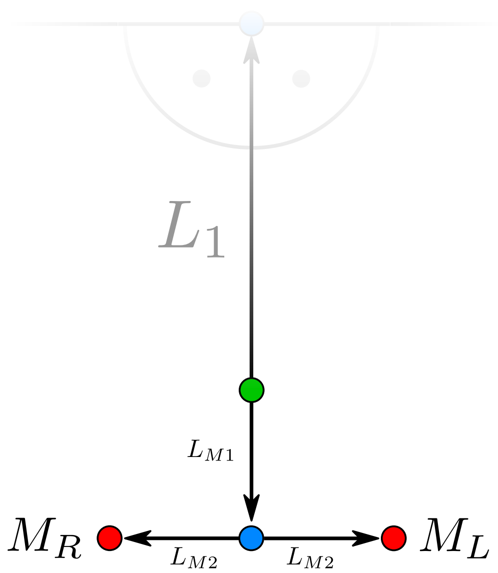
Figure 4.4 shows the distributions of the correct spatial updating response angles for multiple runs of the above-mentioned segment length choices. When considering the correct response angles of all RL and LR routes in Figure 4.4(a), it turns out that the distributions are even smaller than the ones of triangular routes, which makes RL and LR routes also impractical for the user study. The LL and RR routes illustrated in Figure 4.4(b), on the other hand, offer a much wider spectrum of correct response angles. This is because when performing the same turn twice, the length of the third segment in relation to the first one determines whether the user stops in front of, at the same height or behind the start position. Due to this large correct response angle spread, it has been decided to use instances of LL and RR routes in the spatial updating study of this thesis. The concrete parameter choices for each individual route will be explained as part of the user study procedure in Chapter 5.

4.2.3 Manifestation Task

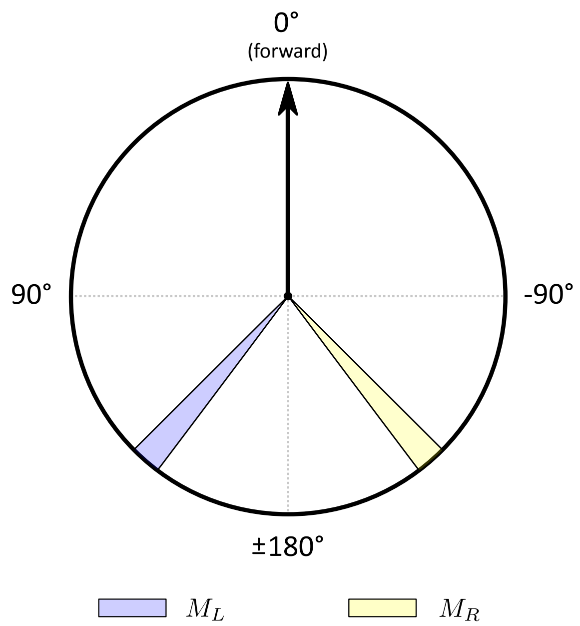
LL and RR routes offer a larger correct response angle spread than the triangular counterparts and are thus more suitable for the spatial updating study of this thesis. However, when given a concrete pointing error of a user, it is challenging to judge how good this pointing performance is on an absolute scale, which is due to the lack of proper baseline measurements. We reasoned that very short and simple triangular routes could be used as baseline measurements before performing the experimental task with a longer and more complex rectangular route. Traversing this pre-route and pointing to its origin will be referred to as the *manifestation task*.

In order to combine a rectangular route with a manifestation route in one layout, it has been decided to extend the setup visualized in Figure 4.3 by two segments of lengths L_{M1} and L_{M2} starting in the opposite direction of the rectangular route. This extension is shown in Figure 4.5(a) for both possible turn directions at the checkpoint. For the purpose of the envisioned user study, $L_{M1} = \frac{1}{20} \cdot (L_1 + L_2 + L_3)$ and $L_{M2} = \mu \cdot (L_1 + L_2 + L_3)$ were set, where μ is chosen randomly with $\mu \in [\frac{1}{20}; \frac{1}{15}]$. Figure 4.5(b) shows the resulting correct response angle spreads depending on the turn direction at the checkpoint.

Due to the similar lengths L_{M1} and L_{M2} for all possible choices of μ, the angle spread is very small. When the total length of the manifestation route is very short, the pointing task should be very easy to complete. Users simply need to travel around a corner and point back to their origin location. Such a manifestation task thus gives a good baseline on how accurate the pointing performance can become in general. It furthermore ensures that the users have understood their task correctly.



(a) The manifestation route is a very short triangular route, which starts in the opposite direction of the actual rectangular route. The green start position is the same as the one shown in Figure 4.3), and the blue and red circles symbolize checkpoint and possible end positions, respectively.



(b) The correct response angle spread of the manifestation task is very small (from ±135° to ±143°) since the lengths of both segments have been chosen to be very similar.

Figure 4.5: Analysis of the manifestation task used to find proper baseline measurements of the spatial updating performance.

4.3 Virtual Environment

The previous section motivated the usage and parametrization of LL and RR routes in combination with triangular manifestation routes for the spatial updating task of the envisioned user study. This section is going to describe how these abstract route descriptions are transformed into explorable virtual environments. For this purpose, an urban context was chosen as application scenario.

Along the segments of route layouts, houses are placed in order to create the impression of navigating through a city. In total, four different house models are used repeatedly in combination with five different textures (see Figure 4.6). The houses are placed with random gaps between them and along all pathways illustrated in Figure 4.3. The created streets are visually enhanced by the random placement of further assets, namely trees, benches, lanterns and cars. Figures 4.7(a) and 4.7(b) show two exemplary egocentric views of a generated virtual environment.

The corner points of the currently active route are highlighted by cones. Green, blue and red cones visualize the start, checkpoint and the end positions of a route. Arrows on top of green and blue cones indicate the directions in which the route continues. Once the user has passed a blue cone, it disappears such that they can't estimate the distance of the next segment by simply turning around at its end. This is supported by the aforementioned algorithm to place houses with random gaps and along all four possible path layout shown in Figure 4.3.

As motivated in Section 3.4, the experimental task was to memorize the location of the green start cone and point to it after having travelled the route. When a user approached the red cone marking the end of a route, an arrow was attached to their controller (see Figure 4.7(c)). The user was then asked to indicate the straight-line path to the start position of the travelled route, represented by the green cone. The current orientation of the arrow in the plane was confirmed by pressing a separate button on the controller not used for navigation.

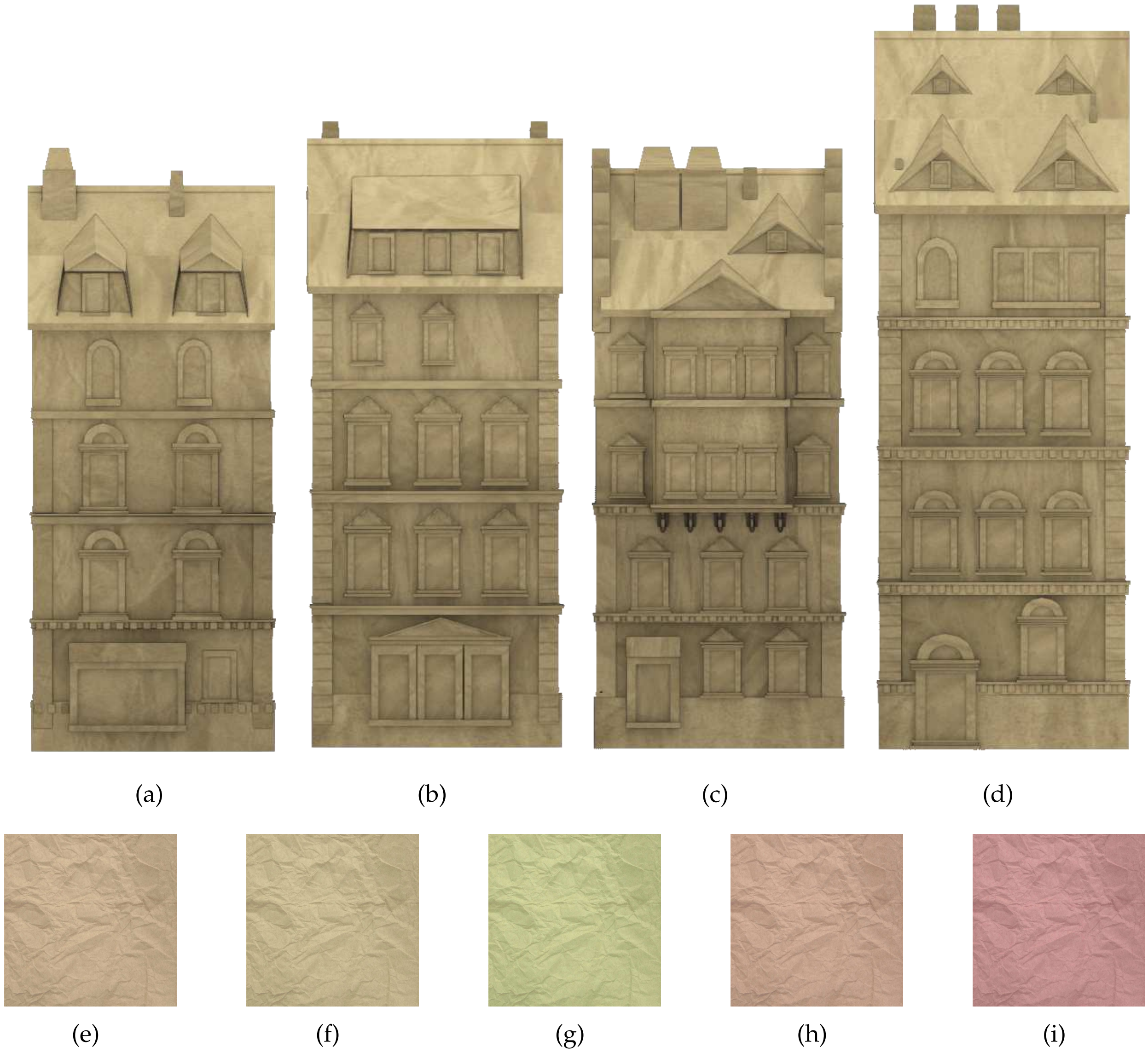
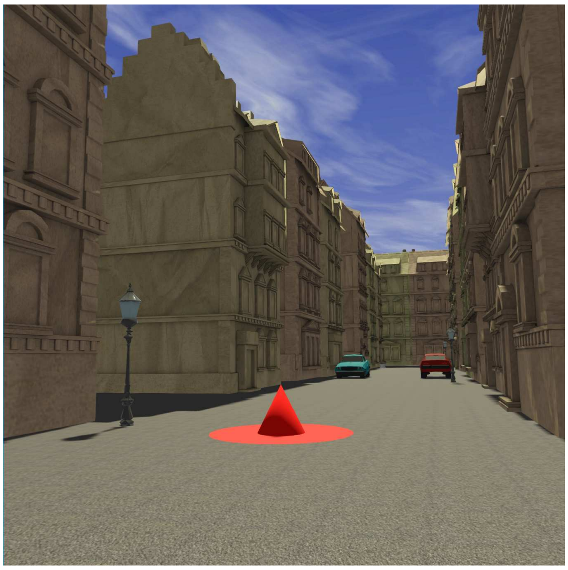
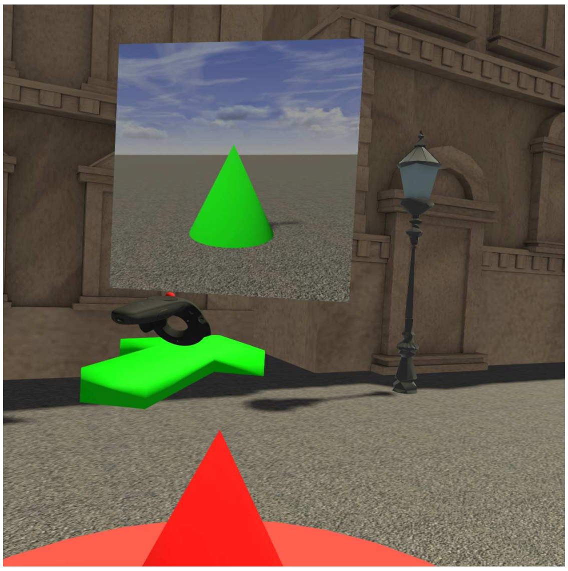


Figure 4.6: Four house models (a-d) are used in combination with five different textures (e-i) in order to build cities along the routes to be travelled by the users.

(a) Colored cones symbolize waypoints of the currently loaded rectangular route. The green and blue cones mark the start and a checkpoint, respectively. Arrows on top of the cones indicate the directions in which the route continues.



(b) The end of a route is marked by a red cone without any further direction indicators. When entering the surrounding area, the view changes to the one of (c), and the spatial updating performance of the route's origin is measured.



(c) Spatial updating of the route's origin is tested by attaching an arrow to the user's controller and asking them to indicate the straight-line path to the green cone, which is shown as a picture above the controller.

Figure 4.7: Three exemplary egocentric views of a randomly generated city around a rectangular route. The spatial updating task is to memorize the location of a route's origin and point to it after all of its segments have been traversed.

