Scene Transitions and Teleportation in Virtual Reality and the Implications for Spatial Awareness and Sickness

Kasra Rahimi, Colin Banigan, and Eric D. Ragan

Abstract—Various viewing and travel techniques are used in immersive virtual reality to allow users to see different areas or perspectives of 3D environments. Our research evaluates techniques for visually showing transitions between two viewpoints in head-tracked virtual reality. We present four experiments that focus on automated viewpoint changes that are controlled by the system rather than by interactive user control. The experiments evaluate three different transition techniques (*teleportation*, *animated interpolation*, and *pulsed interpolation*), different types of visual adjustments for each technique, and different types of viewpoint changes. We evaluated how differences in transition can influence a viewer's comfort, sickness, and ability to maintain spatial awareness of dynamic objects in a virtual scene. For instant teleportations, the experiments found participants could most easily track scene changes with rotational transitions without translational movements. Among the tested techniques, animated interpolations allowed significantly better spatial awareness of moving objects, but the animated technique was also rated worst in terms of sickness, particularly for rotational viewpoint changes. Across techniques, viewpoint transitions involving both translational and rotational changes together were more difficult to track than either individual type of change.

Index Terms—Virtual reality, view transitions, scene transitions, travel, immersive cinema, 3D movies, teleportation, navigation, sickness, spatial orientation, spatial awareness

1 Introduction

Immersive virtual reality (VR) takes advantage of enhanced displays and body-based input to enable interactive viewing of 3D virtual worlds. While VR commonly supports a variety of different forms of interaction with virtual content, travel and view control form the most basic type of interaction needed to interactively explore 3D space. Travel is a core topic of VR research that has been studied extensively (e.g., [1], [2], [3]). The importance of facilitating cognitively simple and easy-to-use travel techniques is well accepted, and numerous studies have demonstrated how different forms of view control can influence sickness (e.g., [4], [5], [6]), spatial understanding (e.g., [7], [8], [9]), and cognitive processing (e.g., [5], [10], [11]).

In most cases, more realistic interaction techniques are more beneficial for travel and view control, with preferred techniques involving normal body movements such as physical head rotation or real walking. However, in some cases, less realistic types of interaction can be beneficial or desirable in VR [12]. For example, virtual teleportation from place to place can allow instant travel across large distances that would take considerable time or physical effort to traverse with realistic travel techniques.

Similar approaches can also be used in cases when a virtual space is larger than a tracked physical space, and a virtual view change is needed to allow continued physical travel (e.g., [13]). In such cases, the view change may not be intentionally initiated by the user but rather system-initiated in response to reaching a boundary in physical space. View changes can also be applied in immersive cinematic experiences. Just as scene transitions are frequently used in traditional film, directorial control of immersive experiences could assist to directing viewer attention, demonstrate a change in time, or transition the narrative to a new scene.

The method of view change is a component of travel techniques that involve a transition between two viewpoints. Often times, research of VR travel techniques is primarily concerned with how a user controls a view change through interactive input. In contrast, the research presented in this paper focuses on *view transitions*—the method for visually showing the change between two viewpoints. For example, once a new viewpoint is specified, the viewpoint could be instantly updated or gradually moved over time. Our research demonstrates that differences in how the transition is shown can influence a viewer's comfort or ability to maintain spatial awareness in a virtual environment.

While the mechanism for specifying a new viewpoint can vary depending on the VR application or travel technique, our study considers automated view transitions that are initiated by the system rather than by the user. In this paper, we refer to such changes as *scene transitions*. These are the types of transitions that might be used to change the context in immersive movies, change a level or map in immersive games, or update the mapping of virtual to physical environments via "resetting" techniques.

We conducted four controlled experiments with head-mounted displays (HMDs) to study three different types of scene transitions:

- *Teleportation*: an instant viewpoint change.

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- *Animated interpolation*: a smooth viewpoint motion from one state to another.
- *Pulsed interpolation*: a sequence of progressive updates showing intermediate views along the transition from one state to another.

Our experiments collected metrics related to sickness, spatial orientation, and preference as participants kept track of moving objects in dynamic virtual scenes. The first three experiments compared different variations of each technique, and the final experiment compared the three techniques to each other.

2 Related Work

Here, we summarize prior research about travel techniques and the effects on spatial awareness, and we also discuss relevant challenges in immersive VR movies and experiences.

2.1 Travel and Teleportation in VR

Researchers have explored a wide variety of techniques for travel in VR. Studies have shown advantages for spatial orientation and feelings of presence for travel techniques that involve more realistic physical input methods of travel (e.g., [1], [6], [8], [14], [15]). For example, Chance et al. [6] compared techniques that differed in level of similarity to real walking in the physical world. They found that the more similar to real walking, the better participants were able to maintain spatial orientation as compared to techniques using virtual motion while users remained still. Past research has also shown that supporting physical rotation is beneficial for navigation and maintaining orientation (e.g., [8], [14], [16]).

However, practical limitations of workspace sizes and ranges of tracking sensors make it impossible to use the most realistic types of travel and viewing techniques in all cases. Many techniques exist to allow travel across large distances using physical input without regular real walking. For instance, modified walking techniques can be used to scale walking input to increase the distance of virtual movement beyond the physical footsteps used to control the technique [17], [18], and researchers have also experimented with allowing users to walk in place rather than physically move around (e.g., [19], [20]). Sargunam et al. [4] and Ragan et al. [21] experimented with semi-natural view rotation that could be used in situations where physical rotation is limited. These studies tested rotation amplification that increases the mapping between physical and virtual view rotations, and the results showed significant sickness effects with amplified or modified rotation in HMDs.

Other techniques prioritize convenience over the concept of realism for physically-based input. *Teleportation* is a common metaphor that generally involves a discrete movement to a target destination (as opposed to allowing the user to continuously control or steer travel along the way). Teleportation is commonly used in *target-based* travel techniques, which allow users to select the destination and then automate the viewpoint change to the destination [22].

In studies of numerous travel techniques and metaphors, research by Bowman et al. [2] found the abrupt view changes of teleportation can be disorienting, and smooth, interpolated transitions allow better maintenance of spatial orientation during travel. In another study, Bowman et al. [9] studied the effects of velocity and acceleration on spatial awareness. This study did not find significant differences in spatial awareness with different levels of velocity or acceleration, but teleportation again resulted in greater disorientation. These studies provided an important foundation for our current research, it is important to note that Bowman's older research studied user-controlled travel, while our studies focus on automated transitions that can be more difficult due to the user lacking prior knowledge of how the view will change. In addition, these prior studies were conducted in sparse, highly simplistic virtual environments with minimal content or detail, which makes the studies difficult to generalize to many current practical applications.

Many other researchers have also studied the use of teleportation as part of travel techniques. Bolte et al. [23] presented the *jumper* technique that lets users travel short distances by walking, whereas if the user wanted to travel large distances, it predicted the intended end location virtually jumped to that position. They compared this technique with teleportation and real-walking techniques. The results from a map sketching task showed worse spatial understanding after using teleportation compared to real walking and the jumper metaphors, indicating potential problems with teleportation disrupting the sense of space and orientation. Moreover, the users preferred the jumper technique's smooth viewpoint animations compared to the instant viewpoint change of teleportation.

