Spatial Updating and Simulator Sickness during Steering and Jumping in Immersive Virtual Environments

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ABSTRACT

Many recent head-mounted display applications and games implement a range-restricted variant of teleportation for exploring virtual environments. This travel metaphor referred to as *jumping* only allows to teleport to locations in the currently visible part of the scene. In this paper, we present a formal description and classification scheme for teleportation techniques and its application to the classification of jumping. Furthermore, we present the results of a user study ($N = 24$) that compared jumping to the more conventional steering with respect to spatial updating and simulator sickness. Our results show that despite significantly faster travel times during jumping, a majority of participants (75%) achieved similar spatial updating accuracies in both conditions (mean difference $0.02°$, $\sigma = 5.05°$). In addition, jumping induced significantly less simulator sickness, which altogether justifies it as an alternative to steering for the exploration of immersive virtual environments. However, application developers should be aware that spatial updating during jumping may be impaired for individuals.

Index Terms: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques H.1.2 [Models and Principles]: User/Machine Systems—Human information processing

1 INTRODUCTION

The interactive exploration and understanding of large virtual environments such as buildings, cities or whole landscapes requires travel. A straightforward and intuitive metaphor of travel is *steering*, during which users continuously control the direction and speed of movement. The resulting visual motion flow, however, contradicts motion cues of the vestibular system. Users visually experience self-motion, but they do not feel the corresponding acceleration. This is considered one of several reasons for simulator sickness [19, 21].

Direct *teleportation* to points of interest avoids these conflicting cues, but the spatial understanding of the connecting routes may also be impaired, which can negatively impact one's spatial awareness of the scene as a whole [5]. In particular, when the teleportation target is located beyond vista space [24], the spatial relation between the target and the origin cannot be traced, which leads to disorientation in unknown environments without the help of additional mediators. Thus, both steering and teleportation can have undesirable side effects that should be carefully considered.

As an alternative, various recent head-mounted display applications and games implement *jumping*, which limits the range of possible teleportation targets to vista space. Consequently, distant destinations can only be reached with a sequence of jumps along a route. In contrast to teleportation beyond vista space, the traveled path between two locations can be integrated based on perceived spatial information during the specification of intermediate jumping targets. We refer to this process as forward path integration. From this stance, jumping is an intermediate technique between steering and regular teleportation (Figure 1).

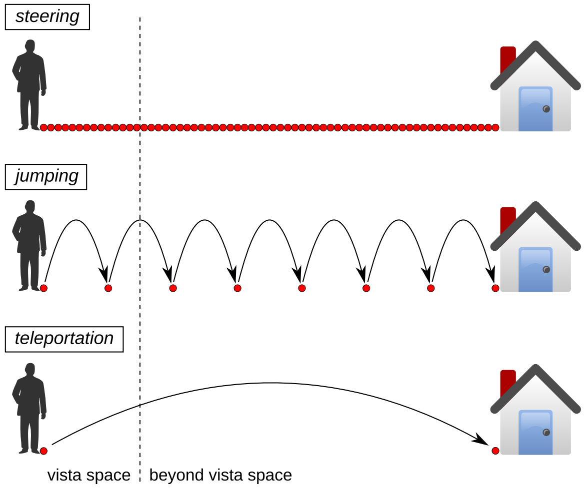

Figure 1: During steering, the user continuously perceives the scene along the path to the destination. When teleporting, the scene is viewed from two distinct points only. The jumping metaphor is located in between. Each of the three techniques offers a different extent of spatial information for path integration (indicated by red dots).

In this paper, we explore the design space of teleportation techniques in more detail, derive a comprehensive classification scheme and use it for the classification of jumping. Furthermore, we report on a user study that compares jumping and steering with respect to their effects on spatial awareness and simulator sickness. For our study task, we designed a parametric virtual city for generating routes to be traveled by users in a head-mounted display. At the end of each route, we measured *spatial updating* performance by asking users to point back to the start.

Our work is motivated by the increasing use of jumping as a travel metaphor in recent virtual reality games. Reduced symptoms of simulator sickness are often mentioned as a reason of its popularity although recent work did not reveal significant differences between steering, jumping and walking in place [7]. Furthermore, prior work indicated disadvantages of passive teleportation techniques [5] concerning spatial awareness. However, previous research did not analyze the effects of *active* jumping on spatial awareness. Our work bridges this gap and provides the following contributions:

- a formal description of the design space of teleportation techniques and the classification of various implementations, e.g. jumping as a range-restricted variation
- the design of a parametric spatial orientation task to measure *spatial updating* performance
- a statistical evaluation of spatial updating performances after steering and jumping and a follow-up analysis to reveal that

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a subset of 18 participants (75%) achieved similar spatial updating accuracies, indicated by a mean accuracy difference of 0.02° ($\sigma = 5.05°$)

- statistical evidence that jumping induced significantly less simulator sickness symptoms and a follow-up analysis to reveal that, in contrast, a subset of 15 participants (62.5%) were similarly affected, indicated by a mean SSQ score difference of 0.75 ($\sigma = 5.86$)

Our results indicate that jumping is a viable alternative to steering for exploring and understanding immersive virtual environments.