4.4 Distractor Task

The main tasks of participants in the spatial updating study are to *encode* the distances of and turns between three segments, to relate them to each other, to convert this *mental spatial reasoning* into a pointing angle and to *execute* the computed pointing gesture. In Section 3.3, it was outlined that three complementary sources of information for perceiving distances are the number of environmental features, the travel time and the travel effort [52]. Depending on the travel technique, different of these information sources can deliver helpful cues for distance perception. Several pilot tests showed that users can actively focus on individual cues and develop distance perception strategies based on counting them. In the case of steering, for instance, some users tried to count the time needed to travel the segments. Others focused on counting the number of houses along each segment. Although these strategies did not result in perfect accuracies, they strongly biased the users' spatial updating responses. In order to avoid such counting strategies, it was decided to confront the user with a secondary task during travel.

The challenge of finding a proper distractor task is adjusting its difficulty. It should be difficult enough to eliminate counting strategies but not too demanding to significantly worsen the spatial updating performance. Rashotte [65, pp. 19-27] has summarised four spatial updating studies comparing the influences of non-spatial and spatial distractor tasks on the primary measure. Non-spatial tasks included counting backwards and repeating tape-recorded object names and nonsense syllables while spatial tasks involved performing irrelevant to-be-ignored movements. Although the four study results were ambiguous and did not point into a clear direction, both studies that showed no effect of the distractor task on the primary measure used non-spatial tasks. As a result, it was decided to use a non-spatial distractor task for this thesis as well. The main purpose of the task should be the elimination of counting strategies; therefore, it seems reasonable to involve numbers. However, performing calculations like counting backwards in steps of 3 seemed too distracting in pilot tests. Hence, it was decided to use a simpler exercise, which is a mixture of both non-spatial task types presented by Rashotte. During travel, the user is asked to listen to and repeat two-digit numbers verbalized by the experimenter. Once the user gives their answer, the next number follows. This task is very easy to fulfil without much cognitive effort, yet it seemed to effectively eliminate counting strategies in the pilot tests. This was still true when users actively tried to focus on counting.

5 User Study Procedure

"Please note that any appearance of danger is merely a device to enhance your testing experience."

— GLaDOS, PORTAL

The previous chapter illustrated important background considerations and design decisions which shape the formal spatial updating study of this thesis. Based on these thoughts, the goal of this chapter is to introduce the reader to the concrete user study procedure that has been carried out to investigate the effects of steering and jumping techniques on spatial updating. For this purpose, each individual stage of the study is explained in more detail in Sections 5.1 to 5.4. An overview of these stages is given graphically in Figure 5.1. Section 5.5 concludes this chapter by naming dependent variables

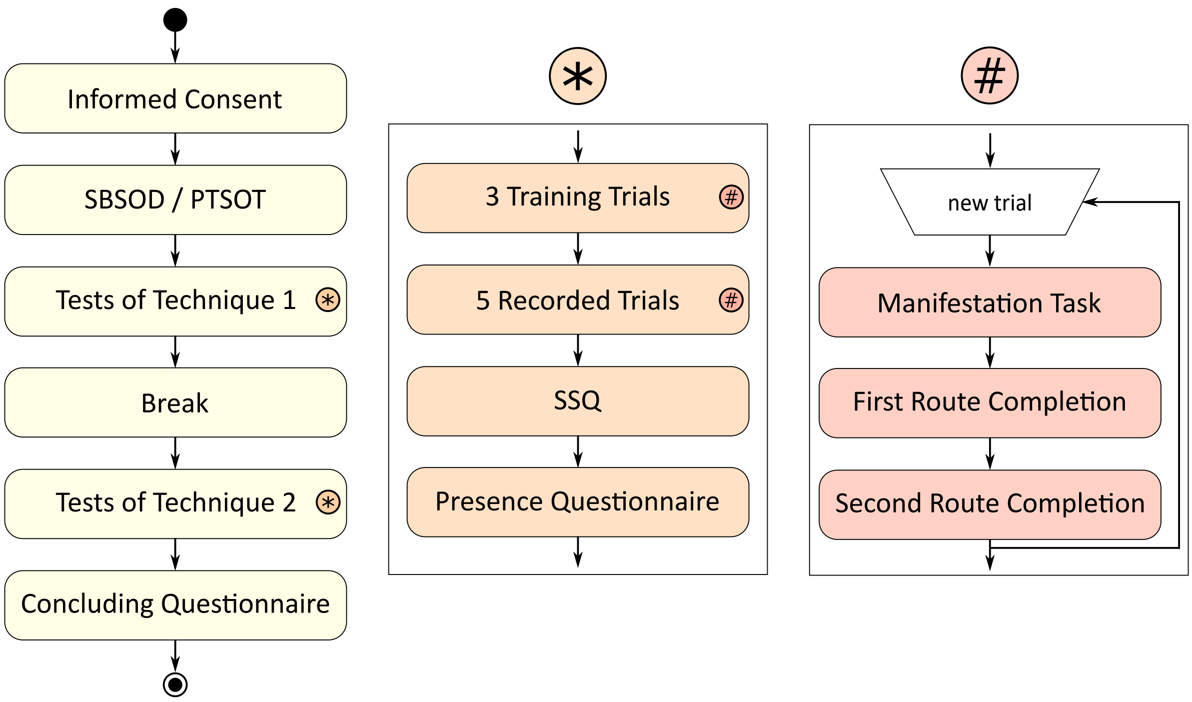


Figure 5.1: Graphical illustration of the user study procedure conducted to investigate the effects of steering and jumping techniques on spatial updating.

and hypotheses arising from the proposed study design. These hypotheses will be tested, evaluated and interpreted in the next chapter. All study materials and instructions were provided in both English and German variants.

5.1 Informed Consent

When arriving at the user study, each participant was asked to sign an informed consent form. Participants were briefed that their data were captured, processed and published anonymously and that they could withdraw from the study at any time if they did not feel well. Additionally, it was ensured by two questions that participants did not feel sick and that they were in their usual state of fitness. The exact wording of the English consent form can be found in Appendix A.1.

5.2 Pre-Tests of Spatial Abilities

As motivated in Section 4.1, it is reasonable to test the participants' general spatial abilities in order to investigate if mental spatial reasoning is a determining factor for task performance. However, the two spatial tests used in the studies of Riecke et al. [64] are quite time-intensive and not freely available. As a result, participants were asked to complete two shorter tests of spatial abilities: the Santa Barbara Sense-of-Direction Scale (see Subsection 5.2.1) and the Perspective Taking/Spatial Orientation Test (see Subsection 5.2.2). Both tests were performed on a standard 2D desktop computer setup as shown in Figure 5.2.

5.2.1 Santa Barbara Sense-of-Direction Scale (SBSOD)

The Santa Barbara Sense-of-Direction Scale (SBSOD) developed by Hegarty et al. [68] is a 15-item questionnaire asking participants to subjectively rate their spatial orientation skills. All questions are answered on a Likert scale from 1 to 7. A total sense-of-direction score is computed by averaging the individual responses after reversing the positively phrased items. For the exact wording of the English questions, the reader is referred to Appendix A.2.

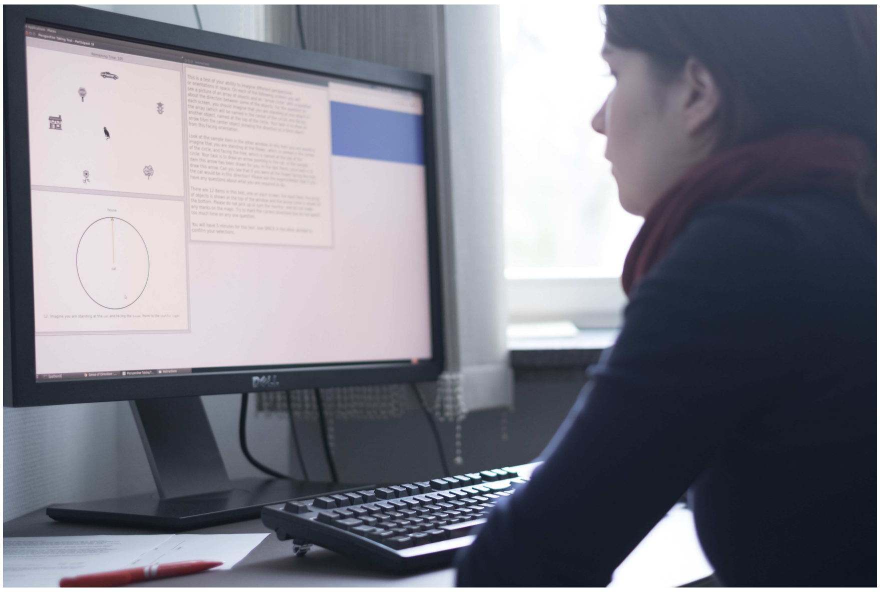


Figure 5.2: A standard 2D desktop computer setup was used for pre-tests of spatial abilities and questionnaires of the user study.

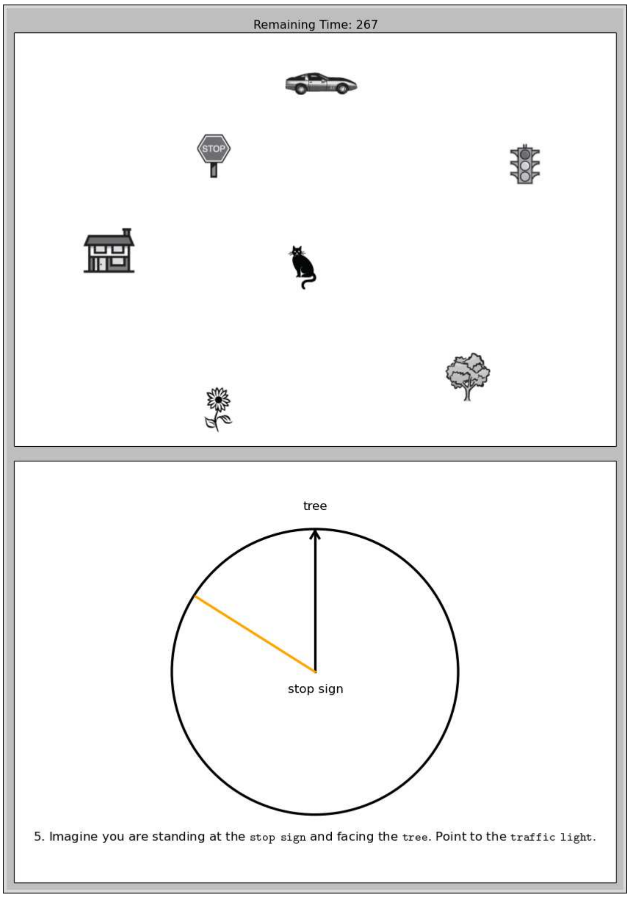


Figure 5.3: Screenshot of the implemented electronic version of the Perspective Taking/Spatial Orientation Test by Hegarty, Kozhevnikov and Waller [66, 67].

5.2.2 Perspective Taking/Spatial Orientation Test (PTSOT)

The Perspective Taking/Spatial Orientation Test (PTSOT) by Hegarty, Kozhevnikov and Waller [66, 67] is a more objective measure compared to the SBSOD. Participants are shown a set of spatially distributed objects and are asked to imagine standing at one of these objects facing the direction of another one. The task is to indicate on a circle in which orientation a third object is located with respect to the imagined view direction. It is not allowed to rotate one's head during the test. The total score is the average angular error over all 12 trials.

Originally, this test is given to the participants as a paper booklet. In order to save resources and to facilitate the evaluation, an electronic version was developed as a byproduct of this thesis. A personal correspondence with the lead author, Prof. Hegarty, yielded the information that according to studies in her own lab, performing the test electronically is as valid as its paper-based counterpart. The permission was granted to publish the source code online[1]. A screenshot of the user interface is given in Figure 5.3, and the exact wording of the tasks can be found in Appendix A.3.

5.3 Spatial Updating Sessions

After the successful completion of the pre-tests, the first of two spatial updating sessions in VR began. The purpose of each session was to test one specific travel technique only, with steering and jumping being presented in counterbalanced order. A five minute break separated the first session from the second one. The following subsections are going to illustrate the setup of the experiments in more detail.

5.3.1 Hardware Setup

The experimental task was performed using a HTC Vive head-mounted display, which offers both position and orientation tracking. The tracking space was approximately 3m x 3m in size, and the cables were mounted to the ceiling to avoid tripping over them.

1 https://github.com/TimDomino/ptsot

(a) The room in which the user study took place. A HTC Vive head-mounted display was used for the spatial updating sessions, and its cables were mounted to the ceiling to avoid tripping over them. The tracking space was approximately 3m x 3m in size.

(b) During travel, the experimenter read out numbers to be repeated by the participant (distractor task). Upon reaching the end of a route, the distractor task paused such that the participant could solely focus on pointing to the route's origin.

Figure 5.4: Two photographs taken from a spatial updating session of the user study.

The layout of the room is shown in Figure 5.4(a). To control the travel techniques, a Vive controller was used as shown in Section 2.4.