In another relevant study, Vasylevska et al. [24] studied an elevator metaphor for navigation in virtual environments, with the main concept being the use of a small virtual room (i.e., an elevator) that moves to different locations. They compared their technique to existing flying and teleportation techniques with respect to presence, comfort, and real-world awareness. Their results showed that teleportation had the lowest score for spatial presence while the flying and elevator techniques were not significantly different. For comfort and awareness of the real-world environment, flying had the lowest scores, but there were no significant differences between the teleport and elevator techniques.

Demonstrating another variation of teleportation, Bozgeyikli et al. [25] experimented with a target-based teleportation technique that shows an arrow at the target destination pointing in the direction the user would be facing after the transition. Relevant to our study of transitions, the researchers also explored different types of cues and fade effects to use for the teleportation transition, but they did not formally compare such design alternatives. While teleportation is heavily used for virtual travel and a common component of many techniques, less work has explicitly focused on transition types between view updates, which is the focus of our studies.

2.2 Automated Movement and View Transitions

The studies presented in this paper focus on transition types for teleportations that do not allow users to have control of movement or view change. Bowman et al. [2] characterized the primary stages of 3D travel techniques (*direction and target selection*, *velocity/acceleration selection*, and *input conditions*) and discussed the importance of the interplay between stages. For situating our experiments using Bowman's taxonomy, it is important to note that we study transition techniques for travel with automatic start and stop conditions. In other words, users do not decide when to begin, when to end, or where to go.

Chrastil and Warren [15] discussed how the level and type of user control may affect spatial learning and the ability to maintain orientation. They conclude that having physical control over movement is important for maintaining spatial understanding, and they argue that user decision-making during travel is less important. Research has considered varying degrees of user control in VR travel. Bowman et al. [2] compared system-automated travel and user-controlled travel with respect to spatial awareness using a pointing task. The system-automated technique produced a slightly lower average error for spatial pointing, but differences were not significant.

In other work, Ragan et al. [5] studied the tradeoffs between sickness and spatial memory for techniques involving different levels of interactive control of travel. In a study with a CAVE VR system, the study compared interactive joystick steering with a target-based technique that allowed participants to point to predefined locations. Participants who used the steering technique had more sickness but better memory of object locations, while the target-based technique had less sickness but worse recall results. The authors concluded the higher amount of total movement in the steering condition likely caused more sickness, and the alternative target-based travel required lower cognitive effort. In another study, Ragan et al. [26] compared user-controlled steering to automatic animated transitions not controlled by the user for a memory task where participants viewed textually-displayed information in the environment. The results showed a variety of learning and memory outcomes to be consistently higher with the automatic travel technique, but the differences were not significant.

Along these lines, a study by Christou et al. [27] found evidence of spatial disadvantages with reduced control over view changes. They found manual view control helped users to understand object locations in the 3D model more accurately than by viewing an automated movie.

Automated techniques have also been considered for VR situations where physical limitations require a change in the mapping between the virtual world and physical environment, such as when a user is at risk of physically moving beyond the bounds of a tracked space. Such methods are sometimes referred to as "resetting" techniques [13]. Williams et al. [13] studied different resetting techniques that automatically intervene and either temporarily change or disable tracked motion while the user physically resets in orientation. Yu et al. [28] explored two alternative travel metaphors for resetting: a virtual spinning platform to adjust the rotating mapping between real and virtual spaces, and a technique for translational travel based on the metaphor of a giant bird picking the user up, flying through the air, and dropping the user off at a new location. In research by Suhail et al. [29] a resetting transition was automatically applied in a VR game; a reorientation transition was applied with a fade-to-black effect to align the user with a physical passive-haptic prop that would match a virtual game object.

Less is known about how different types of transition effects influence spatial understanding of a scene. Christou et al. [30] conducted a VR study of instant view changes showing a 3D object from different perspectives. By manipulating consistency between the environment and object orientations during view changes, the researchers found evidence of the importance of visual context cues for understanding object changes. In research on spatial updating by Klatzky [31] with virtual movement combining both translation and rotation, the authors discuss the difficulty of spatial updating of combined viewpoint changes compared to orientation and positional changes alone. A study by Rieser [32] evaluated orientation through a task that had participants estimate the direction to a target object in a room after closing their eyes and imagining a change in their position or orientation from their starting point. Participants unanimously agreed that rotation-only trials were more difficult than translation-only changes. An additional study reported by Rieser used the same "imagination" method and found that both pointing errors and response times were greater with rotation-only changes than translation-only changes.

Studies by Teramoto and Riecke [33] and by Riecke et al. [34] demonstrated the importance of following dynamic view changes for understanding viewpoint rotations. Considering the results within the context of scene transitions, their findings highlight the importance of visual motion cues for maintaining accurate understandings of view changes, and this is true even without physical input to control the view changes.

Kohn and Rank [35] studied different approaches to using physical movements in VR to control scene transitions to different locations. They evaluated different full-body motion controls (i.e., sitting and standing; leaning; rotating), and they compared two levels of control: (1) a version where the transition was user initiated and its progression was mapped to the execution of the full body motion, and (2) a version where the scene transition was only initiated by the user but then progressed automatically. They found that participants preferred the option where they only initiated the transition. However, it may not be necessary to involve physical movement to maintain understanding of virtual movements. Research by Riecke et al. [36] found that participants can automatically update their sense of spatial orientation during rotation using only visual cues, and that the accompanying physical rotation may not be necessary for fast and reflexive updating. In their study, no significant benefit was observed through the addition of physical rotation via a motion platform.

Thus, prior work suggests that the type of visual cues (e.g., [33], [34], [36]) and motion type (e.g., [31], [32]) may influence the ease of maintaining orientation during viewpoint updates. Our studies explicitly investigate the implications of such factors in more detail in an effort to provide practical design knowledge for teleportation transitions commonly used in VR applications and 360-degree movies.

2.3 360-Degree Movies and Immersive Experiences

With the recent increased popularity in mobile VR applications and commercial VR headsets, a large number of 360-degree movies and immersive experiences have emerged that take advantage of physical head rotations for view control. For example, Google Spotlight Stories [37] and Oculus Story Studios [38] each have a large variety of immersive movies available for both mobile VR and dedicated HMDs. While many commercial VR applications also support positional head tracking and tracked hand/controller input, our discussion focuses on viewing only, and many immersive movies are designed with physical rotation as the only means of interaction.

The designs of existing immersive movies vary greatly. Consider, for example, two immersive movies from Oculus Story Studios [38]: *Henry* and *Lost*. Both are entirely computer-generated animations where the viewpoint is roughly fixed for the duration of the experience. The viewer is free to rotate, but the virtual camera stays in the same room at approximately the same position throughout the narrative. By contrast, Google Spotlight Stories' [37] *Help* combines computer-generated and live-action content. Physical rotation is always supported, but the viewpoint occasionally drifts (with system-controlled rotation) towards action areas. The camera follows the characters of this movie in their escape from a monster. The viewpoint moves (translates) through the world via slow and continuous motion. As another example, USA Network's *Mr. Robot: Virtual Reality Experience* [39] uses both instant scene changes and interpolated view transitions. The movie also uses instant scene changes for cuts between different locations, and it uses animated motions to move the viewpoint in the scenes.