2 RELATED WORK

Spatial awareness is a complex cognitive construct and challenging to measure. To study effects of travel techniques on spatial awareness, we analyze spatial orientation tasks in the literature and motivate the evaluation of user performance in *spatial updating* tasks. Furthermore, we review related work on the classification of virtual travel techniques and discuss their limitations with respect to the disambiguation of recent teleportation implementations.

2.1 Evaluation of Spatial Awareness

Bowman et al. [5] defined spatial awareness as "the ability of the user to retain an awareness of her surroundings during and after travel". In a study, they measured the time after travel to find a previously seen object in the scene as a quantification of spatial awareness. A prerequisite of this approach is that the searched item can be seen from both locations.

More generally, Siegel and White [32] proposed a tripartite division of spatial knowledge into *landmark*, *route* and *survey* knowledge. When learning the layout of a previously unknown environment, acquiring survey knowledge is the "key to successful wayfinding" [12] as it 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* [29, Section 12.2]. Spatial updating tests commonly require participants to estimate the relative location of places in the scene after a series of active or passive body movements (e.g. [4, 8, 26, 28]). Riecke et al. [30] showed that optical flow information (like during steering in Virtual Reality) can provide sufficient information to perform these tasks without any vestibular cues. For a detailed overview of spatial updating methodologies and further related studies, we refer to the PhD theses of Riecke [29, Chapter 12] and Vuong [34, Chapter 1]. Generally, spatial updating seems to be a fundamental building block for the acquisition of higher-level spatial skills like route and survey knowledge. On a lower level, spatial updating builds on correct judgements of distances and angles.

In earlier experiments on spatial updating in real and virtual environments, triangle completion tasks were commonly applied (e.g. [22, 23]). Fujita et al. [16] introduced an error model for these task setups, which distinguishes three consecutive phases that are potentially prone to errors: *encoding* during travel, *mental spatial reasoning* after travel and the *execution* of the task. When the same task is performed with different travel techniques, this corresponds to different inputs in the encoding phase. We decided to use pointing accuracy to the route's origin as the measure of spatial updating since the expected errors due to hand tremor and tracking noise in the execution phase are smaller than those related to walking back, where each step can introduce variance.

2.2 The Design Space of Travel Techniques

Steering and teleportation techniques mark the far ends of a parameter space between continuous visual motion (steering) and the immediate change of location and orientation (teleportation). In terms of steering, teleportation can be understood as travel at infinite velocity [6]. Steering, on the other hand, can also be understood as a sequence of teleports between infinitely close locations. In this sense, teleportation in vista space (jumping) offers a compromise between both extremes. The design space of travel techniques, however, involves many more parameters than the distance of sub-steps and the travel velocity. Bowman et al., for example, suggested the classification of travel techniques in terms of their methods for *direction/target selection*, and *velocity/acceleration selection* as well as their *input conditions* [6]. Later, Bowman, Davis et al. extended this approach with a more fine-grained decomposition of the target selection subtask and start/stop conditions [4]. Also, the classification by metaphor was suggested [3,6]. Most existing steering techniques can be unambiguously classified on this basis: as a combination of *input conditions* with specific methods to control the motion *direction* and the motion *velocity or acceleration*.

In addition to movement control (travel), navigation techniques may offer *mediators* and *visual effects* to improve usability. Darken and Peterson, for example, explored mediators as wayfinding aids [11]. Fernandes and Feiner recently showed that a visual effect like the dynamic reduction of the user's field-of-view during travel significantly reduces symptoms of simulator sickness [14]. Bowman et al. considered such interface extensions separately from the classification of different steering techniques [3].

The mentioned taxonomies support the general classification of teleportation as a disparate technique from steering, i.e. a specific type of discrete target selection combined with infinite motion velocity and an input condition to initiate the transition. However, they do not seem appropriate for a fine-grained classification of the wide range of teleportation techniques that have been suggested recently. We considered an extension of existing taxonomies to account for further relevant characteristics of teleportation, but the distinction between travel direction (steering) and travel target (teleportation) results in different interaction sequences that are not entirely compatible. In contrast to steering through a 3D scene, for example, teleportation also allows transitions between two locations in image space (e.g. blending between both views). Moreover, the selection of a target location allows to provide related information before the transition occurs. In fact, teleportation techniques often build on the creation or selection of visual references for the target location [17, 20], which would be considered as auxiliary wayfinding aids for most steering techniques. Therefore, we suggest distinguishing steering and teleportation by metaphor, which is also motivated by different interaction goal of the user. When the experience of the traveled route is of interest, steering techniques are more appropriate. When, instead, only particular locations are relevant, teleportation techniques should be considered. We propose a novel classification scheme for teleportation techniques in the next section.

3 A CLASSIFICATION SCHEME FOR TELEPORTATION TECHNIQUES

Our classification scheme for teleportation techniques builds on the decomposition of the teleportation process into four subsequent stages: target specification, pre-travel information, transition and post-travel feedback. Concrete implementations can be described as a specific configuration of mechanisms for each stage (Figure 2).