5.3.2 Travel Techniques

As motivated in Section 2.5, the concrete technique instances to be compared are pointing-directed steering (without field-of-view restrictions) and jumping with instant transitions. For jumping, the maximum reach of the bent ray was set larger than the longest segment such that each target could in theory be reached with a single jump. Users were instructed to complete the route with as few jumps as possible in order to maximize the spread on the steering-teleportation continuum. For steering, the maximum speed was set to 50 km/h since this resembles the maximum driving speed in German cities and was thus considered an ecologically valid value. To achieve equality between both conditions, a special instruction was also given for steering; the users were told to complete the routes with the fastest speed that still feels comfortable and controllable for them.

5.3.3 Trials

In order to familiarize the users with the travel technique and the task, each spatial updating session began with three training trials, in which the experimenter gave verbal instructions and feedback. Afterwards, five recorded trials without feedback followed.

For each individual trial, the user was placed in a new city built around a combined layout of manifestation and rectangular route as explained in Subsection 4.2.3 and Section 4.3. The total length of each rectangular route was $L_1 + L_2 + L_3 = 300m$; hence, the length of the manifestation route was $(L_{M1} + L_{M2}) \in [30m; 35m]$.

The participants were asked to perform tasks in three consecutive phases. In the first phase, the manifestation task was completed. In the second phase, the user returned to the previously indicated start position and began travelling the rectangular route. When the end of the route was reached, the user pointed back to the start as in the manifestation task. Afterwards, the user was reset to the start (one-time teleport) and asked to indicate where they came from. This is very similar to the passive one-time teleportation performed in the study of Bowman et al. [18]. Afterwards, the third phase began, in which the user was asked to complete the same rectangular route and both pointings again. This repetition was done in order to give the user a chance to improve the results. In total, a user completed five pointing tasks per trial. In parallel to travelling the rectangular route, the user was confronted with the distractor task (see Subsection 4.4). During the manifestation task and during pointing, no distractions were given. While Figure 4.7 has already illustrated some screenshots of the described trial procedure in the previous chapter, Figure 5.4(b) shows a photograph of a participant completing it.

The rectangular route parametrizations used in the study are illustrated in Table 5.1. The columns L_1, L_2, L_3 show the individual segment lengths as percentages while the column γ indicates the resulting correct response angle. The goal proximity to answer the spatial updating task (i.e. the radius of the red disk shown in Figure 4.7(c)) was 1.5m, resulting in a maximum deviation of γ by $\pm 2^\circ$ depending on the actual user position when performing the pointing.

The routes T1, T2 and T3 appeared in the training phase while the remaining ones were used for the recorded trials in a randomized order. The recorded routes were chosen to cover large parts of the spectrum that was shown in Figure 4.4(b). The turn directions (LL

Route ID	γ	L_1	L_2	L_3
T1	90°	0.33	0.33	0.33
T2	45°	0.50	0.33	0.17
T3	135°	0.33	0.17	0.50
1	30°	0.59	0.27	0.14
2	60°	0.46	0.18	0.36
3	90°	0.40	0.20	0.40
4	120°	0.19	0.39	0.42
5	150°	0.13	0.27	0.60

Table 5.1: Route parametrizations used in the spatial updating study (rounded to two digits). The correct response angle γ is shown depending on the three segment lengths L_1, L_2 and L_3 (given as percentages). The routes T1, T2 and T3 appeared in the training phase while the remaining ones were used for the recorded trials in a randomized order.

or RR) were assigned randomly but equally to the rectangular routes; the same holds for the turn direction of the manifestation task.

5.3.4 Post-Exposure Questionnaires

After the three training and five recorded trials have been completed, the user was asked to put the head-mounted display off and to return to the computer, where they were given two post-exposure questionnaires: the Simulator Sickness Questionnaire and the igroup Presence Questionnaire.

The Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [69] is a list of undesired symptoms a system may induce. Participants are asked to rate their subjective perception of each of the 16 symptoms on a four-point Likert scale. Based on these answers, subscores for nausea, oculomotor, disorientation and a total simulator sickness score can be computed. The English list of symptoms is given in Appendix A.4. It was topic of discussion whether the questionnaire should be given to the participants twice, namely before and after the exposure in order to compare the captured scores and obtain relative effects of the study conditions. However, the authors advise against a pre-exposure questionnaire with the condition that "a screening of 'unhealthy' subjects is required". The two additional questions asked in the informed consent form (Section 5.1) were suggested by Kennedy et al. to do so [69, p. 206]. Implications of performing pre- and post-exposure SSQs are investigated and discussed by Yuong et al. [70] in more detail.

The igroup Presence Questionnaire was developed by Schubert et al. [71] (available on the igroup's homepage[2]) and was validated to measure the subjective sense of presence in a virtual environment. It consists of 14 questions to be rated on a 7-point Likert scale. From the answers, scores for the perceived spatial presence, involvement and experienced realism can be computed. An additional general question forms a score describing the "sense of being there". The exact English wordings of the questions and the corresponding anchors of the Likert scale can be found in Appendix A.5.

5.4 Concluding Questionnaire

After the spatial updating sessions for both travel techniques were completed, participants were asked to fill in a final concluding questionnaire involving questions on technique preferences and demographics. Furthermore, it was asked for strategies used to solve the spatial updating task. This had the purpose to find out if the distractor task really eliminated counting strategies as intended. The concrete layout of the concluding questionnaire in English is given in Appendix A.6. After the concluding questionnaire was completed, the user study session terminated, and each participant received an expense allowance of 10 euros.

5.5 Dependent Variables and Hypotheses

The user study procedure illustrated in this chapter allows the measurements of several dependent variables. Based on previous findings in the literature and the research questions of this thesis, a set of hypotheses can be formulated about each variable. The following subsections motivate and explain these hypotheses in more detail.

2 `http://www.igroup.org/pq/ipq/`

5.5.1 Pointing Accuracy

Pointing to previously seen targets is the main measurement to quantify spatial updating performance in this user study. In particular, a user has to perform five pointing tasks per trial (see also Subsection 5.3.3):

- point to the green start cone after travelling the manifestation route (*manifestation error*)
- point to the green start cone after travelling the rectangular route for the first time (*first point-to-start error*)
- point to the red goal cone after being teleported back to the green start cone (*first point-to-goal error*)
- point to the green start cone after travelling the rectangular route for the second time (*second point-to-start error*)
- point to the red goal cone after being teleported back to the green start cone (*second point-to-goal error*)

The terms in brackets refer to the names of corresponding errors and will be used in the remainder of this thesis. Related hypotheses are given in following subsections.

Accuracy by Travel Technique

H_1: The point-to-start error differs for steering compared to jumping.

H_{1a}: The first point-to-start error differs for steering compared to jumping.

H_{1b}: The second point-to-start error differs for steering compared to jumping.

H_2: The point-to-goal error differs for steering compared to jumping.

H_{2a}: The first point-to-goal error differs for steering compared to jumping.

H_{2b}: The second point-to-goal error differs for steering compared to jumping.

$\mathbf{H_1}$ and $\mathbf{H_2}$ focus on the main research question of this thesis; they investigate whether travelling the rectangular route by different techniques results in a different pointing performance. Sub-hypotheses needed to verify an overlying hypothesis have been indicated by alphabetic enumeration. Since Bowman et al. [18] advise against teleportation in general, we could expect jumping to be worse than steering. However, the study setup, spatial awareness measure and travel techniques used for this thesis have been revised. The implemented active, user-initiated jumping technique offers more distance perception cues than passive one-time teleportation as performed by Bowman et al., and it may be possible that these cues are even more helpful for some participants than the ones of steering. In order to capture a potential effect in this opposite direction as well, it seems reasonable to formulate the hypotheses in an undirected fashion.

The point-to-start tasks and thus also $\mathbf{H_1}$ are used to investigate travel technique effects on spatial updating of the route's origin. The point-to-goal tasks, on the other hand, test if participants can perform a transfer of their obtained knowledge when they are one-time teleported back to the origin. Due to the lack of direct experience of the travelled path back to the origin, participants need to rely on their mental model of the route built beforehand. $\mathbf{H_2}$ analyses if the travel technique has an influence on this spatial reasoning process.

Learning by Repetition

$\mathbf{H_3}$**:** The pointing errors in the second run are smaller compared to the first run.

H_{3a}: For steering, the second point-to-start error is smaller than the first point-to-start error.

H_{3b}: For jumping, the second point-to-start error is smaller than the first point-to-start error.

H_{3c}: For steering, the second point-to-goal error is smaller than the first point-to-goal error.

H_{3d}: For jumping, the second point-to-goal error is smaller than the first point-to-goal error.

$\mathbf{H_3}$ assesses if travelling the route a second time helps the users to improve their results. In order to find out if the locomotion method has an influence on this potential learning effect, the point-to-start and point-to-goal errors are going to be evaluated in isolation for each travel technique.

Baseline Measurements

H_4: The manifestation error is smaller than all other pointing errors.

H_{4a}: The manifestation error is smaller than the first point-to-start error.

H_{4b}: The manifestation error is smaller than the second point-to-start error.

H_{4c}: The manifestation error is smaller than the first point-to-goal error.

H_{4d}: The manifestation error is smaller than the second point-to-goal error.

Across both travel techniques, the purpose of **H_4** is to confirm that the manifestation error gives a baseline measurement on how accurate the pointing performance can be in general. It should show that users can perform very simple pointing tasks with high accuracy and that this performance degrades when more difficult routes are travelled. A small manifestation error furthermore ensures that the users have understood the task correctly.

5.5.2 Travel Time

H_5: The time to travel the rectangular route is higher for steering than for jumping.

The travel time measurement of a rectangular route starts when the user crosses the horizontal line defined by the start cone. It ends when the red area around the goal cone (see Figure 4.7(b)) is entered. **H_5** expects a faster travel for jumping, which is reasonable as each straight segment can potentially be covered with one instant jump while steering requires to follow the segment's path constrained by a maximum speed.

5.5.3 Response Time

H_6: The point-to-start response time is higher for jumping compared to steering.

H_{6a}: The first point-to-start response time is higher for jumping compared to steering.

H_{6b}: The second point-to-start response time is higher for jumping compared to steering.

H_7: The point-to-goal response time is higher for jumping compared to steering.

H_{7a}: The first point-to-goal response time is higher for jumping compared to steering.

H_{7b}: The second point-to-goal response time is higher for jumping compared to steering.

Point-to-start response times are measured from entering the red area around the goal cone (see Figure 4.7(b)) until the pointing direction is confirmed by the user. Point-to-goal response times start directly after the one-time teleportation to the start cone and also last until the user confirmation. The hypotheses $\mathbf{H_6}$ and $\mathbf{H_7}$ are motivated by the work of Bowman et al. [18] since their study has used response times as the primary measure for spatial awareness. If jumping also had higher response times in this study, this would indicate that the involved mental spatial reasoning process is more complex compared to steering.

5.5.4 Simulator Sickness

H_8: The user's perceived simulator sickness is higher for steering than for jumping.

H_{8a}: The nausea score is higher for steering than for jumping.

H_{8b}: The oculomotor score is higher for steering than for jumping.

H_{8c}: The disorientation score is higher for steering than for jumping.

H_{8d}: The total simulator sickness score is higher for steering than for jumping.

The investigation of $\mathbf{H_8}$ aims at reproducing the main motivation of using jumping instead of steering techniques for travelling through immersive virtual environments. The sensory conflict between the visual and the vestibular system introduced by steering is often presumed to be a major factor influencing simulator sickness [16, 17]. If this was also true in the present study setup, each individual score of the SSQ should be higher for steering than for jumping.

5.5.5 Presence

> **$\mathbf{H_9}$:** The user's perception of presence is higher for steering than for jumping.
>
> ***H_{9a}*:** The general presence score (PRES) is higher for steering than for jumping.
>
> ***H_{9b}*:** The spatial presence score (SP) is higher for steering than for jumping.
>
> ***H_{9c}*:** The involvement score (INV) is higher for steering than for jumping.
>
> ***H_{9d}*:** The experienced realism score (REAL) is higher for steering than for jumping.

As Bowman et al. [18] have also stated that their variant of passively induced one-time teleportation led to a reduced sense of presence, $\mathbf{H_9}$ investigates if this observation does still hold for the actively executed jumping variant of this user study. Since steering is a travel metaphor known from real life as opposed to the metaphor of jumping, it is reasonable to assume higher presence values for steering in all four categories of the igroup Presence Questionnaire.

5.5.6 Correlations with other spatial ability measures

H_{10}: The SBSOD score correlates negatively with the mean error of the PTSOT.

H_{11}: The SBSOD score correlates negatively with the overall task error.

H_{11a}: The SBSOD score correlates negatively with the overall task error of steering.

H_{11b}: The SBSOD score correlates negatively with the overall task error of jumping.

H_{12}: The PTSOT mean error correlates with the overall task error.

H_{12a}: The PTSOT mean error correlates with the overall task error of steering.

H_{12b}: The PTSOT mean error correlates with the overall task error of jumping.

The Santa Barbara Sense-of-Direction Scale is a subjective rating of spatial skills while the Perspective Taking/Spatial Orientation Test forms its results solely based on objective measures. **H_{10}** was designed to find out if a good result in one of these tests also correlates with a good result in the other one. Based on the illustrations in Section 4.1, **H_{11}** and **H_{12}** aim at investigating if a positive result in either of the tests also correlates with a better overall task performance in the spatial updating study. The overall task error of a participant is given by averaging all point-to-start and point-to-goal errors to a single value. A correlation of this value with spatial abilities would imply that mental spatial reasoning is a determining factor of the results.