The growing popularity of immersive video has highlighted a number of open research and design issues for investigation. Focusing on display configurations for cinematic VR, MacQuarrie et al. [40] compared the experiences of watching immersive movies using a VR HMD, a normal TV, and a surround video setup combining TV with additional surround projection. The study found that the HMD benefited participants' spatial awareness significantly. Taking a broader view, Yu et al. [41] presented design guidelines for immersive movies based on their work designing experiences for dome theaters. They discuss how directing viewer attention is a challenge in immersive media due to the freedom of view control, but use of visual cues such as motion followed by brightness, color variations, human faces, and persistent objects can help direct viewer focus.

Other researchers have also considered techniques for directing attention in VR. For instance, Peck et al. [42] studied dynamic objects that act as distractors to encourage users to turn towards specific directions. Looking at attention for multiple viewers, Wernert and Hanson [43] discuss a variety of techniques for guiding users' viewing experiences in collaborative virtual environments, with some designs involving the system taking control of view manipulations to point out areas of interest. Along similar lines, Brown et al. [44] discussed techniques and preliminary work in coordinating attention for immersive stories for multiple viewers, with options including distractors, instant transitions, and animated rotations. While this work does involve transitions, empirical results about effects on spatial orientation and sickness are lacking.

A recent study by Kjær et al. [45] suggests that viewers are generally tolerant of transitions in immersive VR movies, though some participants reported having more difficult with orientation with a greater number of transitions or scene cuts. Tomlinson et al. [46] explored the use of different scene transition methods for an interactive virtual cinematographer. Their *cut* method immediately changes the camera position, and their *whip-pan* method swoops the camera through space rapidly when changing its position. However, this work did not compare the two methods. Other work by MacQuarrie and Steed [47] also investigated the effects of transition type in 360 videos. Unlike our work with automated scene transitions, their study was concerned with manual control of the view points for cases where multiple 360 camera locations were used to compile different perspectives of real environments. This study compared three transition types: teleportation, a linear interpolation, and a unique Möbius view transformation. No differences were detected for spatial orientation based on a pointing task, though participants took a longer time after teleportations to initiate the next movement, which may be a result of extra time needed to re-establish orientation.

In our own work, we recently presented a preliminary study comparing scene transitions [48]. Like the research presented in this paper, the preliminary study also tested variations of teleportation, animated interpolation, and pulsed interpolations, but the small number of participants was not sufficient to draw conclusions. We note that the new research we present in the current paper uses a revised methodology from the prior study and reports all new experiments.

3 Study Design Overview

This paper presents four experiments conducted to evaluate the effects of different scene transition techniques on spatial awareness, sickness, and user preference. All experiments were conducted using repeated-measures designs with the same study setup using the same general procedure and methodology, though each experiment compared different transition variations for the independent variables. Each participant only participated in one of the four experiments. This section describes the three primary types of techniques studied and provides an overview of the common study design used across experiments.

3.1 Overview of Techniques and Study Rationale

In this research, we sought to study a variety of transition types while also evaluating variations of each transition type. To do this, our experiments tested three main types of transition techniques: *teleportation*, *animated interpolation*, and *pulsed interpolation*. *Teleportation* involves an instant change in viewpoint position and/or rotation. The viewer will not see the process of viewpoint motion in this technique, and she is instantly translated or rotated. *Animated interpolation* uses a smooth viewpoint motion from one state to another, which allows the viewer to observe the process of being moved to the new state. The third technique is *pulsed interpolation*. Unlike the continuous motion of the *animated interpolation* technique, the *pulsed* technique shows a sequence of intermediate viewpoints along the transition from the originating viewpoint to the final viewpoint.

In general, we expected more gradual view changes to make it easier to maintain spatial awareness in the virtual scene, but we also expected a higher level of system-controlled view updates to bring about worse feelings of sickness and discomfort. Our goal was to systematically compare variations of techniques to test these hypotheses and collect empirical data about the tradeoffs of the different variations for different types of viewpoint changes. Because we expected individual user differences to play a major role in preferences and effects, we opted for a repeated-measures experimental design for each experiment to allow the same participant to test multiple technique variations. The first experiment focused on evaluating *teleportation*, the second focused on *animated interpolation*, and the third focused on *pulsed interpolation*. Then, after analyzing the data collected from these studies, we chose a single variation for each of the three main techniques (i.e., our best judgment of the "best" version of each based on the results), and we conducted a fourth experiment comparing these techniques.

3.2 Experimental Task

To test the techniques and allow assessment of spatial awareness during scene transitions, we designed a simple object-tracking task involving three moving objects (barrels). In every experiment, participants watched the barrels as they moved in different directions, and they were instructed to focus on their positions. After 5 to 10 seconds of comfortable viewing, a scene transition started and the viewpoint changed to a new view. Halfway through the transition, one of the barrels was removed (disappeared instantly), and participants were then asked to indicate the last position of the missing barrel. This task allowed us to evaluate how well participants could maintain their spatial awareness of a dynamic scene with different scene transition types. The exact time before the transition started was randomly determined from the 5 to 10 second range so the participants would not know exactly when it would occur.

The barrels were constrained to the ground and moved linearly in the environment following the terrain. Barrel movement speed varied from 1–2 meters per second, with each object's initial speed determined randomly at run time. The barrels continued moving at the same speed and in the same direction unless they reach the edge of the open area in the environment, in which case: (1) the movement direction reversed along the same straight path, and (2) the barrel's speed was reset as a new random speed from the 1–2 m/s range. The reason for this design decision was to make sure the barrels were not always moving in the same path so that the participants did not get used to fixed motion paths.

3.3 Test Environments

Participants tested different variations of the techniques in two simple scenes: (1) a Viking village with monotonous colors and (2) a cartoonish fort with high color contrast (see Figure 1). The Viking village had more realistic graphics and a larger number of landmarks (mostly log cabins). Its contents were mostly brown buildings that looked similar to each other. This environment also had a wider open area for the movement of the barrels compared to the fort scene. The fort scene had a greater variety of distinct objects such as buildings, trees, surrounding walls, and stationary barrels. The fort environment also had a portion of sloped ground in the open area where barrels moved in the scene.

3.4 Types of Viewpoint Changes

Our evaluations of transition techniques also considered whether different techniques were better suited for different types of viewpoint changes. The experiments studied viewpoint changes over relatively short distances, where the new destination is visible from the original location. Transitions to entirely new locations or settings are outside the scope of the presented research. We were particularly interested in assessing differences in translational and rotational view changes. Based on previous research, we suspected rotational changes to be more problematic for sickness. For example, a study by So and Lo [49] compared different types of virtual rotations (i.e., rotations around different axes) and found that all forms of rotations caused increased sickness compared to the baseline with no scene movement. Virtual rotations have even been used to intentionally induce motion sickness (e.g., [50]).