3.1 Target Specification

The first stage of the teleportation process is the specification of the target's location and orientation. In some cases, this step is implemented without any user involvement to control the variables in formal user studies [1, 5].

Active target specification by the user, on the other hand, requires an appropriate *input method*. This can be pointing with a tracked input device in the simplest case, but other selection mechanisms

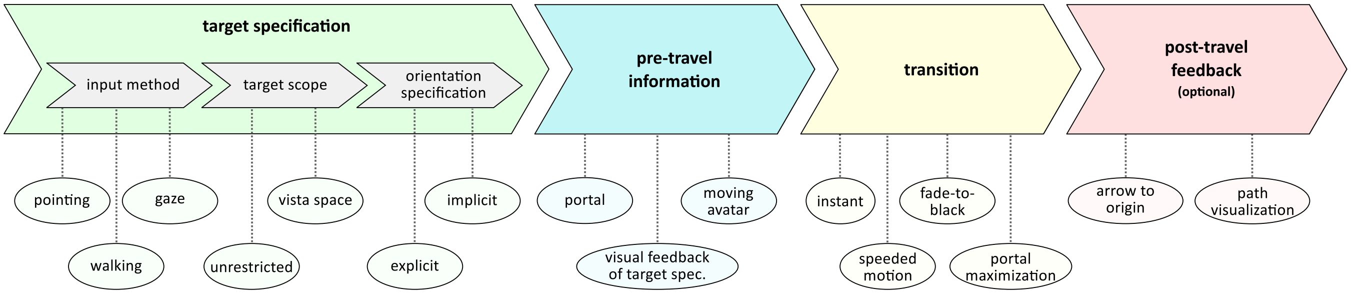

Figure 2: Four stages of the teleportation process with common options for their implementation.

such as gaze [2], direct walking into a gallery portal [13] or the selection among preview perspectives using dedicated hardware [20] have been demonstrated.

The *scope of reachable targets* can be unrestricted or restricted, e.g. to vista space. This part of the taxonomy relates to the disambiguation of jumping and teleportation. With a restricted target distance, several jumps must be performed to reach distant destinations. Unrestricted target specification, on the other hand, requires additional mediators to support selections beyond vista space (e.g. a map or World-in-Miniature [33]). Once the target location is specified, the *target orientation* must be determined either explicitly or implicitly. In many implementations, the users will maintain their previous orientation in the scene. Choosing a target from a set of preview perspectives also implies an orientation, but it may differ from the one before the transition. In contrast, Pausch et al. allowed users to explicitly control both target location and orientation in a World-in-Miniature [27]. An example for an explicit orientation mechanism from an egocentric perspective was implemented by Bozgeyikli et al. [7] and can also be found in the game "The Gallery" (Cloudhead Games Ltd.). Both approaches rely on the manipulation of an orientation widget after the target location was specified.

3.2 Pre-Travel Information

In the second stage, the system may give the user additional information about the teleportation to be performed. First, the visual feedback given during target indication (e.g. pointing ray, gallery preview, etc.) can already be considered pre-travel information. Additional mediators can provide further information after the target was successfully selected. Bolte et al., for instance, suggested gaze-based placement of location markers that can be corrected before the teleportation is applied [2]. Bakker et al., instead, used numbers to indicate the target location and orientation [1]. The game "Spell Fighter VR" (Kubold Games) shows an abstract avatar walking to the target before the actual transition begins. Preview techniques like the reorientation mechanism by Freitag et al. [15], Photoportals by Kunert et al. [20] or the jumping technique used in the game "Budget Cuts" (Neat Corp.) open a portal view to the indicated travel target. This allows users to prepare for the destination and to apply adjustments if they are not yet satisfied.

3.3 Transition

The transition stage is the core of teleportation, in which the actual travel from the origin to the target happens. The simplest form is the *instant transition*, in which the old view in one frame is directly replaced by the new one in the next frame. Some games like "The Lab" (Valve) implement *fade-to-black transitions*, which animate the old view to a black screen, perform the teleportation and then fade back into the new view. When portal views are used as pre-travel information, its *maximization* can be used for a seamless transition as suggested by Kunert et al. [20] and used in the game "Budget Cuts" (Neat Corp.). Another approach are *speeded motion transitions*, which move the camera very quickly from the origin to the target location. Examples of this transition mode were implemented by Bolte et al. [2] and in the game "Raw Data" (Survios).

3.4 Post-Travel Feedback

Additional information could be provided to improve the sense of orientation and spatial awareness after the transition. So far, we could not find implementation examples of such post-travel feedback, but we believe that path visualizations in an overview, simple arrows or even portal views to the teleportation origin could help the users to maintain a sense of orientation and to recover if necessary.