6 User Study Evaluation

"Your true face... What kind of... face is it? I wonder... The face under the mask... Is that... your true face?"
— Moon Child, THE LEGEND OF ZELDA: MAJORA'S MASK

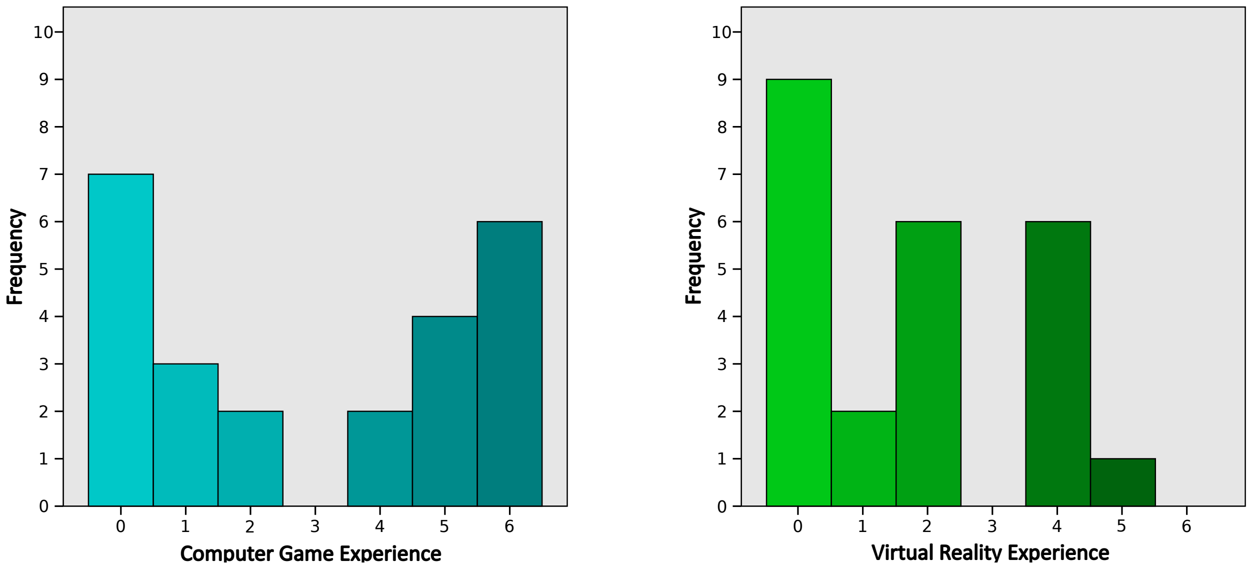
The previous chapter described a user study procedure investigating the effects of steering and jumping techniques on spatial updating in immersive virtual environments. Section 5.5 listed several hypotheses on the effects of the tested conditions. The purpose of this chapter is to evaluate and interpret these hypotheses statistically using the data of 24 study participants.

All statistical procedures, methods and result reports were chosen as suggested by Andy Field's textbook on statistics [72]. The means, medians and standard deviations are abbreviated by M, Mdn and σ, respectively. When analysing data for normality, a visual inspection of the normal QQ-plots was used in combination with the Shapiro-Wilk Test [73] since the latter was shown to have the largest statistical power compared to other normality tests [74]. When reporting on effect sizes r, the threshold values introduced by Cohen [75] were applied, with 0.1, 0.3 and 0.5 representing small, medium and large effects, respectively. The default significance level was $\alpha = 0.05$; α-corrections, if required, were performed using the Bonferroni method [72, pp.68-69].

Section 6.1 and Section 6.2 start with descriptives and demographics of the participants and their subjective ratings of the tested travel techniques. Sections 6.3 to 6.8 continue by evaluating the previously presented hypotheses in the same order of Section 5.5. Finally, Section 6.9 concludes this chapter by interpreting and discussing the presented statistical results.

6.1 Participants

In total, 25 subjects participated in the user study. All participants had normal or corrected-to-normal vision. The data of one participant was excluded since they stated to have used a counting strategy despite the presence of the distractor task. The age of the remaining 17 males and 7 females ranged between 19 and 38 years ($M = 25.54, \sigma = 4.88$). All participants were either students or employees of our university, with half of them having a background in Computer Science. Figure 6.1 shows the distributions of computer game experience and VR experience as stated in the concluding questionnaire. In terms of computer game experience, both extremes were equally present (bimodal distribution). Concerning Virtual Reality, some advanced subjects participated, but the majority had low to none prior experience.



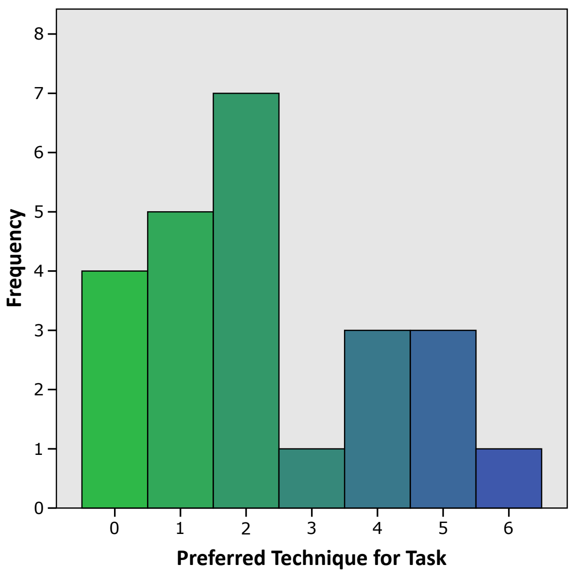
(a) "How do you rate your previous experience with 3D computer games?" (0 - very small, 6 - very high), $M = 2.96, \sigma = 2.55$

(b) "How do you rate your previous experience with Virtual Reality?" (0 - very small, 6 - very high), $M = 1.79, \sigma = 1.74$

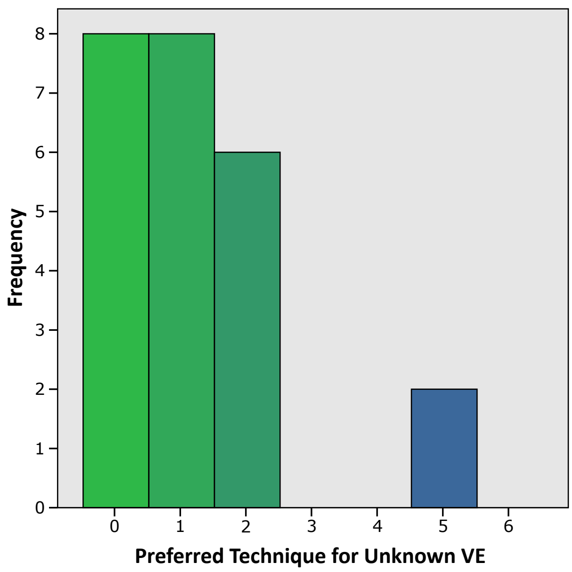
Figure 6.1: Histograms illustrating the participants' prior experience with 3D computer games and Virtual Reality as captured by the concluding questionnaire.

6.2 Travel Technique Preference

Figure 6.2 shows the responses given to two of the three technique preference ratings in the concluding questionnaire. The left end of the scale represents a strong preference for steering (green) while the right end indicates the equivalent for jumping (blue). In all questions, the majority of participants made their choice in the direction of steering. This tendency was particularly strong when asked which technique was preferred for the exploration of unknown virtual environments in general (Figure 6.2(b)). When asked to indicate the preferred technique to solve the performed spatial updating task, however, more participants expressed high preferences for jumping as well (Figure 6.2(a)). The third question focusing on which technique was more fun to use (not illustrated as a histogram) yielded a bimodal distribution at both ends of the scale, with a higher peak for steering than for jumping ($M = 2.17, \sigma = 2.37$).



(a) "Which technique do you prefer to solve orientation tasks like this?" (0 - steering, 6 - jumping), $M = 2.29, \sigma = 1.81$



(b) "Which technique do you prefer to explore an unknown virtual environment?" (0 - steering, 6 - jumping), $M = 1.25, \sigma = 1.39$

Figure 6.2: Histograms illustrating the participants' travel technique preference as captured by the concluding questionnaire.

6.3 Pointing Accuracy

This section focuses on the evaluation of pointing errors, which quantify the spatial updating performance. In order to do so, each of the five pointing errors was averaged over the trials of a spatial updating session to a single value. As a result, $N = 24$ per pointing task per travel technique holds. Subsection 6.3.1 analyses if the order of travel techniques had a significant influence on the pointing performance. The remaining subsections continue by evaluating $\mathbf{H_1}$ to $\mathbf{H_4}$ in the same structure as Subsection 5.5.1.

6.3.1 Order Effects

In order to analyse if the order of travel techniques had an influence on the pointing accuracy, the participants' data were split into two distinct groups based on the order in which the travel techniques were presented. It was then investigated for both techniques separately whether the pointing errors were significantly better in the second appearance of the respective technique. For normally distributed errors, the independent t-test was used and means were reported; otherwise, the non-parametric Mann-Whitney U-Test was executed and medians were reported.

The results are presented in Table 6.1 for steering and Table 6.2 for jumping. The columns *first* and *second* state descriptive statistics of the respective error formed by the group who used the travel technique in their first and second spatial updating sessions, respectively. The column *test result* states the results of the statistical test used to compare the two groups. It is visible that none of the comparisons yielded a significant result. However, the manifestation tasks of both techniques and two further errors of steering show small effect sizes with slightly better results in the second run (indicated in red).

6.3.2 Accuracy by Travel Technique

Figure 6.3 shows the distributions of the mean errors for each of the five pointing tasks separated by travel technique. All of the comparisons needed for the sub-hypotheses of $\mathbf{H_1}$ and $\mathbf{H_2}$ contain at least one non-normally distributed variable, which is why the median-comparing Wilcoxon signed-rank test was performed. As the investigated values

	first	second	test result
manifestation error*	$M = 6.83°$, $\sigma = 4.24°$	$M = 4.98°$, $\sigma = 2.49°$	$t(22) = 1.304$, $p = 0.206, r = 0.257$
first point-to-start error*	$M = 17.37°$, $\sigma = 4.80°$	$M = 17.31°$, $\sigma = 7.72°$	$t(22) = 0.023$, $p = 0.982, r = 0.005$
first point-to-goal error	$Mdn = 20.17°$, $\sigma = 13.08°$	$Mdn = 18.11°$, $\sigma = 10.2°$	$U = 58, z = -0.808$, $p = 0.443, r = 0.165$
second point-to-start error*	$M = 16.91°$, $\sigma = 4.29°$	$M = 15.7°$, $\sigma = 6.26°$	$t(22) = 0.55$, $p = 0.588, r = 0.112$
second point-to-goal error	$Mdn = 14.72°$, $\sigma = 15.23°$	$Mdn = 15.73°$, $\sigma = 10.30°$	$U = 65, z = -0.404$, $p = 0.713, r = 0.082$

Table 6.1: Order effect analysis for **steering**. The columns *first* and *second* state descriptive statistics of the respective error formed by the group who used steering in their first and second spatial updating sessions, respectively. The column *test result* states the results of the statistical test used to compare the two groups. Errors marked with an asterisk (*) were normally distributed.

	first	second	test result
manifestation error	$Mdn = 5.78°$, $\sigma = 6.31°$	$Mdn = 5.06°$, $\sigma = 3.65°$	$U = 88, z = 0.924$, $p = 0.378, r = 0.189$
first point-to-start error	$Mdn = 21.12°$, $\sigma = 14.73°$	$Mdn = 16.72°$, $\sigma = 17.55°$	$U = 80, z = 0.462$, $p = 0.671, r = 0.094$
first point-to-goal error	$Mdn = 19.02°$, $\sigma = 19.76°$	$Mdn = 18.01°$, $\sigma = 15.18°$	$U = 67, z = -0.289$, $p = 0.799, r = 0.059$
second point-to-start error	$Mdn = 18.01°$, $\sigma = 11.01°$	$Mdn = 18.03°$, $\sigma = 8.99°$	$U = 75, z = 0.173$, $p = 0.887, r = 0.035$
second point-to-goal error	$Mdn = 17.37°$, $\sigma = 17.59°$	$Mdn = 17.16°$, $\sigma = 8.77°$	$U = 77, z = 0.289$, $p = 0.799, r = 0.059$

Table 6.2: Order effect analysis for **jumping**. The same structure as for Table 6.1 applies.