Our experiments tested three different types of changes: (1) *translation only*, (2) *rotation only*, and (3) *both translation and rotation* at the same time. *Translation only* involved a transition that changed the viewpoint position but not its orientation. *Rotation only* used an in-place rotation along the vertical axis of the viewpoint, and the position of the viewpoint did not change. In transitions with *both translation and rotation*, both the position and orientation were changed. For the *pulsed* and *animated* interpolation transition techniques, which involve incremental or gradual views, the translation and rotation occurred together during the viewpoint transition in the *both translation and rotation* conditions.

For transitions that included translational changes, the new position was chosen randomly from a set of 12 predetermined positions in the scene. The distance the viewpoint moved for translational changes varied from 5 to 30 meters. A variety of distances and directionality for viewpoint translations prevented participants from learning the positional changes, which could have assisted in guessing object positions for the experimental task. For transitions with rotational changes, the degree of rotation varied from 45 to 140 degrees.

3.5 Measures and Data Analysis Methods

Measures for the dependent variables included three main categories: spatial awareness, sickness, and preference. To assess spatial awareness of the scene during the transition, we used a pointing test after the transition. One of the moving barrels disappeared halfway through the transition, and the participant was asked to align a cursor with the location of where the barrel was when it disappeared. The cursor was overlaid over the viewport and centered in the view, and participants positioned the cursor using head movement. Participants verbally confirmed the indicated direction, which was then recorded by the experimenter

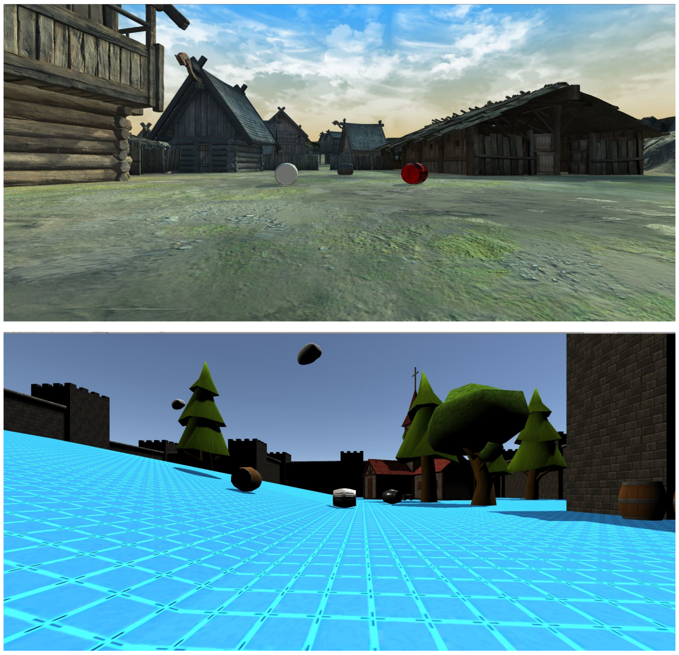

Fig. 1. The two virtual environments used in the study. We refer to the top as the *Viking village* and the bottom as the *cartoon fort*.

pushing a button. We measured pointing error as the unsigned difference in angle between the correct direction of the removed barrel and the direction indicated by the participant. This was done immediately after each transition.

To analyze the results of the pointing assessment, we conducted two-way repeated-measures factorial ANOVAs to test for effects of the different viewpoint change types, the transition variations, and interactions between the two factors. When checking assumptions for parametric testing, we found Sphericity was an issue for some metrics; in such cases, we report the test results with Greenhouse-Geisser (GG) correction. Pairwise effect sizes are reported with the Cohen's d statistic, and ANOVA test effect sizes are provided by generalized eta-squared (η_G^2). Reported tests use a significance level of $\alpha = 0.05$.

We measured the sickness the participant felt during the study was measured in two ways: (1) the Simulator Sickness Questionnaire (SSQ) from Kennedy et al. [51] and (2) relative ratings of techniques in terms of sickness. The SSQ involves ranking a variety of different sickness symptoms as *none*, *slight*, *moderate*, and *severe*. We report total SSQ scores (following the formula in [51]) to provide a standardized measure of sickness for the overall experience. Participants completed the SSQ multiple times throughout the study. Consequently, the effects of the specific technique differences on the SSQ scores are confounded due to repeated trials and extended use of VR. We therefore also assessed sickness by asking participants to rate the technique variations relative to each other using a set of 1–10 scales.

Similar to the relative ratings for sickness, we also measured participant preference for techniques using a set of 1–10 scales. We used this data to understand how much participants liked or disliked the techniques in relation to each other. Due to the ordinal nature of such ratings, we use non-parametric Friedman tests to check for differences due to different transition variations. We note that these were only one-way comparisons because participants provided rating responses for the different transitions techniques but not for different types of viewpoint change.

We also report outcomes using standard box-and-whisker plots. A colored rectangle represents the interquartile range (IQR) with a horizontal black band for the median. Each whisker extends to the most extreme value falling within an additional half-IQR beyond the IQR (in both directions), and black dots show outliers beyond this range.

3.6 Procedure

The study was approved by our university's Institutional Review Board (IRB). Participation was voluntary and no compensation was given. Each of the four experiments followed the same general procedure but assessed different types of transition techniques. Participants first completed a background questionnaire about age, gender, occupation, and prior experiences with video games and virtual reality. Participants also completed a baseline SSQ questionnaire [51] at this time. We then described the task and ran a practice trial for participants familiarity with the task. When participants were ready, we began the main trials.

Each experiment followed a repeated-measures design that required each participant to complete multiple trials for each variation of transition technique, where ordering of variations was balanced by a Latin square. Additional details about the experimental design are given in the appropriate *Experimental Design* sections for each experiment later in the paper, but the general procedure was as follows. In each test environment, participants completed blocks of nine trials (three for each type of the three viewpoint changes, randomly ordered) for each transition variation. Participants completed an additional SSQ after each block of trials for the technique variations, and they could also take an optional two-minute break in between blocks.

The participants first tested all trials for each technique in one of the two test environments. Participants then took a five-minute break before repeating the procedure for the second test environment (ordering of environments was balanced among participants).

After completing all trials, participants completed a post-study questionnaire about sickness, preferred technique variations, and ease of task completion. We also asked for general feedback about the techniques in an informal interview. The entire procedure took approximately 30-60 minutes depending on the experiment.

3.7 Study Materials

Participants viewed the environments in an Oculus Rift (consumer version 1.0). Positional and rotational head-tracked viewing was enabled through the Oculus Rift's Constellation tracking system. Participants sat in a rotating chair for the study, and they could turn and lean freely. The study application was implemented in Unity3D version 5.4.1f1. The software ran on a computer running 64-bit Windows 7 Professional with a 3.6 Ghz Quad Core processor and a GeForce GTX 980 4GB graphics processing unit.

4 EXPERIMENT 1: TELEPORTATION

The first experiment focused on *teleportation* transitions. We compared two variations to study whether the use of a fade effect would cause differences in spatial awareness or comfort for different types of viewpoint changes.

4.1 Experimental Design

The study followed a 2x3 within-subjects design with two types of *teleportation* transitions and the three types of viewpoint change as described in section 3.4. The two types of *teleportation* were: (1) *instant*, where the viewpoint immediately changes without any delay, and (2) *fade to black*, where the transition first fades to black at the starting location and then fades back to the scene at the new location. The entire *fade to black* transition took 1.5 seconds from start to end.