4 AN EXPERIMENTAL TASK FOR THE EVALUATION OF SPATIAL UPDATING

One of the most common experimental tasks to measure spatial updating performance requires participants to travel along a given route and point to its origin after they have reached the terminal location. In many studies, triangular route layouts were used since they constitute the most elementary unit of any navigation path. Only the lengths of two path segments (L_1, L_2) and their enclosing angle α may vary. If the rotation control of the tested travel techniques does not differ (as in our case), the angle can be kept constant to focus on effects of varying segment lengths (e.g. $\alpha = \pm 90^\circ$). With a fixed angle, however, the responses in triangle completion tests will be prone to false positives. The maximum range of admissible pointing angles is less than 90°, and if both path segments do not differ extremely, the correct pointing direction towards the origin will be close to 45° relative to the last path segment. Pointing responses based on guessing may thus still be close to the correct answers.

As a result, we decided to add a third segment to the route layout (see L_1, L_2 and L_3 in Figure 3). This extension increases the range of admissible pointing directions to a maximum range close to 180°. Additionally, we used the simpler triangle task to obtain baseline measurements of pointing accuracy to a hidden target location, which is "just around the corner" (see L_{B1} and L_{B2} in Figure 3).

4.1 Task Sequence

Each task starts with a measurement of baseline pointing accuracy in the mentioned triangle completion task. Participants travel along the segments L_{B1} and L_{B2}. At the end of the second path segment (top red circle in Figure 3), they are asked to point back to the start position. L_{B1} and L_{B2} can be deliberately kept short to make this triangle task very simple to complete, so the results can serve as a reference measure of the maximally attainable accuracy. Thereafter, participants travel back to the start and continue along the route (L_1, L_2, L_3). At the end of the third path segment of this longer route (bottom red circle in Figure 3), participants are asked again to point to the start position. In the next step, participants are passively teleported back to the start (facing along L_1), and the task is repeated without the initial baseline measurement. As a result, each trial involves three different measures of spatial updating performance: *baseline*

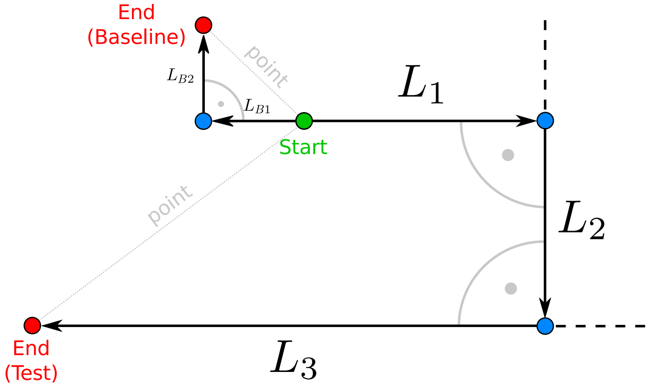

Figure 3: Parametrizable route layout used in the spatial updating trials. From the start point, a simple route (L_{B1}, L_{B2}) and a more complex route (L_1, L_2, L_3) emerges. At each end, subjects were asked to point back to the start position. In our study, both routes could also appear mirror-invertedly.

accuracy, accuracy after traveling along the three path segments (*first point-to-start*) and the repetition thereof (*second point-to-start*). In all three pointing tasks, the angular mismatch between the correct and the given response serves as a dependent variable.

4.2 Virtual Environment

The proposed route layout facilitates the creation of many individual task instances by varying the lengths of the path segments. We devised a scene generator that, given the lengths of the three segments, automatically creates urban virtual environments by placing buildings and decorating objects. We made the Python code of this generator publicly available on our website to facilitate reproduction[1]. We use four different house models of a similar style in combination with five differently colored textures. The houses are placed with random gaps between them, and the streets are visually enhanced by the random placement of trees, benches, lanterns and cars. The corner points of the current route to be traveled are highlighted by cones with arrows on top to indicate the next intermediate target. Once a cone is passed, it disappears such that its location and thus also the distance of a segment cannot be estimated by looking back. Figure 4 shows the virtual environment from a user perspective at three exemplary moments during the experimental task.

4.3 Distractor Task

User performance in spatial updating experiments depends on the judgements of distances during travel. Montello [25] described three complementary sources of information for perceiving the distances of a motion path: the number of environmental features, the travel time and the travel effort. Several pilot tests of the described experimental task showed that people can actively focus on these cues and develop distance judgement strategies based on counting. In the case of steering, for instance, some people tried to count the time needed to travel each street; others focused on counting the number of houses. We incorporated a distractor task to avoid such strategies. During travel in both conditions, participants are asked to listen to and repeat two-digit numbers verbalized by the experimenter. Once the answer is given, the next number follows. When the route's endpoint is reached, the distraction stops such that the participant can focus solely on completing the pointing task. This task is very easy to fulfill without much cognitive effort. In a pilot test, we validated the effectivity of this task as users were not capable of pursuing counting strategies anymore when the distraction was present.

5 USER STUDY

Prior work of Bowman et al. showed that "the level of spatial awareness was significantly decreased with the use of a jumping technique" in comparison to two other conditions that implemented continuous movement between locations [6]. In all three conditions, however, participants were moved passively and without any pre- or post-travel information. It is not surprising that they lost spatial awareness after the instant transition to an unknown location and orientation. In most applications, however, users actively control their virtual travel, e.g. by selecting target locations. We expected that this deliberate selection of a travel target allows users to prepare for the transition and maintain a certain level of spatial awareness. Nevertheless, the continuous experience of the traveled route during steering seems to offer more information in that regard. We conducted a formal user study with 24 participants to investigate the effects of user-controlled steering and jumping techniques on spatial updating performance and simulator sickness. The experimental task described in the previous section was used for this purpose.