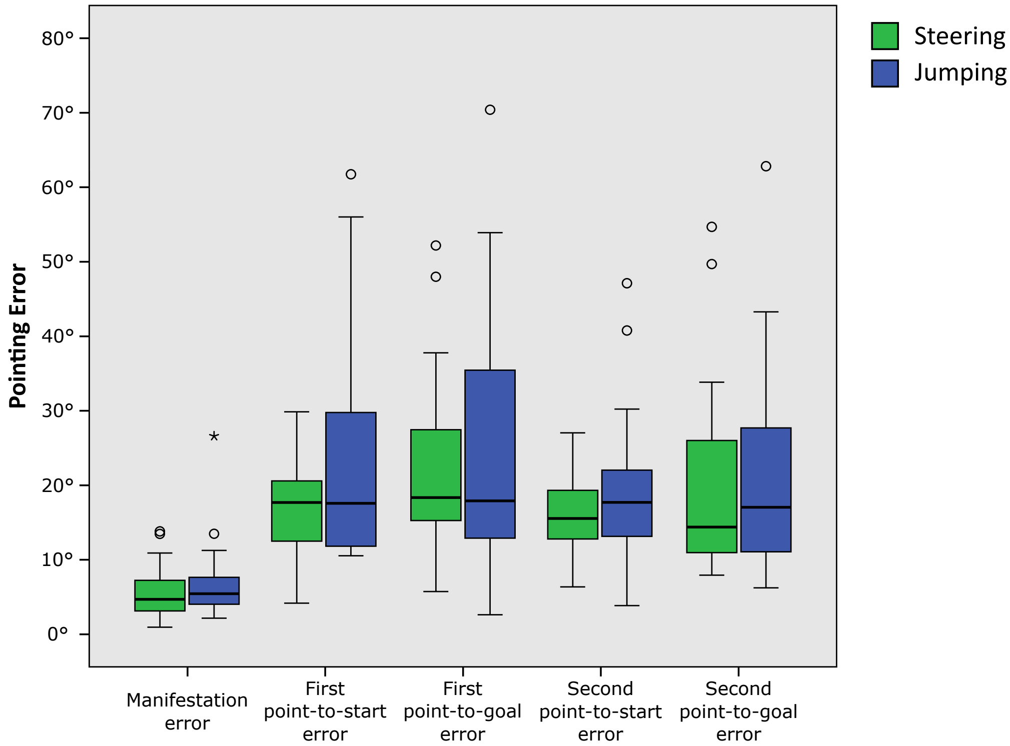
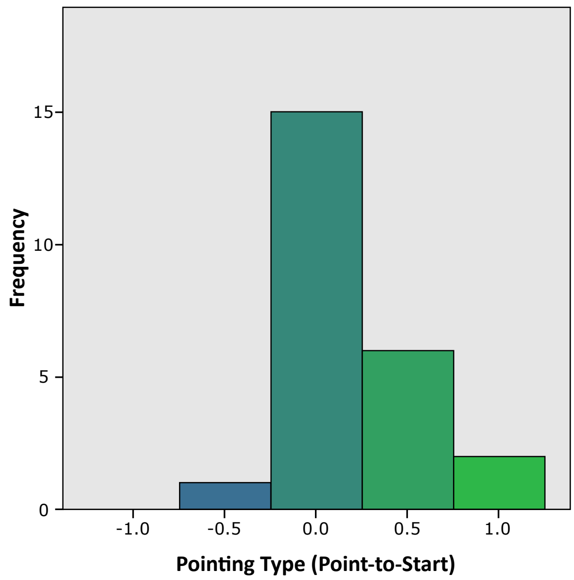
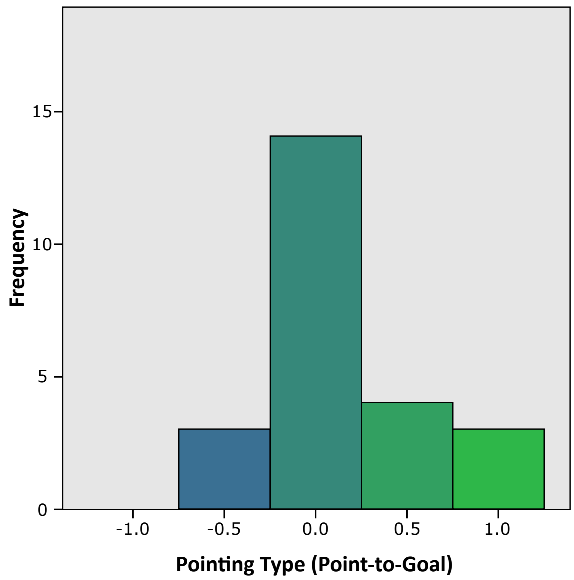


Figure 6.3: Boxplots illustrating the distributions of average errors (per participant) of the five pointing tasks separated by travel technique.



(a) Pointing types computed from the point-to-start tasks. A score of -1 represents a better performance when jumping while a score of +1 represents the equivalent for steering.



(b) Pointing types computed from the point-to-goal tasks. A score of -1 represents a better performance when jumping while a score of +1 represents the equivalent for steering.

Figure 6.4: Histograms illustrating the distributions of pointing types for the point-to-start and point-to-goal tasks, respectively.

will be used in four further statistical tests in Subsection 6.3.3, the Bonferroni-corrected α-level is $0.05/8 = \frac{1}{160}$.

The first point-to-start error of steering ($Mdn = 18.03°$, $\sigma = 6.29°$) did not significantly differ from the one when jumping ($Mdn = 17.91°$, $\sigma = 15.9°$), $z = 1.371$, $p = 0.17$, $r = 0.28$. Thus, $\boldsymbol{H_{1a}}$ needs to be rejected. However, a small effect size is present.

The second point-to-start error of steering ($Mdn = 15.87°$, $\sigma = 5.29°$) did not significantly differ from the one when jumping ($Mdn = 18.03°$, $\sigma = 9.85°$), $z = 1.486$, $p = 0.137$, $r = 0.303$. Thus, $\boldsymbol{H_{1b}}$ needs to be rejected. However, a medium effect size is present.

The first point-to-goal error of steering ($Mdn = 18.68°$, $\sigma = 11.74°$) did not significantly differ from the one when jumping ($Mdn = 18.23°$, $\sigma = 17.23°$), $z = 0.029$, $p = 0.977$, $r = 0.006$. Thus, $\boldsymbol{H_{2a}}$ needs to be rejected.

The second point-to-goal error for steering ($Mdn = 14.72°$, $\sigma = 12.76°$) did not significantly differ from the one when jumping ($Mdn = 17.37°$, $\sigma = 13.85°$), $z = 0.6$, $p = 0.549$, $r = 0.122$. Thus, $\boldsymbol{H_{2b}}$ needs to be rejected. However, a small effect size is present.

Since all sub-hypotheses were rejected, $\mathbf{H_1}$ and $\mathbf{H_2}$ need to be rejected as well. Nevertheless, it is interesting to have a look on the data in more detail to gain deeper insights into where the observed effect sizes may stem from. It is visible in the boxplots that for the variables where an effect was observed, the upper whisker of jumping is larger than for steering, indicating that higher errors were present in the data. This difference was not enough to produce significant results; nevertheless, it seems to be the cause for the observed small effect sizes.

As a result, it makes sense to investigate the data on a more fine-grained level. For this purpose, a delta score between the mean error of jumping and the mean error of steering was computed per pointing task for each participant. A positive delta score indicates a better performance when steering while a negative score does the equivalent for jumping. Scores around zero suggest that the travel technique did not have an influence on the pointing performance. For the resulting variables *DeltaFirstStart*, *DeltaFirstGoal*, *DeltaSecondStart* and *DeltaSecondGoal*, the respective standard deviations were taken as thresholds to judge which technique performed better. Deltas $< -\sigma$ and $> +\sigma$ were assigned the values -1 (jumping was better) and +1 (steering was better), respectively. The remaining deltas got a score of 0 for no difference. Finally, both point-to-start and both point-to-goal scores were averaged to a single score each. These scores were named *pointing type* and their distributions are visualized in Figure 6.4. Both distributions are very similar, with most of the scores being 0. However, when the score deviated from zero, this happened more frequently in favour of steering.

6.3.3 Learning by Repetition

Among the investigated variables, only the first point-to-start error and the second point-to-start error of steering were normally distributed. As a result, a paired-samples t-test was used instead of a Wilcoxon signed-rank test for their comparison. As the investigated values were already used in four statistical tests in the previous subsection, the Bonferroni-corrected α-level is $0.05/8 = \frac{1}{160}$.

For steering, the first point-to-start error ($M = 17.34°$, $\sigma = 6.29°$) did not significantly differ from the second point-to-start error ($M = 16.30°$, $\sigma = 5.29°$), $t(23) = 0.827$, $p = 0.417$, $r = 0.089$. Thus, $\boldsymbol{H_{3a}}$ needs to be rejected.

For jumping, the first point-to-start error ($Mdn = 17.91°$, $\sigma = 15.9°$) did not significantly differ from the second point-to-start error ($Mdn = 18.03°$, $\sigma = 9.85°$), $z = -1.343$, $p = 0.179$, $r = 0.274$. Thus, $\boldsymbol{H_{3b}}$ needs to be rejected. However, a small effect size is present.

For steering, the first point-to-goal error ($Mdn = 18.68°$, $\sigma = 11.74°$) did not significantly differ (adjusted alpha level) from the second point-to-goal error ($Mdn = 14.72°$, $\sigma = 12.76°$), $z = -2.057$, $p = 0.04$, $r = 0.42$. Thus, $\boldsymbol{H_{3c}}$ needs to be rejected. However, a medium effect size is present.

For jumping, the first point-to-goal error of jumping ($Mdn = 18.23°$, $\sigma = 17.23°$) did not significantly differ from the second point-to-goal error for jumping ($Mdn = 17.37°$, $\sigma = 13.85°$), $z = -1.8$, $p = 0.072$, $r = 0.367$. Thus, $\boldsymbol{H_{3d}}$ needs to be rejected. However, a medium effect size is present.

Since all sub-hypotheses were rejected, $\mathbf{H_3}$ needs to be rejected as well. When investigating the boxplots in Figure 6.3 to interpret the observed effects, it is visible that the corresponding upper whiskers of the first runs are larger than the ones of the second runs. This indicates that higher errors were present in the first runs, but this difference was not large enough to produce significant results. However, it may be the explanation for the observed effect sizes.

6.3.4 Baseline Measurements

For the analyses of the manifestation performance compared to all other pointings, the respective errors for both travel techniques were averaged to a single value. All of these values were non-normally distributed. Since the manifestation error is reused in four hypotheses, the Bonferroni-corrected α-level is $0.05/4 = \frac{1}{80}$.

The first point-to-start error ($Mdn = 17.04°$, $\sigma = 9.25°$) was significantly higher than the manifestation error ($Mdn = 5.43°$, $\sigma = 3.62°$), $z = 4.257$, $p < 0.001$, $r = 0.869$ (large effect). Thus, $\boldsymbol{H_{4a}}$ can be accepted.

The first point-to-goal error ($Mdn = 20.71°$, $\sigma = 12.11°$) was significantly higher than the manifestation error ($Mdn = 5.43°$, $\sigma = 3.62°$), $z = 4.257$, $p < 0.001$, $r = 0.869$ (large effect). Thus, $\boldsymbol{H_{4b}}$ can be accepted.

The second point-to-start error ($Mdn = 16.86°$, $\sigma = 6.53°$) was significantly higher than the manifestation error ($Mdn = 5.43°$, $\sigma = 3.62°$), $z = 4.257$, $p < 0.001$, $r = 0.869$ (large effect). Thus, $\boldsymbol{H_{4c}}$ can be accepted.

The second point-to-goal error ($Mdn = 15.72°$, $\sigma = 11.52°$) was significantly higher than the manifestation error ($Mdn = 5.43°$, $\sigma = 3.62°$), $z = 4.143$, $p < 0.001$, $r = 0.846$ (large effect). Thus, $\boldsymbol{H_{4d}}$ can be accepted.

Because all sub-hypotheses were accepted, $\mathbf{H_4}$ can be accepted as well.

6.4 Travel Time

For the statistical analyses, the travel times of each participant were averaged over the five trials of a spatial updating session. Furthermore, both runs of a route were averaged to a single value such that $N = 24$ holds for steering and jumping. Figure 6.5 shows the distributions of the obtained travel times. The values of both techniques were non-normally distributed, which is why a Wilcoxon signed-rank test was used for their comparison.

The travel time of steering was significantly higher ($Mdn = 26.82s$, $\sigma = 6.54s$) than the one of jumping ($Mdn = 13.65s$, $\sigma = 9.77s$), $z = -3.629$, $p < 0.001$, $r = 0.741$ (large effect). Thus, $\mathbf{H_5}$ can be accepted.

6.5 Response Time

In the same way as the pointing accuracies in Section 6.3, the response times were averaged over all trials such that $N = 24$ holds per pointing task per travel technique. Figure 6.6 shows the distributions of the resulting times. All values except the second point-to-start time (jumping) and the second point-to-goal time (steering) were non-normally distributed, which is why Wilcoxon signed-rank tests were used in the following.

The first point-to-start response time for steering ($Mdn = 8.26s$, $\sigma = 5.2s$) did not significantly differ from the one of jumping ($Mdn = 8.8s$, $\sigma = 7.71s$), $z = 1.886$, $p = 0.059$, $r = 0.385$. Thus, $\boldsymbol{H_{6a}}$ needs to be rejected. However, a medium effect size is present.