Participants completed all combinations of technique and change type in both the *Viking village* and *cartoon fort* environments. For each of the two *teleportation* variations, participants first completed nine randomly-ordered trials (three with each viewpoint change) in one environment, and then the procedure was repeated in the second environment. This resulted in a total of 36 trials (not counting practice). The procedure took approximately 30 minutes.

4.2 Hypotheses

For spatial awareness of object positions, we did not expect differences between the *instant* and *fade to black* types of teleportation because the view changes were similar and immediate in both versions.

We hypothesized sickness would be worse with the *instant* variation due to the abrupt change in visual states, whereas the *fade to black* variation had a more gradual change. We expected participants to prefer *fade to black* teleportation for the same reason. Because the transitions were not initiated by the user, we thought the gradual transition would be a less jarring experience.

4.3 Participants

The comparison of *teleportation* transitions in Experiment 1 was completed by 18 participants (14 males and 4 females). All were university students with ages ranging from 21 to 27 (median of 23 years). Nine participants reported they play 3D video games for at least one hour a week. Participants reported mixed levels of experience with VR. Twelve participants had tried VR at least once before the study.

4.4 Results

We report the results for the spatial awareness, sickness, preferences, and participant comments. See Section 3.5 for an overview of measures and analysis methods.

4.4.1 Spatial Awareness Results

We analyzed the results of the pointing assessment with a repeated-measures factorial ANOVA to test for effects of viewpoint change, teleportation variation, and interactions between the two factors. Figure 2 shows the pointing error from the spatial awareness assessment. The ANOVA found a significant main effect of view change type on pointing

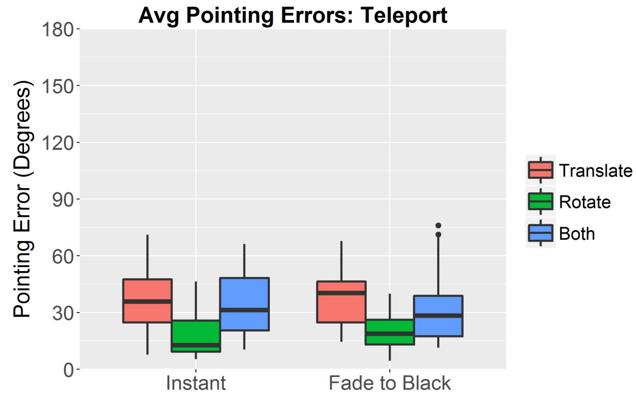

Fig. 2. Average pointing error for different variations of the *teleportation* technique from Experiment I. Errors were significantly lower with *rotation only* transitions.

error with $F(2,34) = 14.15$, $p < 0.001$, and $\eta_G^2 = 0.19$. Posthoc Bonferroni-corrected pairwise t-test comparisons found that *rotation only* view changes had significantly lower errors than both *translation only* and *both translation and rotation*. The effect size was large; *translation only* and *both translation and rotation* each had approximately twice as much error as *rotation only* (with Cohen's $d = 1.65$ and $d = 1.39$, respectively).

No evidence of differences were detected between *instant* and *fade to black* for pointing error, and no interaction effects were found. We also tested for correlations of pointing error with participant gaming hours and gender, finding no significant correlations.

4.4.2 Sickness and Preference Results

Sickness scores from the SSQ tests were low, with scores from the final test having $M = 12.26$, $Mdn = 7.48$, and $SD = 16.44$ (the SSQ has a maximum score of 235.62 for total sickness). For the relative ratings on the 1–10 scale, sickness ratings were low overall ($M = 2.00$, $Mdn = 1.00$, and $SD = 1.80$). A Friedman test found no evidence of differences due to teleportation type.

Personal preference of transition type varied by individual, and there was no clearly preferred variation. Differences in ratings were not statistically significant. Overall, 8 out of 18 participants preferred the *instant* version, 5 preferred the *fade to black* version, and 5 rated both equally. Sickness ratings were not significantly correlated with preference ratings (Spearman's $\rho = -0.17$), likely because sickness was mostly a non-issue for the *teleportation* transitions.

4.4.3 Qualitative Results

Participants provided feedback as part of the post-study experience questionnaire and the informal interview at the very end of the experiment. Half of the participants reported preference for the *instant* version of the *teleportation* technique, while 4 preferred *fade to black*, and 6 had no preference. The *fade to black* was chosen as a more gradual transition that provides some indication that the view change was coming, and all but one participant reported the *fade to black* version was easier to understand the view change. Despite this benefit, more participants (9 of 16) found the *fade to black* version more disrupting, which we

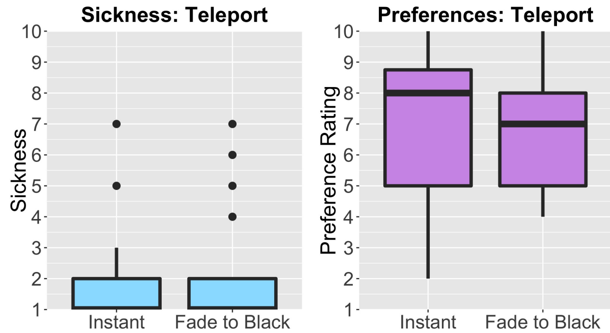

Fig. 3. The ratings for the sickness caused by different variations of the *teleportation* technique. On the left, higher values correspond to more sickness. On the right, higher values mean more preferred.

expect is due to its longer duration and the brief instant of lost visibility of the scene. A few participants thought they performed better when completing the object tracking task using the *fade to black* version; one mentioned that the fade gave her "some time to think about where I was in the scene and where the barrels were".

5 Experiment 2: Animated Interpolation

Another option for scene transition is to animate the view by smoothly interpolating the viewpoint. Animated view transitions might make it easier to understand a view change, but such an approach overrides the use of physical head-tracked viewing during the transition, which could cause discomfort or sickness. Experiment 2 compared different movement speeds in animated transitions.

5.1 Experimental Design

This experiment tested implementations of *animated interpolation* that moves the viewpoint smoothly between the start and end points with a fixed velocity. Positional and rotational head tracking was enabled during the experiment—including during transitions, so participants were able to move their heads to look around while the animated transition was in progress. The experiment used the same object-tracking task, and as with all techniques in the experiments, the barrels were removed halfway through each transition.

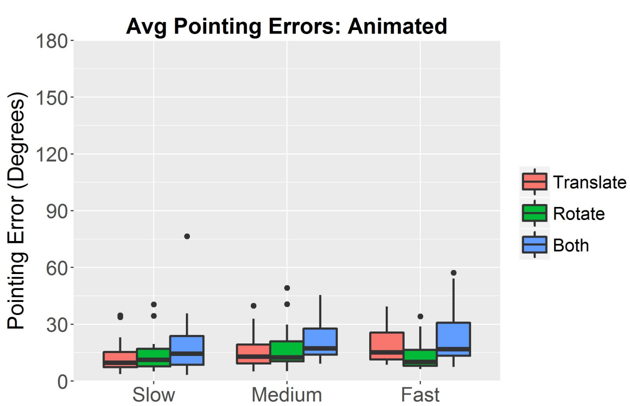

Fig. 4. Average pointing error for different variations of the *animated* technique. No significant effects were detected.