5.1 Experimental Setup

The VR-setup consisted of a HTC Vive[2] head-mounted display with its lighthouse tracking system offering 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. Input for both travel techniques was obtained using a Vive handheld controller. The virtual content was rendered using the Avango-Guacamole framework [31] with an update rate of 90Hz. We measured an end-to-end latency of 27ms without and 12.5ms with the prediction methods of *OpenVR*[3] applied. Questionnaires were completed on a regular 2D desktop workstation.

5.2 Conditions

For the initial evaluations carried out in this paper, we tried to keep steering and jumping as simple as possible, so optional *mediators* or *visual effects* were deliberately omitted. Travel movements were always restricted to ground level along the streets that represented the pre-defined routes. Collisions with decorating objects (cars, trees, lamps and benches) were ignored.

Following the taxonomy of Bowman et al. [6], the *Steering* condition can be described as a combination of direction selection through a continuous 3D pointing gesture and velocity control on a continuous range with a finger-operated lever on the Vive controller. The maximum steering speed was set to 50 km/h. In a pilot test comparing gaze-directed with pointing-directed steering, participants clearly preferred the latter because of the ability to freely look around during travel.

The *Jumping* condition can be described according to the classification scheme suggested in Section 3. We implemented a parabolic ray for pointing-based target indication in vista space with implicit orientation specification. The maximum reach of this ray was 180 m, which allowed covering the distance of any straight street segment in our study. Therefore, each path segment could potentially be traveled with a single jump. The implemented transition was an instant transition, and no additional pre- or post-travel information were given to the user. We hypothesized that if significant effects between steering and jumping exist, they will most likely become visible when the difference between both techniques is maximal. As a result, participants were instructed to use as large jumps as possible in the *Jumping* condition.

5.3 Procedure

Initially, each participant signed an informed consent form and provided basic demographic information. Thereafter, all participants

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[1] http://www.uni-weimar.de/vr/steering-jumping

[2] http://www.vive.com

[3] https://github.com/ValveSoftware/openvr

(a) Colored cones symbolize waypoints of the current route. The green and blue cones mark the start and a checkpoint. Arrows on top indicate the direction to continue traveling.

(b) The end of a route is marked by a red cone. When entering the surrounding area, the view changes to the one shown in (c) and spatial updating is tested.

(c) Spatial updating of the start is tested by attaching an arrow to the controller and asking the participant to indicate the straight-line path to the expected position of the green cone.

Figure 4: Three user perspectives of the virtual environment during the spatial updating task (screenshots from the control monitor).

Table 1: Route parametrizations used in both conditions. The correct pointing angle γ when arriving at the route's end is shown depending on the three segment lengths L_1, L_2 and L_3.

Route ID	γ	L_1	L_2	L_3
1	30°	177 m	81 m	42 m
2	60°	138 m	54 m	108 m
3	90°	120 m	60 m	120 m
4	120°	57 m	117 m	126 m
5	150°	39 m	81 m	180 m

tested both travel techniques subsequently (within-subjects design) in counterbalanced order. Each test session involved three training and five recorded spatial updating trials. For each trial, participants were placed within a new virtual street layout as illustrated in Figures 3 and 4. During all trials, the first path segment of the initial triangle-completion test (L_{B1}) was fixed to 15 m while the second one (L_{B2}) varied between 15 m and 20 m. All three-segment routes of the actual test (L_1, L_2, L_3) had an overall length of 300 m and appeared in a randomized order. The individual segment lengths for each recorded trial are given in Table 1 together with the correct response angles γ for pointing back to the start. Each test session concluded with a Simulator Sickness Questionnaire (SSQ) [18]. Between both sessions, participants took a break of five minutes. After completing both conditions, participants filled in a concluding questionnaire on subjective preferences with respect to different application cases and received an expense allowance of 10 Euros.

5.4 Participants

In total, 24 participants (17 males, 7 females) aged between 19 and 38 years ($M = 25.54$, $\sigma = 4.88$) participated in the user study. All of them were either students or employees of our university, with half of them having a background in Computer Science. On a Likert scale from 0 to 6, participants rated their previous experiences with Virtual Reality rather low ($Mode = 0$, $Mdn = 2$).

5.5 Dependent Variables

In each trial, three errors were captured as measures of spatial updating performance: the *baseline* error, the *first point-to-start* error and the *second point-to-start* error. In addition, the travel times to complete the routes along (L_1, L_2, L_3) were captured. Each of these values was measured during five consecutive trials per condition. These repeated measures were averaged to single scores per user and travel technique. From the Simulator Sickness Questionnaire (SSQ), we derived scores on nausea (N), oculomotor disturbance (O) and disorientation (D) as well as a total simulator sickness score (T) as advised in [18].

5.6 Hypotheses

Based on findings from prior work (see Section 2.1) and the research questions of this paper, we set up the following hypotheses:

$\mathbf{H_1}$**:** The travel time is lower for jumping than for steering.