The second point-to-start response time for steering ($Mdn = 8.69s$, $\sigma = 4.43s$) was significantly higher than the one of jumping ($Mdn = 8.52s$, $\sigma = 4.73s$), $z = 1.971$, $p = 0.049$, $r = 0.402$ (medium effect). Thus, $\boldsymbol{H_{6b}}$ can be accepted.

The first point-to-goal response time for steering ($Mdn = 8.01s$, $\sigma = 3.86s$) did not significantly differ from the one of jumping ($Mdn = 6.92s$, $\sigma = 4.72s$), $z = -0.6$, $p = 0.549$, $r = 0.122$. Thus, $\boldsymbol{H_{7a}}$ needs to be rejected. However, a small effect size is present.

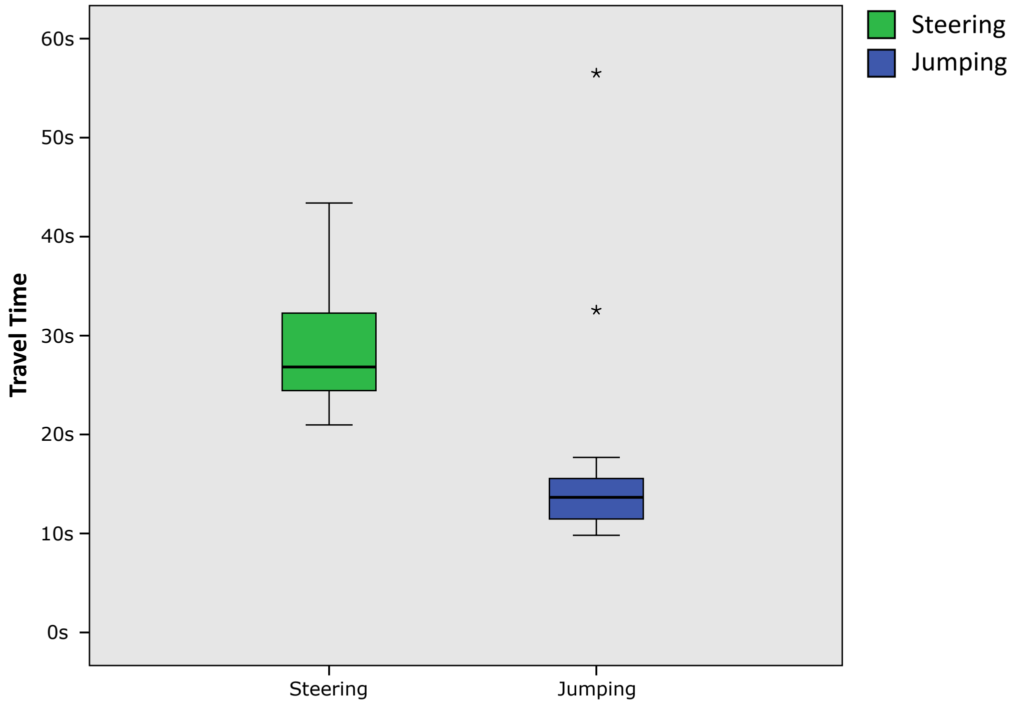


Figure 6.5: Boxplots illustrating the distributions of average travel times per participant separated by travel technique.

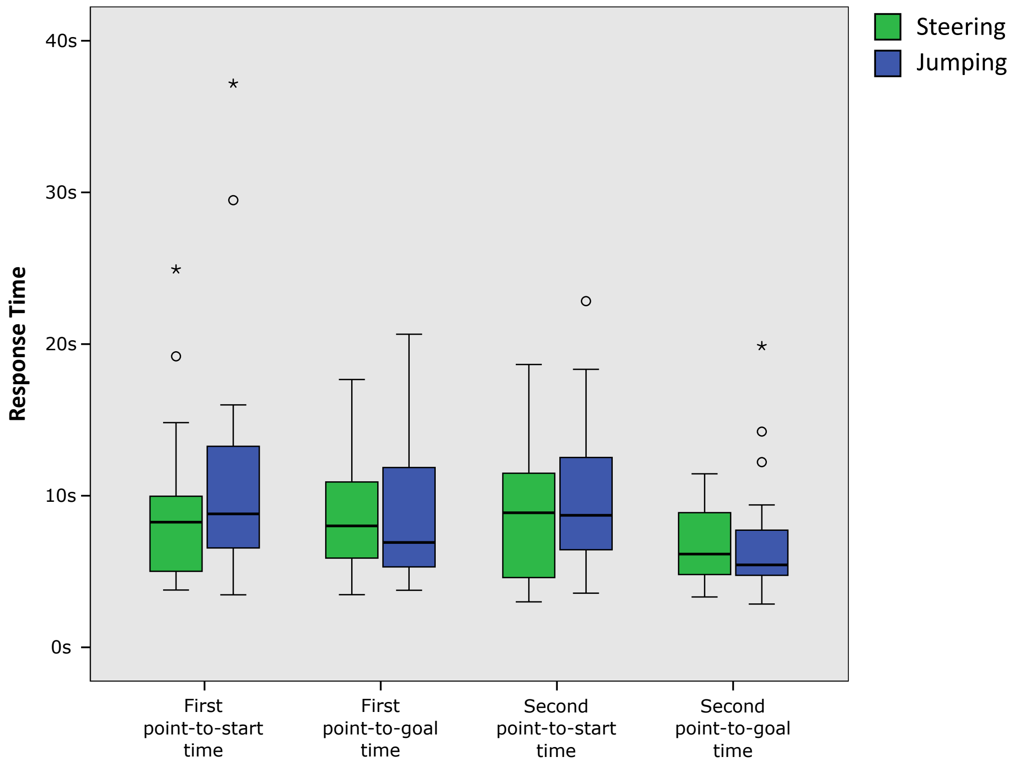
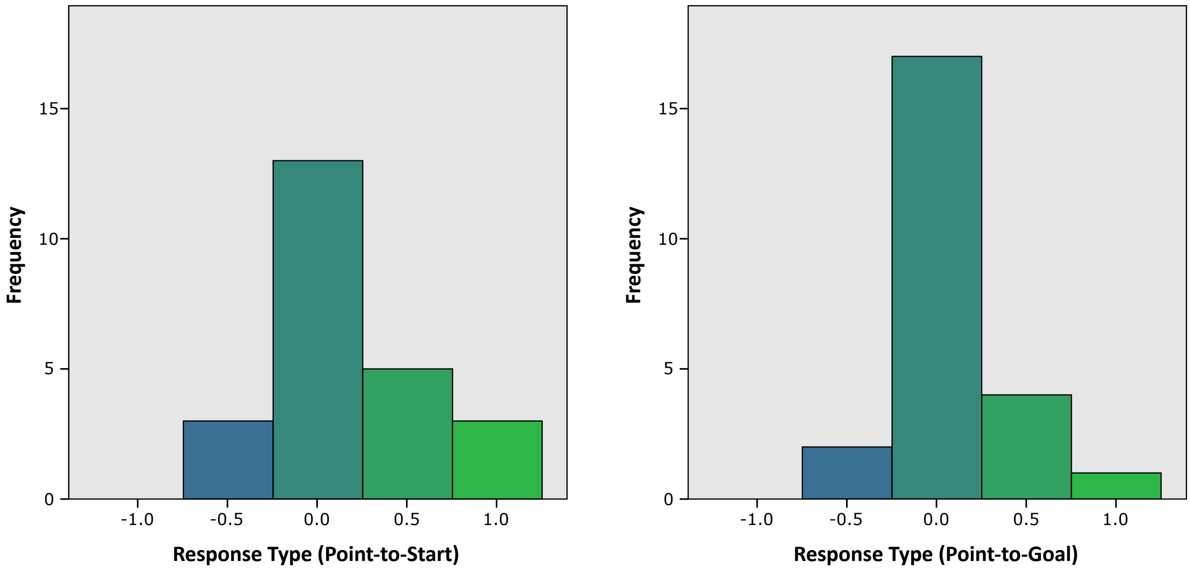


Figure 6.6: Boxplots illustrating the distributions of average response times per participant separated by travel technique.



(a) Response types computed from the point-to-start tasks. A score of -1 represents a faster response when jumping while a score of +1 represents the equivalent for steering.

(b) Response types computed from the point-to-goal tasks. A score of -1 represents a faster response when jumping while a score of +1 represents the equivalent for steering.

Figure 6.7: Histograms illustrating the distributions of response types for the point-to-start and point-to-goal tasks, respectively.

The second point-to-goal response time for steering ($Mdn = 6.15s$, $\sigma = 2.35s$) did not significantly differ from the one of jumping ($Mdn = 5.435s$, $\sigma = 3.86s$), $z = -0.629$, $p = 0.53$, $r = 0.128$. Thus, $\boldsymbol{H_{7b}}$ needs to be rejected. However, a small effect size is present.

When investigating the Boxplots in Figure 6.6 in order to interpret the observed effects, it seems that for $\boldsymbol{H_{6a}}$, $\boldsymbol{H_{7a}}$ and $\boldsymbol{H_{7b}}$, the stronger outliers of jumping are responsible for the observed small and medium effect sizes. For $\boldsymbol{H_{6b}}$, on the other hand, no outliers are present for both techniques, resulting in the conclusion that the slightly larger value range between the whiskers of jumping was solely responsible for the significant result. Nevertheless, since this was the only accepted sub-hypothesis, $\mathbf{H_6}$ and $\mathbf{H_7}$ need to be rejected.

In a similar fashion to the computation of pointing types in Subsection 6.3.2, the same calculations were performed on the basis of the response times to compute two *response type* scores. The point-to-start and point-to-goal response type distributions are visualized in Figure 6.7 and look similarly to the pointing type distributions in Figure 6.4. However, no significant relationships were observed between the pointing type and the response type of the participants.

6.6 Simulator Sickness

The distributions of the four Simulator Sickness Questionnaire scores were non-normally distributed for both travel techniques, which is why Wilcoxon signed-rank tests were used for the following comparisons. Boxplots of the nausea, oculomotor and disorientation scores are given in Figure 6.8.

The nausea score after steering was significantly higher ($Mdn = 28.62$, $\sigma = 30.42$) than the one after jumping ($Mdn = 19.08$, $\sigma = 14.62$), $z = -2.639$, $p = 0.008$, $r = 0.539$ (large effect). Thus, $\boldsymbol{H_{8a}}$ can be accepted.

The oculomotor score after steering was significantly higher ($Mdn = 15.16$, $\sigma = 21.47$) than the one after jumping ($Mdn = 11.37$, $\sigma = 15.16$), $z = -2.678$, $p = 0.007$, $r = 0.547$ (large effect). Thus, $\boldsymbol{H_{8b}}$ can be accepted.

The disorientation score after steering was significantly higher ($Mdn = 27.84$, $\sigma = 39.86$) than the one after jumping ($Mdn = 20.88$, $\sigma = 29.73$), $z = -2.48$, $p = 0.013$, $r = 0.506$ (large effect). Thus, $\boldsymbol{H_{8c}}$ can be accepted.

The total score after steering was significantly higher ($Mdn = 31.79$, $\sigma = 29.7$) than the one after jumping ($Mdn = 22.33$, $\sigma = 18.34$), $z = -2.59$, $p = 0.01$, $r = 0.529$ (large effect). Thus, $\boldsymbol{H_{8d}}$ can be accepted.

Since all sub-hypotheses were accepted, $\mathbf{H_8}$ can be accepted as well. In a similar fashion to the computation of pointing types and response types, simulator sickness types were computed on the basis of the total score of the Simulator Sickness Questionnaire. The distribution of this score is visualised in Figure 6.10(a). It is visible that most of the participants did not experience any difference in simulator sickness between both techniques; however, the remaining 9 participants had all less simulator sickness during jumping as hypothesised, which probably caused the significant difference observed in the statistical test.

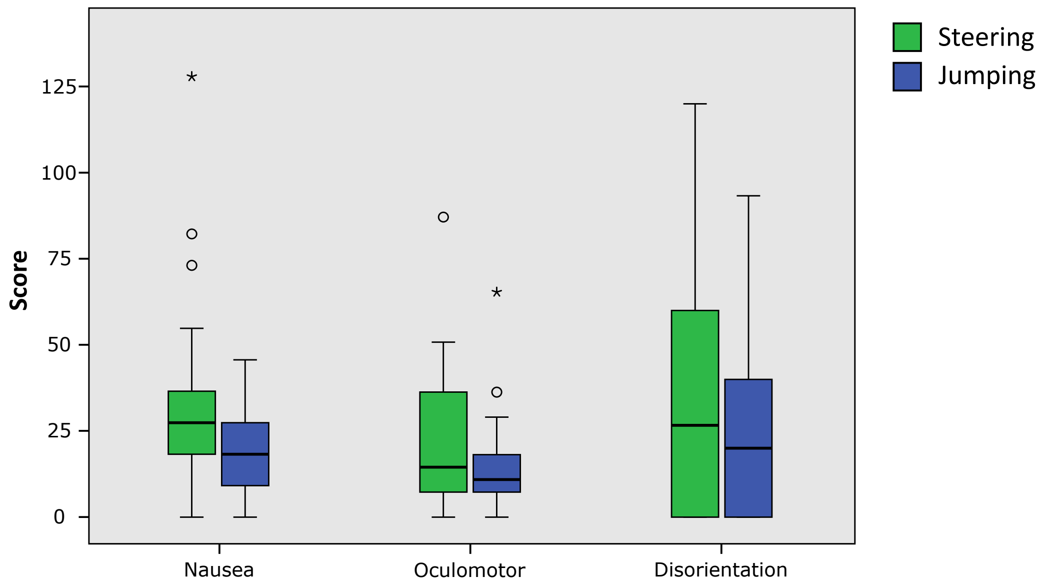


Figure 6.8: Boxplots illustrating the distributions of simulator sickness scores separated by travel technique. The total simulator sickness score was omitted for scaling reasons.