The study followed a 3x3 within-subjects design with three animation speeds and the same three viewpoint changes previously described in section 3.4. The three animation speeds for were: *slow* (10 m/s), *medium* (25 m/s), and *fast* (50 m/s). The task and procedure were the same as the other experiments (explained in section 3). The specifics for ordering trials for the different experimental conditions were configured in a manner analogous to the method for Experiment 1. Participants completed trials with all variations of *animated* transitions in both test environments. For each of the three speed variations, participants first completed three trials with each type of viewpoint change in one environment, and then the procedure was repeated with the second environment. This resulted in a total of 54 trials (after instructions and practice). The procedure for Experiment 2 took approximately 45 minutes.

5.2 Hypothesis

We expected that the slow variation would allow participants to perform the best for the spatial awareness task because the viewer would have more time to follow the scene changes while being transitioned. We hypothesized that the fastest variation might be too fast to effectively understand the changes while the objects were moving. However, we hypothesized that the fast variation would cause less sickness because it was so quick that it was similar to a *teleportation* technique, which Experiment 1 showed to have low sickness effects. We expected the slower animations to have worse sickness problems due to the viewer having reduced control for a longer period of time movement, meaning a longer duration of mismatch between visual changes and head movements.

5.3 Participants

The *animated interpolation* experiment was completed by 18 participants (14 male, 4 female). All were university students. Ages ranged between 20 to 27 (median was 21 years). Eleven participants reported playing 3D video games for at least one hour a week, and 14 of the 18 participants reported having some prior experience with VR.

5.4 Results

The results of the animated interpolation experiment are again organized by spatial awareness results, sickness and preference results, and qualitative feedback.

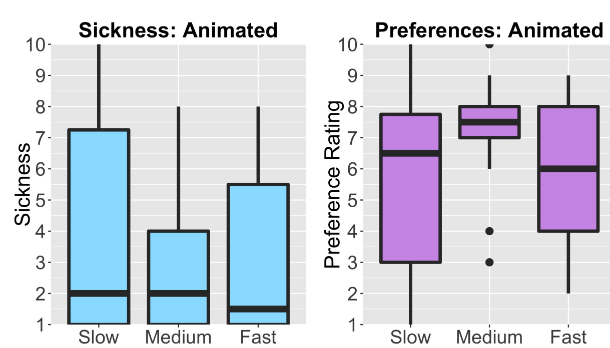

Fig. 5. The ratings for the sickness caused by different variations of the *animated* technique. On the left, higher values correspond to more sickness. On the right, higher values mean more preferred.

5.4.1 Spatial Awareness Results

Errors on the pointing task after animated transitions were relatively low ($M = 17.48$ degrees, $SD = 11.83$). Figure 4 shows the distribution of error broken down by the experimental factors. A repeated-measures factorial ANOVA found no significant differences in pointing error due to animation speed. We attribute the lack of differences to the low overall error, which demonstrates that animated transitions can facilitate spatial awareness reasonably well even with fast speeds.

The ANOVA detected a significant effect of viewpoint change with $F(2, 34) = 6.57$, $p = 0.004$, and $\eta_G^2 = 0.06$. A posthoc analysis with Bonferroni-corrected pairwise t-tests found *both translation and rotation* to have significantly higher error than *rotation only* as well as *translation only*. The effect was large, as conditions with *both translation and rotation* saw approximately 40% greater error compared to *translation only* ($d = 0.71$) and *rotation only* ($d = 0.87$). Thus, even though animation supported relatively low overall error for spatial awareness, combining rotational and translational updates significantly increased task difficulty.

As with Experiment 1, no correlations were detected between gaming hours or gender with pointing errors.

5.4.2 Sickness and Preference Results

Sickness responses varied by participant. On average, SSQ scores were again low, with scores from the final test in the study session having $M = 22.44$, $Mdn = 9.35$, and $SD = 26.77$. The comparative sickness ratings (on a scale of 1 to 10) were also low (M = 3.11, Mdn = 2.00, and SD = 2.68). Of all participants, 10 of the 18 participants only rated the transitions at 1 or 2 for all speeds, indicating no or very low sickness. Figure 5 (left) provides an overview of sickness ratings for the different speeds. A Friedman test failed to detect significant differences due to animation speed, though the main effect was nearly significant with $\chi^2(2) = 5.24$ and $p = 0.07$.

Preference results were also not significant, though a trend might be interpreted from the Friedman results showing $\chi^2(2) = 5.21$ and $p = 0.07$ for the main effect. The variance of personal preferences was high (see Figure 5, right). The *medium* speed was most preferred among the speeds, with 7 out of 18 participants rating it above the alternatives, but no speed received majority preference. Not surprisingly, there was a significant inverse correlation between sickness ratings and preference ratings (Spearman's $\rho = -0.54$, $p < 0.001$), suggesting that participants preferred techniques they felt had lower sickness.

5.4.3 Qualitative Results

From the post-study questions, no animation speed was clearly strongly preferred among the others, though only 3 of the 16 participants reported the *slow* speed as least preferred. Most participants thought that when the movement speed was the slowest they could complete the spatial awareness task easier, with 15 participants rating the slowest version as best or tied for best in terms of ease of following the objects. The most common feedback was that rotating with the *animated* technique caused high discomfort and noticeable sickness. Representative comments about rotating using the *Animated* technique include: "Rotation is weird because you inherently want to try to fight it" and "Fast rotations gave me a high degree of dizziness".

6 Experiment 3: Pulsed Interpolation

In the third experiment, we studied a transition technique we call *pulsed interpolation*. This type of transition is similar to teleportation except instead of transitioning directly from the starting view to the final view, the viewpoint changes to a number of intermediate points along the way. The rationale for the additional intermediate points is that seeing a sequence of smaller scene changes rather than the entire change at once might help a user retain understanding of the change. On the other hand, more intermediate points also extends the duration of the transition and could further disrupt the experience.

6.1 Experimental Design

We compared different variations of the *pulsed* transition technique with varying amounts of intermediate points between the start and end points. We tested three variations with different amounts of intermediate transitions to get to the end: 2 jumps (*low*), 3 jumps (*medium*), and 4 jumps (*high*). In our implementation, it always took 1 second to transition between each pair of intermediate points.

The study followed a 3x3 within-subjects design with the three numbers of intermediate points and the same three viewpoint change types as the previous experiments, and the task and procedure were the same. The specifics for ordering trials for the different experimental conditions were configured in a manner analogous to the methods of Experiments 1 and 2, resulting in a total of 54 trials (after instructions and practice). The procedure for Experiment 3 took approximately 45 minutes.

6.2 Hypothesis

Previous research supports the benefit of intermittent jumps for spatial awareness. Riecke et al. [36] found that instant jumps of images with new orientations are sufficient for fast, effortless spatial updating with no significant difference compared to continuous rotation. These findings support the notion that jump-like transitions might be promising for use in VR applications, but further research is necessary to learn more about user preferences and the effectiveness of different transition types for different types of view updates beyond rotation-only changes.