As the implemented jumping technique allows to cover large distances with just one jump and since participants were instructed to complete the route with as few jumps as possible, it is reasonable to assume that the routes are completed faster compared to steering.

$\mathbf{H_2}$**:** The baseline error is smaller than the other pointing errors.

The pointing task after traveling along (L_{B1}, L_{B2}) should be very simple to complete, thus giving baseline measurements on how accurate participants can become in solving spatial updating tasks of this study. More specifically, it serves as a reference measure for errors during the execution phase of our spatial updating task.

$\mathbf{H_3}$**:** Point-to-start errors are higher for jumping than for steering.

As illustrated in Figure 1, jumping allows to perceive the scene from fewer points compared to steering. As the main research question of this paper, H_3 investigates if this has negative effects on spatial updating accuracy.

$\mathbf{H_4}$**:** Reported simulator sickness symptoms are higher for steering than for jumping.

H_4 aims at confirming one of the main motivations to implement jumping techniques. Since jumping avoids conflicting motion cues between the visual and the vestibular systems, the obtained simulator sickness scores should be lower compared to steering.

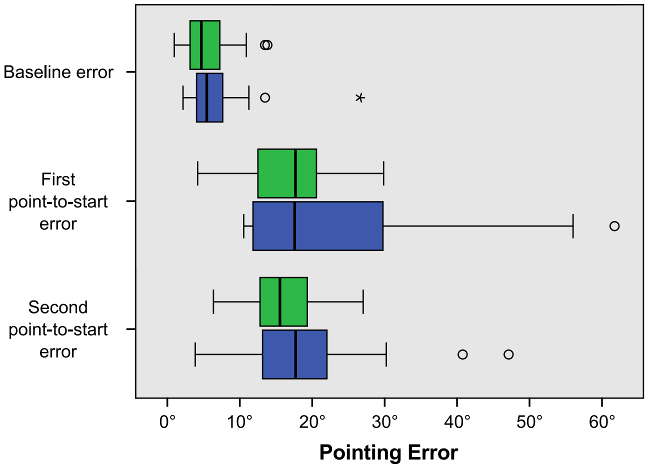


Figure 5: Boxplots of pointing errors for each of the three pointing tasks separated by travel technique (green: steering, blue: jumping). Interquartile ranges (IQRs) are represented by boxes while the whiskers show the full data ranges without outliers. Outliers (distance to box $> 1.5 \cdot$ IQR) and extreme outliers (distance to box $> 3 \cdot$ IQR) are indicated by circles and asterisks, respectively.

6 RESULTS AND EVALUATION

In this section, we evaluate and interpret the data of our user study according to the given hypotheses. For this purpose, the means, medians and standard deviations are abbreviated by M, Mdn and σ, respectively. When analyzing data for normality, visual inspections of the normal QQ-plots were used in combination with Shapiro-Wilk Tests. For effect sizes r, the threshold values 0.1 (small), 0.3 (medium) and 0.5 (large) introduced by Cohen [10] were applied. $N = 24$ holds in all statistical tests and analyses.

6.1 Travel Times

The average travel times along (L_1, L_2, L_3) for all participants were non-normally distributed for both travel techniques. Hence, a Wilcoxon signed-rank test was used for statistical comparison. The travel time was significantly longer with the steering technique ($Mdn = 26.82s$, $\sigma = 6.54s$) as compared to jumping ($Mdn = 13.65s$, $\sigma = 9.77s$), $W = 23$, $p < 0.001$, $r = 0.74$. This result supports H_1.

6.2 Pointing Accuracy

Figure 5 shows the distributions of pointing errors separated by task and travel technique. All errors were non-normally distributed.

6.2.1 Baseline Measurements

The average pointing error in the baseline task (triangle completion after traveling along (L_{B1}, L_{B2})) was compared individually against the average pointing errors in the two more challenging spatial updating tasks using Wilcoxon signed-rank tests with a Bonferroni-corrected α-level of $\alpha = 0.025$. The baseline error ($Mdn = 5.43°$, $\sigma = 3.62°$) was significantly lower than both other pointing errors (both $W = 299$, $p < 0.001$, $r = 0.869$), which supports H_2.

6.2.2 Accuracy by Travel Technique

The pointing accuracy was compared with a Wilcoxon signed-rank test for each of the three subtasks and a Bonferroni-corrected α-level of $\alpha = 0.017$. No significant difference between steering and jumping could be found in the baseline task ($W = 188$, $p = 0.278$, $r = 0.222$), the first point-to-start task ($W = 198$, $p = 0.17$, $r = 0.28$) and the second point-to-start task ($W = 202$, $p = 0.137$, $r = 0.303$). As a result, H_3 must be rejected. However, the effect sizes indicate relevant differences between both techniques for individuals, which is why a *follow-up analysis* was carried out.