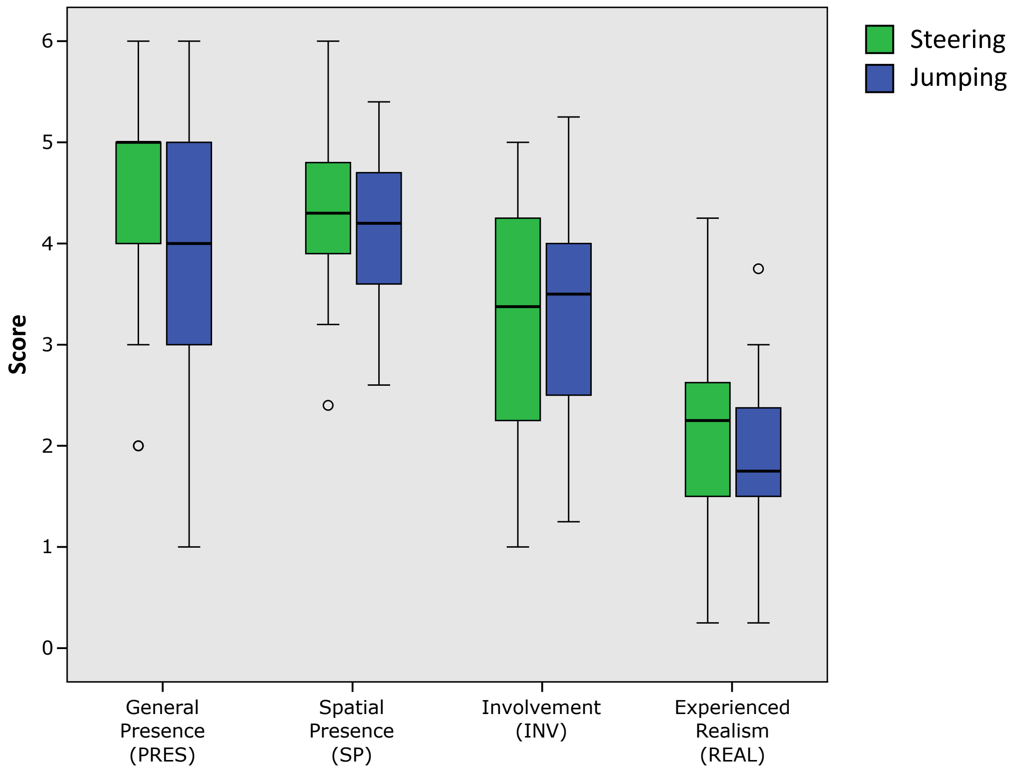
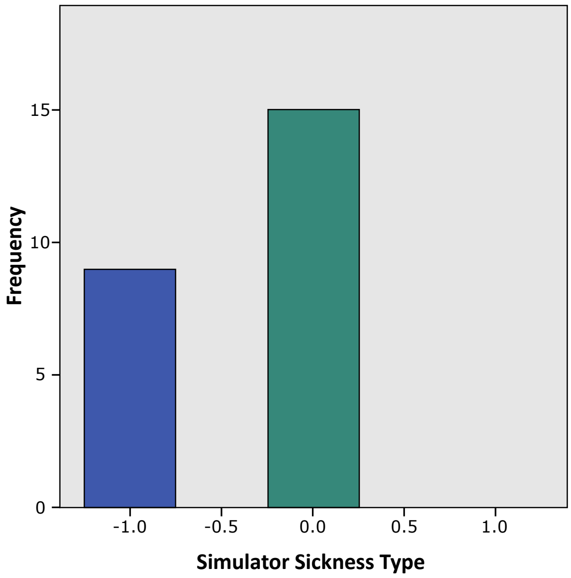


Figure 6.9: Boxplots illustrating the distributions of presence scores separated by travel technique.



(a) Simulator sickness types computed from the total scores of the SSQ. A score of -1 represents less simulator sickness for jumping while a score of +1 represents the equivalent for steering.

	Presence Type		
	-1.0	0.0	1.0
PRES	2	17	5
SP	3	18	3
INV	3	18	3
REAL	1	16	7

(b) Frequency table of the presence types computed for each category of the igroup Presence Questionnaire. A score of -1 represents higher presence for jumping while a score of +1 represents the equivalent for steering.

Figure 6.10: Analysis of the distributions of simulator sickness and presence types.

6.7 Presence

The distributions of the four presence scores are visualized in Figure 6.9. Except the general presence score (PRES), all of them were normally distributed for both travel techniques. As a result, spatial presence (SP), involvement (INV) and experienced realism (REAL) were compared using a paired-samples t-test while a Wilcoxon signed-rank test was performed for PRES.

The PRES score of steering ($Mdn = 5$, $\sigma = 1.14$) was not significantly different from the one of jumping ($Mdn = 4$, $\sigma = 1.26$), $z = -1.487$, $p = 0.137$, $r = 0.304$. Thus, $\boldsymbol{H_{9a}}$ needs to be rejected. However, a medium effect size is visible.

The SP score of steering ($M = 4.35$, $\sigma = 0.82$) was not significantly different from the one of jumping ($M = 4.17$, $\sigma = 0.77$), $t(23) = 1.132$, $p = 0.269$, $r = 0.115$. Thus, $\boldsymbol{H_{9b}}$ needs to be rejected. However, a small effect size is visible.

The INV score of steering ($M = 3.28$, $\sigma = 1.27$) was not significantly different from the one of jumping ($M = 3.29$, $\sigma = 1.13$), $t(23) = -0.04$, $p = 0.968$, $r = 0.004$. Thus, $\boldsymbol{H_{9c}}$ needs to be rejected.

The REAL score for steering ($M = 2.17$, $\sigma = 0.93$) was significantly higher than the one of jumping ($M = 1.82$, $\sigma = 0.76$), $t(23) = 3.058$, $p = 0.006$, $r = 0.197$ (small effect). Thus, $\boldsymbol{H_{9d}}$ can be accepted.

When looking at Figure 6.9 to interpret the observed effects, it is visible that the PRES-spread of jumping is larger than the one of steering, which seems to be the cause for the observed medium effect. Nevertheless, no clear interpretation can be found for the small effect observed in the SP-values. Jumping seems to have received a little lower scores, but steering contains an outlier which is smaller than the lower whisker of jumping.

When investigating presence types in Figure 6.10(b), which were computed in the same fashion as for pointing types, response types and simulator sickness types, it is visible that a large majority of participants did not experience differences in all four categories. For PRES and REAL, if the score deviated from 0, this was more likely to happen in favour of steering. This is a possible explanation for the observed medium effect and significance, respectively.

All in all, since only $\boldsymbol{H_{9d}}$ was accepted, the overlying hypothesis $\mathbf{H_9}$ needs to be rejected.

6.8 Correlations with other spatial ability measures

For the following correlational analyses, all investigated variables were non-normally distributed. As a result, Spearman's Rho or Kendall's Tau are valid correlation coefficients. Since the latter one has been shown to be more suitable for small datasets, it has been chosen for the following investigations. The conversion of τ to Pearson's correlation coefficient r is given by $r = 2/\pi \cdot sin^{-1}(\tau)$ according to [76].

There was no significant relationship between the SBSOD scores and the mean PTSOT errors, $\tau = -0.07$, $r = -0.045$, $p = 0.637$. Thus, $\mathbf{H_{10}}$ needs to be rejected.

	τ	r	p
SBSOD & Overall Task Error Steering	-0.011	-0.007	0.941
SBSOD & Overall Task Error Jumping	-0.297	-0.192	0.044
PTSOT & Overall Task Error Steering	0.196	0.126	0.18
PTSOT & Overall Task Error Jumping	0.174	0.111	0.234

Table 6.3: Correlational analyses of the two pre-tests with the overal task errors for both travel techniques

The overall task errors for steering ranged between 7.12° and 36.49° $(M = 19.05°, \sigma = 7.39°)$. For jumping, the overall task errors were between 6.56° and 42.37° $(M = 22.8°, \sigma = 10.98°)$. Table 6.3 summarises the correlational analyses of the pre-tests with the overall task errors for both travel techniques. Since the same variables are used in their different combinations, the Bonferroni-corrected α-level for these tests is $0.05/4 = \frac{1}{80}$. After these adjustments, there is no significant relationship between any of the variables. As a result, $\mathbf{H_{11}}$ and $\mathbf{H_{12}}$ need to be rejected. However, three coefficients show at least small correlational effects between the variables.

6.9 Discussion

This chapter analysed the data of the performed user study with respect to the formulated hypotheses. As expected due to the sensory conflict between the visual and vestibular systems, it was shown that participants felt significantly more sick during steering, which confirms one of the main motivations to use jumping techniques for travelling through immersive virtual environments (Section 6.6). Nevertheless, the investigation of simulator sickness types revealed that many individual participants were able to cope with both techniques equally well, which is underlined by the fact that steering was the preferred technique in most cases (Section 6.2). Furthermore, the inexperience in VR of most participants (Section 6.1) may be another reason for the observed steering preference since this travel technique was already known from the real world.

The medians of all five pointing errors were smaller than 20° for both travel techniques, which shows that the task was solvable and not too demanding for the users. Moreover, this upper bound is at the lower end of the spatial updating studies reported by Vuong [51, Section 1.3.3], indicating that the rectangular route layouts in the present user study were simpler to the routes of related work. The manifestation task was designed to be as simple and short as possible to obtain baseline measurements; its pointing errors were significantly smaller than the pointing tasks of the rectangular route (Subsection 4.2.3). This implies that travelling through the virtual environment significantly decreased the users' spatial awareness, independent of the travel technique. The median of the manifestation task over both techniques was 5.43°, which seems to be a lower bound on how accurate the spatial updating performance can become in general.

For the comparison of this user study, participants were instructed to perform as few jumps as possible when jumping. This was done in order to maximize the technique spread on the steering-teleportation continuum. Due to the long individual jumps, participants were able to complete the routes significantly faster compared to steering with a fixed maximum speed (Section 6.4). This difference in encoding times did not lead to significantly worse spatial updating errors (Section 6.3.2). When investigating the pointing type distributions based on the per-user differences between travel techniques, this is confirmed for the majority of participants. Nevertheless, subsets of 8 (point-to-start) and 7 (point-to-goal) participants with positive pointing types exist as opposed to 1 (point-to-start) and 3 (point-to-goal) users with negative pointing types. Thus, the pointing type did deviate from zero for a considerable amount of people, and this was more likely to happen in favour of steering. As a result, it can be concluded that spatial updating works properly for the majority of people using jumping, but also that a smaller amount was not able to integrate the motion cues of jumping at all. This is supported by the larger data ranges of jumping in the boxplots and the observed effect sizes. In the most extreme case, the mean first point-to-start error of a participant for jumping (62.1°) was 46.2° worse compared to steering (15.9°), indicating complete disorientation.

All different pointing type scores were spread across both orders of travel techniques, indicating that the presentation order did not have an influence on them. More formal analyses of order effects were non-significant for all pointing tasks and travel techniques

(Subsection 6.3.1). However, small effect sizes were observed for the manifestation task, which is reasonable due to its simple and repetitive structure. Further two effects were present in two pointing tasks of steering, but they have been neglected for the remaining investigations of the user study due to their small size and isolated appearance. Participants were not able to significantly improve their pointing results in the second run of a rectangular route (Subsection 6.3.3); however, especially the medium effects of the point-to-goal tasks suggest that adding a third run could make a significant learning effect visible. This is true for both travel techniques.

The response times were only significantly different in the second point-to-start task, with medium and small effects observed for the other tasks (Section 6.5). Computing response type scores on the basis of per-user differences between travel techniques yields similar distributions compared to the pointing types. This means that the majority of participants did not respond differently fast depending on the travel technique. However, when participants did respond differently, they were faster for steering in the most cases, which may be an explanation for the observed effect sizes. Interestingly, further analyses have shown that there is no relationship between the response type and the pointing type. This implies that people who performed better when steering did not necessarily reply faster with this travel technique. As a result, the response time seems to be an unsuitable metric for spatial updating, and the results of the study by Bowman et al. [18] could not be reproduced.

The user's sense of presence was not significantly worse during jumping in all categories of the igroup presence questionnaire except *experienced realism* (Section 6.7). The main influence of this seems to come from the question REAL2 focusing on how much the experience was consistent with the real world. This is a reasonable result since jumping as performed in the study is impossible in the real world. Among the other scores, only the general presence showed an interpretable medium effect favouring steering. The analysis of presence types serves support for these observed effects in favour of steering since more positive than negative scores were obtained for PRES and INV. However, the scores also illustrate that most participants did not experience presence differences between travel techniques at all.