We expected that a higher number of intermediate points would enable better spatial awareness than fewer intermediate points because seeing a sequence of smaller transitions would make it easier to understand the overall change. Overall, pointing errors were lower with the *animated* technique than with *teleportation*, and the pulsed technique becomes more similar to animated interpolation as more intermediate points are shown.

We hypothesized that a lower number of intermediate points would cause lower sickness because of fewer viewing interruptions. Having fewer intermediate points makes the pulsed technique more similar to the *teleportation* technique, which had markedly low sickness effects in Experiment 1.

6.3 Participants

Eighteen university students (14 male and 4 female) participated in Experiment 3 focusing on *pulsed* transitions. Ages ranged from 20 to 27 years with a median age of 22. Ten participants reported that they currently play 3D video games for at least one hour a week. Thirteen participants reported having tried VR at least once before.

6.4 Results

This section reports the results of the experiment for *pulsed interpolation* transitions.

6.4.1 Spatial Awareness Results

The errors from the spatial pointing task in the *pulsed* transition experiment are shown in Figure 6. A repeated-measures factorial ANOVA for pointing error found a significant main effect due to type of viewpoint change with $F(2,34) = 14.15$, $p < 0.001$, and $\eta^2_G = 0.12$. Posthoc testing with Bonferroni-corrected t tests found *rotation only* transitions had significantly lower errors than *translation only* ($d = 1.00$) and *both translation and rotation* ($d = 1.52$) with large effect sizes. No significant effect on pointing error was detected based on the number of intermediate points, and no interactions were found.

No correlations with pointing errors were detected between either participant gaming hours or gender.

6.4.2 Sickness and Preference Results

In the *pulsed* transition experiment, the SSQ scores from the final test in the study session had a mean score of 25.97 with SD = 30.66 (median was 14.96), which again indicates relatively low overall sickness.

For the relative 1–10 sickness ratings, Figure 7 (left) shows sickness perception increasing along with higher numbers of intermediate points. A Friedman test failed to detect a significant effect of number of intermediate points with $\chi^2(2) = 5.10$ and $p = 0.078$.

In terms of preference, the results varied greatly, and there was no clear majority-preferred number of intermediate points. We do note that the variation with the highest number of points was least preferred by 7 out of 18 participants. Figure 7 (right) shows preference ratings for the variations of the pulsed technique. The differences in preference ratings due to number of points was not significant with the Friedman test yielding $\chi^2(2) = 1.94$ and $p = 0.38$. No evidence of a correlation was detected between preference ratings and sickness ratings (Spearman's $\rho = -0.06$)

6.4.3 Qualitative Results

The feedback from the post-study questions showed preferences for the *pulsed* transition suggest a lack of clear preference. An equal number of participants (4 of 16) preferred versions with either the lowest and highest numbers of intermediate points. The middle variant was only considered the worst by one participant. Several (6) participants felt worse sickness with the highest number of intermediate points, and comments indicated that the multiple jumps and changes were disliked by some participants.

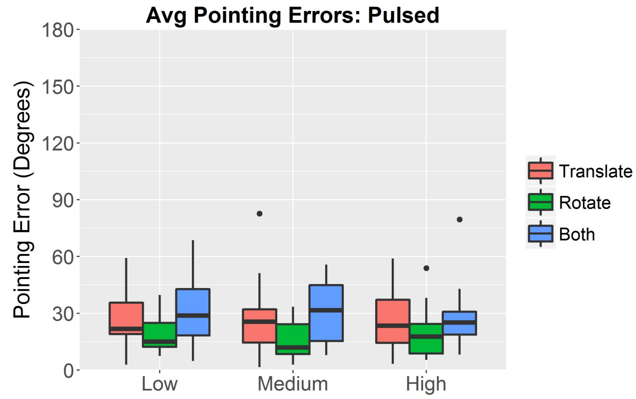

Fig. 6. Average pointing error for different variations of the *pulsed* technique. Errors were significantly lower with *rotation only* transitions.

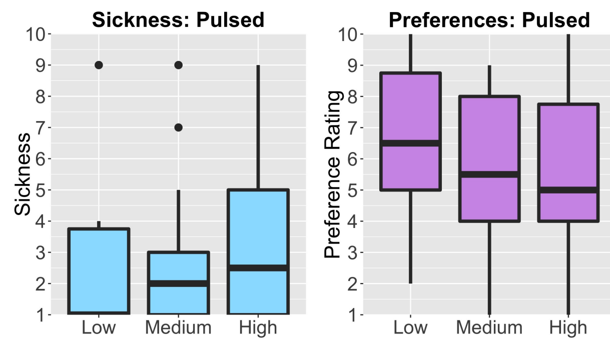

Fig. 7. The ratings for the sickness caused by different variations of the *pulsed* technique. On the left, higher values correspond to more sickness. On the right, higher values mean more preferred.

7 Experiment 4: Comparing Techniques

After testing variations of the *teleportation*, *animated interpolation*, and *pulsed interpolation* techniques in the first three studies, we conducted a final experiment to compare the technique types to each other. We chose a variation of each technique based on participants performance and feedback from the prior experiments, and we conducted a new within-subjects study where each participant tested the three techniques in one session. Rather than post-hoc comparisons of conditions pulled from the previous experiments, the within-subjects design allowed us to control for individual differences and assess subjective comparisons.

7.1 Experimental Design

The study followed a 3x3 within-subjects design to compare the three technique types with the same three movement types, task, and procedure as the other experiments. This experiment used the *instant* version for the *teleportation* technique, the *slow* (10 m/s) version of the *animated* technique, and the *medium* version of the *pulsed* technique with three intermediate points. Note that we cannot claim that these choices are the optimal configurations of each technique because preferences and results varied widely by participant, but we do consider the selected versions as reasonable options for each transition type.

Trial ordering for the experimental conditions were configured in the same way as the prior experiments, which again resulted in 54 total trials (not including instructions and practice). This study took approximately 45 minutes.

7.2 Hypothesis

We expected that participants would perform the best with the *animated* technique for the spatial awareness task. The reason was that with this technique, the viewer could keep track of changes in the scene while moving from the starting point to the destination with smooth viewpoint movement. We also expected the *teleportation* technique to be the worst for the spatial awareness task since the sudden change in the viewpoint could cause disorientation for the viewer and they could lose track of where the barrels where moving to.

For the sickness, the hypothesis was *teleportation* would cause less sickness than *animated* because the viewer could see the whole process of moving from one position to another while not having control, while *teleportation* technique had an immediate change.

Finally, we expected the *pulsed interpolation* technique to be somewhere in the middle for both spatial awareness and sickness, meaning we thought the *pulsed* technique would help participants perform better than *teleportation* but worse than *animated*, and it would cause less sickness than *animated* but more sickness than *teleportation*.

7.3 Participants

Experiment 4 was completed by 18 participants (16 males and 3 females) between 20 to 26 years old (median age was 22 years). All were university students. Thirteen participants reported that they regularly play 3D video games for at least one hour a week, and 10 participants had previous experience with VR.

7.4 Results

This section reports the results of the Experiment 4, which compared the *teleportation*, *animated*, and *pulsed* techniques to each other.