For this purpose, the pointing accuracies of both point-to-start repetitions were averaged to a single performance score per participant in order to compare the overall spatial updating performance on the more complex routes. This seems reasonable since no significant learning effects were observed between the first and the second run (steering: $W = 124$, $p = 0.458$, $r = 0.152$; jumping: $W = 103$, $p = 0.417$, $r = 0.274$). A scatterplot of the resulting performance scores is given in Figure 6(a). The dotted diagonal line represents no accuracy difference between steering and jumping, so accuracy differences between both techniques increase with the distance of a point to this line. It is visible that the data points of most participants are closely scattered around the diagonal line. However, six participants (indicated with blue and orange color) achieved notably lower accuracies in the jumping condition (more than 10° worse). Overall, the mean accuracy difference between jumping and steering was $5.09°$ ($\sigma = 10.57°$). When excluding the six special cases, however, the remaining data points ($N = 18$) are almost equally distributed around the center line (mean accuracy difference between techniques: $0.02°$). Additionally, the standard deviation of difference scores ($\sigma = 5.05°$) is smaller than the average baseline error, which indicates that similar spatial updating performances for both travel techniques were achieved in this reduced sample.

6.3 Simulator Sickness

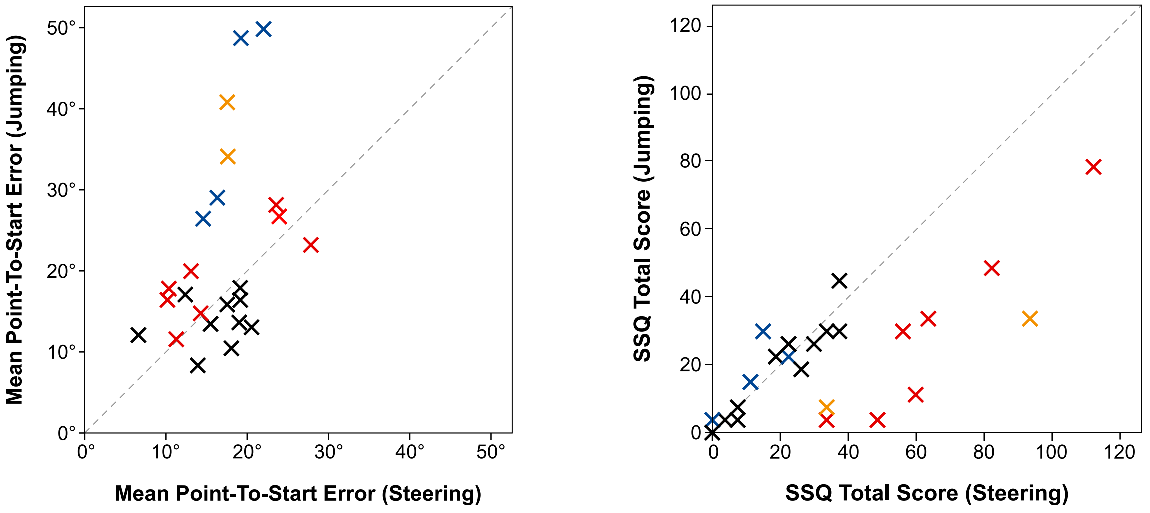
The four SSQ scores were non-normally distributed for both travel techniques, so Wilcoxon signed-rank tests were performed. All three scores on specific symptoms (N, O, D) and also the total scores (T) were significantly higher for steering than for jumping (N: $W = 14$, $p = 0.008$, $r = 0.539$; O: $W = 20.5$, $p = 0.007$, $r = 0.547$; D: $W = 25$, $p = 0.013$, $r = 0.506$; T: $W = 36$, $p = 0.01$, $r = 0.529$), which supports H_4. For a *follow-up analysis* on the impact of these results, Figure 6(b) shows a per-participant scatterplot of the total simulator sickness scores similar to the one of spatial updating accuracies. Overall, the mean difference score between jumping and steering was -13.40 ($\sigma = 20.39$). Despite the significant result, it is visible that only nine participants (indicated with red and orange color) were much stronger affected by simulator sickness during steering. When excluding these cases, the remaining data points ($N = 15$) are almost equally distributed around the diagonal line in Figure 6(b) with a small standard deviation (mean difference between techniques: 0.75, $\sigma = 5.86$), which indicates that participants in this reduced sample were able to cope with both conditions similarly well.

6.4 Subjective Preferences

At the end of the study, participants reported their subjective preferences with respect to different application cases in a questionnaire with 7-point Likert-scales ranging from 0 (strong preference for steering) to 6 (strong preference for jumping). The frequencies of given answers are shown in Figure 7. Most participants expressed a clear preference for steering for the use case of freely exploring unknown virtual environments. This trend is still present but less strong when asked for the more suitable technique to solve the task of the user study. A further question focusing on which technique was more fun to use yielded a bimodal distribution at both ends of the scale with a higher peak for steering than for jumping.

6.5 Discussion

Overall, we observed relatively low pointing errors in our spatial updating experiment (all medians $< 20°$). This indicates good spatial updating performances compared to the results of similar experiments in the literature [34, Section 1.3.3]. We conclude that the experimental task based on a three-segment route layout was solvable and not too demanding. However, pointing errors in the baseline task were significantly smaller than all other measurements, so the



(a) The six participants represented by the blue and orange crosses have pointed notably worse during jumping (more than 10° less accurate).