Interestingly, no correlation was found between the results of the SBSOD and the PTSOT (Section 6.8). A possible explanation to this is the fundamentally different nature of the tests, with the SBSOD being a subjective rating of own skills while the PTSOT is an objectively measured score. Moreover, no significant correlations and only small effects between the user's overall task error per technique and one of the pre-tests could be found. There is a negative and a positive interpretation to this. On the one hand, both pre-tests could simply not have been suitable enough for getting a good picture of a user's general spatial abilities. The correlating tests performed by Riecke et al. [64], for example, were more strongly focused on mental rotation, which was just tested as a sub-ability of the PTSOT in the present study. On the other hand, weak to no correlations with spatial skills are a promising indicator that mental spatial reasoning was not the determining factor for task performance. This can lead to the conclusion that all observed errors can be attributed to encoding and execution only. Which of the two interpretations holds is subject to future investigations.

Although not stated in the hypotheses, further correlational analyses were performed to check for relationships of the overall task performance with the stated game and VR experiences as well as the technique preferences. However, none of these investigations yielded significant results. It thus seems that these attributes as captured in the user study are no good indicators to predict spatial updating performance.

All in all, this user study provided interesting results into the effects of steering and jumping techniques on spatial updating in immersive virtual environments. However, in many cases, hypotheses needed to be rejected although small to medium effect sizes were present. This could be an indicator that the data of 24 participants are simply not enough to draw significant conclusions. For the scope of this thesis, however, the illustrated results show interesting trends and tendencies than can be stabilized by additional study participants in the future.

7 Conclusion and Future Work

"Thank you, Mario! But our princess is in another castle!"
— Toad, SUPER MARIO BROS.

Spatial awareness is an essential cognitive ability that helps humans to not lose orientation in known and unknown environments. Thus, the implemented travel technique of a Virtual Reality application should support and not hinder its formation. In order to reduce simulator sickness, many modern immersive Virtual Reality applications rely only on jumping travel techniques as opposed to the well-established steering metaphor. Although the two techniques are related to each other on a continuum, they offer different cues to encode distances while exploring virtual environments. Steering allows to perceive a motion flow for a specific amount of time whereas jumping gives the opportunity to see and judge step distances before they are executed. It was the goal of this thesis to investigate whether this difference has an influence on a user's spatial awareness.

For this purpose, this thesis reviewed several steering and jumping variants and motivated to compare basic and simple representatives of each category. The topic of spatial awareness was approached on different levels. It has been decided to focus on spatial updating as a process involved in the acquisition of route and survey knowledge, which itself relies on proper distance judgements. The design, implementation and realisation of a spatial updating user study was motivated and explained in detail.

The results indicate that spatial updating during jumping can work for many people. This is particularly interesting since the available time for encoding a route was significantly smaller compared to steering. Thus, the same amount of information is more condensed during jumping, and shortly being inattentive may have more severe consequences regarding the spatial updating performance. It was observed that a non-negligible minority of people cannot cope with these condensed information at all, resulting in disorientation. It is subject to future work to investigate which psychological properties are responsible for this effect. As a result, an application in which the formation of spatial awareness is desired may offer jumping as its default travel metaphor, but it should implement a steering variant as fallback. This is also supported by the stated technique preferences of the users.

This thesis marked the first steps in the analysis of spatial awareness of travel techniques at our chair, which is why future work is vast. The routes in the present study have deliberately been designed to follow simple rules, which reduces the spatial updating task to judging the distances of three segments and converting the result to a pointing angle. Follow-up studies should analyse both techniques on complex routes in organic cities as well; this would extend the available correct response angle spread to full 360°. However, higher total errors must be expected in these cases (see Vuong's [51, Section 1.3] list of spatial updating studies and their associated errors), and it is unclear whether the task complexity may completely obfuscate the marginal differences between steering and jumping observed in this thesis.

The ability of spatial updating was chosen as the main measurement in the presented user study. Still, the simplicity of the selected route layouts reduced the task to the correct encoding of only three segment lengths and their relation to each other. Since correct distance judgements are an integral part of this process, it is interesting to investigate travel techniques on this lower level in isolation. This would simplify the presented study task by omitting the requirement to transfer the encoded distances to a pointing angle. The related papers in Section 3.3 gave some examples of tasks and experimental setups to investigate distance judgements in more detail.

Moreover, the analysis of multiple technique representatives and enhancements seems interesting. For steering, the influence of adding various mediators was already investigated by Darken and Peterson [24]. On the teleportation side, however, manipulations in each of the four illustrated phases can be performed and further analysed. It could be interesting, for example, to investigate several transition modes, different pre- and post-travel information and target indication using explicit orientation mechanisms. Concerning spatial updating, nevertheless, it must be assured that a certain enhancement does not trivialize the task. Adding a permanently visible map as post-travel feedback, for instance, makes the pointing direction to the origin immediately clear; the same is true for an arrow or movement trail constantly leading to the desired target. These technique variants should be evaluated with respect to a higher level of spatial awareness, in particular survey knowledge.

As illustrated in Section 1.2, an enduring research goal at our university is the development of navigation techniques for multiple collocated users in a single physical workspace. The investigations of this thesis, however, were focused on immersive head-mounted displays, which are single-user systems on the hardware side. Deploying travel techniques to our semi-immersive powerwall system leads to different roles of participating users. One of them is usually the navigator and operates the travel technique while the others watch passively and discuss about the content. Since this thesis was concerned with the active exploration of virtual environments, the illustrated results do probably just transfer to the navigator. The spatial awareness of the passive users may be notably worse since they use less attentive resources to pursue the target indications before jumping and the travel process in general. Reserving more time for travel by steering is currently the most viable alternative to overcome this problem, but many users affected by simulator sickness have been observed in our semi-immersive environments as well. Moreover, especially in large virtual environments like scans of whole landscapes, steering to individual targets may be too exhaustive. Thus, in the long run, an easy-to-use jumping or one-time teleportation technique that maximizes the formation of spatial awareness for every participant exploring an unknown virtual environment should be developed.

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A Appendix

"You may not think I look like much, but I can be quite helpful! [...] So don't think of me as a burden!"
— Ooccoo, The Legend of Zelda: Twilight Princess

This appendix serves to give more detailed information on the user study procedure outlined in Chapter 5. For this purpose, each of the following sections focuses on the exact wording of one particular test/questionnaire handed to the participants.

A.1 Informed Consent Form

General Information

You are participating in a study on spatial orientation in virtual environments. We hope to gain a better understanding on the design requirements for interaction techniques in Virtual Reality. The results will be used in a Master's Thesis and potentially published. All data is captured anonymously.

You can withdraw from participation at any time. Please let us know if you do not feel well. You can always ask questions.

The study compares two conditions of exploring a virtual city. To this end, you will delve into several variants of the city and respond to questions regarding your spatial orientation. Please try to solve these tasks as effectively as possible. The participant with the best orientation performance will receive a 50 euros worth voucher in the restaurant "Creperie du Palais" in Weimar. Moreover, you receive an expense allowance of 10 euros. These will be paid after the study.

During the study, we capture your head movements and all movements of input devices. These data will be processed and analysed anonymously. Please switch off your phone.

Study Consent

Do you currently feel sick?	O yes	O no
Are you in your usual state of fitness?	O yes	O no

I hereby confirm that I have read the information above and that I agree with the mentioned procedure of the study. It is my free will to participate. I agree with the above described logging of usage data.

Location, Date: ________________________
E-mail: ________________________
Name: ________________________
Signature: ________________________

A.2 Santa-Barbara Sense-of-Direction Scale

The Santa-Barbara Sense-of-Direction Scale was developed by Hegarty et al. [68]. Each question is answered on a Likert scale from 1 to 7, where the anchor texts of 1 and 7 are "strongly agree" and "strongly disagree", respectively. The exact wording of the questions is as follows:

1. I am very good at giving directions.
2. I have a poor memory for where I left things.
3. I am very good at judging distances.
4. My "sense of direction" is very good.
5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).
6. I very easily get lost in a new city.
7. I enjoy reading maps.
8. I have trouble understanding directions.
9. I am very good at reading maps.

10. I don’t remember routes very well while riding as a passenger in a car.
11. I don’t enjoy giving directions.
12. It’s not important to me to know where I am.
13. I usually let someone else do the navigational planning for long trips.
14. I can usually remember a new route after I have travelled it only once.
15. I don’t have a very good ”mental map” of my environment.

A.3 Perspective Taking/Spatial Orientation Test

The Perspective Taking/Spatial Orientation Test (PTSOT) was developed by Hegarty, Kozhevnikov and Waller [66, 67]. A set of spatially distributed objects is shown as illustrated in Figure 5.3. The task of the participant is to imagine standing at one of these objects facing the direction of another one and to indicate on a circle in which orientation a third object is located with respect to this view direction. In particular, the 12 tasks are phrased as follows:

1. Imagine you are standing at the car and facing the traffic light. Point to the stop sign.
2. Imagine you are standing at the cat and facing the tree. Point to the car.
3. Imagine you are standing at the stop sign and facing the cat. Point to the house.
4. Imagine you are standing at the cat and facing the flower. Point to the car.
5. Imagine you are standing at the stop sign and facing the tree. Point to the traffic light.
6. Imagine you are standing at the stop sign and facing the flower. Point to the car.
7. Imagine you are standing at the traffic light and facing the house. Point to the flower.
8. Imagine you are standing at the house and facing the flower. Point to the stop sign.
9. Imagine you are standing at the car and facing the stop sign. Point to the tree.
10. Imagine you are standing at the traffic light and facing the cat. Point to the car.

11. Imagine you are standing at the tree and facing the flower. Point to the house.
12. Imagine you are standing at the cat and facing the house. Point to the traffic light.

A.4 Simulator Sickness Quesionnaire

In the Simulator Sickness Questionnaire by Kennedy et al. [69], participants are asked to rate their subjective perception of each of the 16 symptoms on a four-point Likert scale, which is labelled with “None” (0), “Slight” (1), “Moderate” (2) and “Severe” (3). The symptoms are general discomfort, fatigue, headache, eye strain, difficulty focusing, salivation increasing, sweating, nausea, difficulty concentrating, “fullness of the head”, blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness and burping. Based on the answers, subscores for nausea, oculomotor and disorientation and a total simulator sickness score can be computed.

A.5 igroup Presence Questionnaire

The igroup Presence Questionnaire was developed by Schubert et al. [71] and was validated to measure the subjective sense of presence in a virtual environment. It consists of 14 questions to be rated on a 7-point Likert scale. From the answers, scores for perceived spatial presence, involvement and experienced realism can be computed. An additional general question forms a score describing the “sense of being there”.

Question focusing on *general presence* (PRES):

- G1: In the computer generated world I had a sense of ”being there”.
  (0 - not at all, 6 - very much)

Questions focusing on *spatial presence* (SP):

- SP1: Somehow I felt that the virtual world surrounded me.
  (0 - fully disagree, 6 - fully agree)
- SP2: I felt like I was just perceiving pictures.
  (0 - fully disagree, 6 - fully agree)

- SP3: I did not feel present in the virtual space.
  (0 - did not feel, 6 - felt present)
- SP4: I had a sense of acting in the virtual space, rather than operating something from outside.
  (0 - fully disagree, 6 - fully agree)
- SP5: I felt present in the virtual space.
  (0 - fully disagree, 6 - fully agree)

Questions focusing on *involvement* (INV):

- INV1: How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?
  (0 - extremely aware, 6 - not aware at all)
- INV2: I was not aware of my real environment.
  (0 - fully disagree, 6 - fully agree)
- INV3: I still paid attention to the real environment.
  (0 - fully disagree, 6 - fully agree)
- INV4: I was completely captivated by the virtual world.
  (0 - fully disagree, 6 - fully agree)

Questions focusing on *experienced realism* (REAL):

- REAL1: How real did the virtual world seem to you?
  (0 - completely real, 6 - not real at all)
- REAL2: How much did your experience in the virtual environment seem consistent with your real world experience?
  (0 - not consistent, 6 - very consistent)
- REAL3: How real did the virtual world seem to you?
  (0 - about as real as an imagined world, 6 - indistinguishable from the real world)
- REAL4: The virtual world seemed more realistic than the real world.
  (0 - fully disagree, 6 - fully agree)

A.6 Concluding Questionnaire

The concluding questionnaire was built specifically for the user study of this thesis and focuses on travel technique preferences, solution strategies and demographics. Participants were explained the meaning of “steering” and “jumping” beforehand.

- Which technique do you prefer to solve orientation tasks like this?
  (0 - steering, 6 - jumping)
- Which technique do you prefer to explore an unknown virtual environment?
  (0 - steering, 6 - jumping)
- Which technique was more fun to use?
  (0 - steering, 6 - jumping)
- Which strategies did you pursue to solve the orientation task when steering?
  (free text field)
- Which strategies did you pursue to solve the orientation task when jumping?
  (free text field)
- How do you rate your previous experience with 3D computer games?
  (0 - very small, 6 - very high)
- How do you rate your previous experience with Virtual Reality?
  (0 - very small, 6 - very high)
- Gender
  (dichotomous answer)
- Age
  (numeric answer)
- Occupation
  (free text field)