(b) The nine participants represented by the red and orange crosses have reported notably more simulator sickness symptoms during steering (score at least 20 points larger).

Figure 6: Per-participant scatterplots of the mean pointing errors over both *point-to-start* repetitions (a) and the total SSQ scores (b). The dotted diagonal lines represent no differences between steering and jumping, so the differences increase as the distance of a point to the line gets larger. Corresponding participant clusters are highlighted with the same color in both scatterplots.

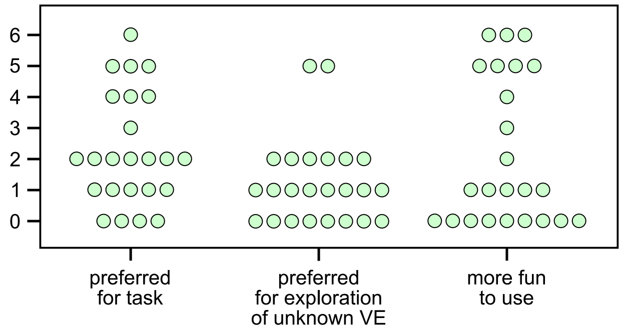


Figure 7: Frequencies of the answers given to the technique preference questions in the concluding questionnaire on a scale from 0 (strong preference for steering) to 6 (strong preference for jumping).

task was sensitive enough to reveal general effects of travel on the mental representation of relative locations in the virtual environment. Apparently, spatial updating errors accumulated during travel.

An inherent difference of the two conditions is that steering requires control of direction and speed whereas jumping requires the specification of a target. When comparing spatial updating performances for both travel techniques, no significant differences could be observed. Although participants traveled significantly faster with the jumping technique and thus experienced the path for a shorter time, a follow-up analysis on a per-participant level revealed that 18 users (75%) achieved similar spatial updating performances. In contrast to the comparisons of passive virtual travel by Bowman et al. [6], the differences between continuous virtual motion and instant transitions seem to affect spatial awareness much less if the travel is actively controlled by the user. The remaining six participants, among which five stated to have no prior experience with VR, pointed more than 10° less accurate after jumping. In four of these cases, the pointing error was even above 30° (see Figure 6(a)). We therefore conclude that integrating spatial information of the path during jumping can be problematic, yet the number of severely affected users seems to be smaller than generally expected.

The participants of our study reported significantly more symptoms of simulator sickness for steering. In contrast, Bozgeyikli et al. [7] did not find any significant differences between steering, jumping and walking in place. Nevertheless, a per-participant follow-up analysis revealed that 15 users (62.5%) also experienced similar simulator sickness symptoms in both conditions. We therefore conclude that replacing a steering by a jumping technique in an application generally results in equal or less simulator sickness.

When investigating the corresponding participant clusters in Figures 6(a) and 6(b), high simulator sickness does not seem to cohere with inaccurate spatial updating. As a result, users who experience more symptoms of simulator sickness with steering could use jumping techniques instead, and users who have difficulties to maintain spatial awareness during jumping could resort to steering. Only for the two participants indicated with orange color in Figure 6, neither of the techniques was ideal. Their lack of prior experience in VR could be an explanation of this observation.

Most participants preferred steering over jumping, particularly for the exploration of unknown virtual environments. Interestingly, even some participants with more symptoms of simulator sickness during steering seem to prefer this technique. The causes of this observation are subject to future investigations.

7 CONCLUSION AND FUTURE WORK

Spatial awareness is an essential cognitive ability that helps humans to avoid losing orientation in known and unknown environments. Travel techniques in VR should support spatial awareness and minimize the risk of simulator sickness. While teleportation beyond vista space is known to impair spatial awareness, the results of our user study indicate that restricting the range of a teleportation technique to vista space helped many, but not all, participants in achieving similar spatial updating performances to steering in our task. Future work should find suitable measures for assisting the remaining users having difficulties during jumping, e.g. by pre- and post-travel information. Our results furthermore revealed significantly higher simulator sickness scores during steering. However, also in this regard, the impact is smaller than expected since 62.5% of our participants showed similar simulator sickness scores in both conditions.

In conclusion, the results of our study justify the implementation of jumping as the default travel metaphor as done in many head-mounted display applications and games. Nevertheless, we argue that steering should not be excluded and always be offered as an alternative, in particular because users seem to prefer the latter for exploration tasks. An effective steering enhancement are the recently proposed field-of-view restrictions by Fernandes and Feiner [14] since they were shown to reduce simulator sickness. However, their effects on spatial awareness are still unexplored.

For steering techniques, the influence of various mediators on wayfinding performance was thoroughly investigated by Darken and Peterson [11]. For teleportation techniques, the benefits of a map mediator was illustrated [9], but the effects of further mediators and visual effects have not been analyzed although they are inherent features of many proposed implementations. We believe that our classification scheme for teleportation techniques offers a valuable tool for formal experimental comparisons and future developments. We made the Python code of our route generator publicly available on our website to facilitate the reproduction of our experimental results as well as follow-up studies.

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