7.4.1 Spatial Awareness Results

The spatial awareness results from the pointing assessment in Experiment 4 are shown in Figure 8. A two-way repeated-measures ANOVA tested for effects of transition technique and viewpoint change on pointing error. The test detected a significant main effect for transition technique with $F(2, 34) = 4.50$, $p = 0.018$ ($p = 0.030$ with GG correction), and $\eta^2_G = 0.07$. Posthoc Bonferroni-corrected t tests found the *animated* technique to have significantly lower error than both the *teleportation* ($d = 0.75$) and *pulsed* ($d = 0.88$) with large effect sizes.

A significant main effect for type of viewpoint change was also found with the same ANOVA producing results of $F(2, 34) = 5.31$, $p = 0.010$, and $\eta^2_G = 0.05$. Bonferroni-corrected pairwise comparisons found that transitions that changed *both translation and rotation* had significantly worse spatial pointing results than both *translation only* ($d = 0.64$) and *rotation only* ($d = 0.69$) with large effects sizes.

The ANOVA found no evidence of an interaction effect between transition technique and viewpoint change type. No correlations were detected between participant gaming hours or gender with pointing errors.

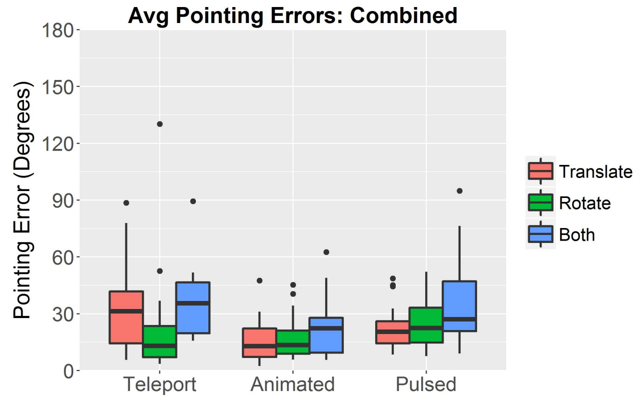

Fig. 8. Pointing error for the comparison of *teleportation*, *animated*, and *pulsed* transition techniques in Experiment 4. *Animated* transitions resulted in the significantly lowest error.

7.4.2 Sickness and Preference Results

In the fourth experiment, the final SSQ scores from the experiment were again low (M = 13.71, Mdn = 5.61, and SD = 17.32). For the relative ratings of sickness, responses varied greatly. Figure 9 (left) shows a summary of ratings for the *teleportation*, *animated*, and *pulsed* techniques. The figure shows most participants indicated that *animated* transitions had the worst (highest) sickness effects. A Friedman test found the difference to be statistically significant with $\chi^2(2) = 16.35$ and $p < 0.001$. A posthoc Nemenyi test found the *animated* technique to be significantly worse than both *teleportation* ($d = 0.96$) and *pulsed* ($d = 0.67$) transitions, showing large and moderate effect sizes, respectively. Of the 18 participants, 9 rated *animated* transitions as the worst for sickness.

Interestingly, despite the clear results for sickness ratings, an analysis of preference ratings did not yield the same results. Figure 9 (right) shows the preference results and the high variance in ratings for all three techniques. A Friedman test did not detect any significant differences in preference ratings. *Animated* transitions were most preferred by 7 participants, *teleportation* was favored by 7 participants, and the *pulsed* method was favored by 4 participants.

Yet, sickness and preference ratings were significantly inversely correlated (Spearman's $\rho = -0.37$ and $p = 0.006$), meaning techniques with worse sickness were rated lower in terms of preference. Thus, we again expect sickness was a major factor for participants' preference ratings.

7.4.3 Qualitative Results

Participants expressed different opinions about the techniques in the post-study questionnaire and interview. In regards to spatial awareness, most participants (16) felt the *animated* technique was best, and participants indicated the animation made the task easier by allowing them to follow object movements while being transitioned. However, similar to the comments about the *animated* technique in Experiment 2 (see Section 5.4.3), all participants had negative feedback about rotations in the *animated* technique. They found it difficult to complete the task when rotating since they lost track of the changes in the scene.

For the sickness caused by the techniques, most of the participants (all but one) said that the *teleportation* technique

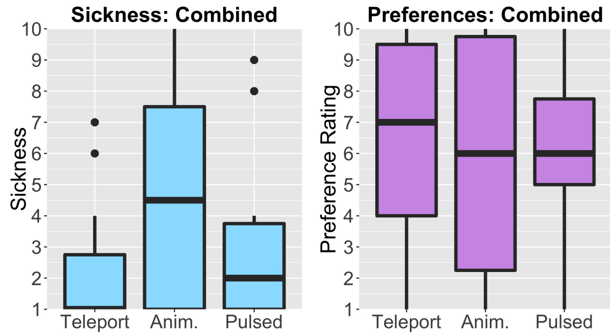

Fig. 9. The ratings for the sickness caused by different techniques in the combination study. On the left, higher values correspond to more sickness. On the right, higher values mean more preferred.

caused the least sickness and the *animated* technique caused the most sickness. Most participants also did not feel sick with the *pulsed* technique, and when comparing it to the *animated* technique, most felt more comfortable with *pulsed*.

8 Discussion

We discuss the results from the four experiments together to highlight the main findings and implications.

8.1 Implications for Spatial Awareness

Overall, the study results showed that the errors for the spatial awareness task were relatively low for all the three scene transition techniques. The task with the disappearing objects was designed to be difficult, and in real immersive experiences, objects of interest would not be expected to disappear during a transition within a single local environment. It also would not be necessary to exactly point towards a target object of interest; practically speaking, so long as the object can still be found quickly after a transition, the disruption would be expected to be small. Even with the more difficult task, participants were able to face roughly the right directions for most trials. Furthermore, real applications would ideally incorporate additional considerations to make it even easier to track object locations. For example, limiting object motion near the time of a transition, providing high color contrast, or providing notable environmental landmarks would be expected to help. Thus, acknowledging the reasonably low error levels for the spatial pointing task, it could be possible to use any type of transition technique with appropriate design choices and still support acceptable spatial awareness. However, our intention is to understand transitions in suboptimal situations, and the goal is to be able to produce design recommendations that facilitate understandable and comfortable experiences.

From Experiments 1 and 3, participants could track scene rotational changes more easily than viewpoint changes that included translational updates. In a way, this was surprising because we thought a simple linear movement would be the easiest type of motion to understand, and we know that rotational changes can interfere with head-tracked viewing. The results also contrast with those of Rieser's study [32] of spatial updating using imagined changes. However, unlike imagined rotation, the visual updates in our study allow the use of landmarks and relative size of objects to help assess the spatial changes. Our experiments involved dynamic objects against a rich background with ample imagery to use as landmarks. With only a rotation in place, it would be reasonably easy to realign to understand how the view had changed based on the surrounding visuals. This explanation also agrees with feedback from our participants, as many noted the importance of using distinct landmarks in the scene to help maintain spatial awareness.

This result does align with other studies of spatial orientation with view changes (e.g., [30], [33]). By understanding the rotation of the environment rather than focusing only on the object movements, it was easier for participants to understand where the objects had been at the time of transition. In contrast, translational movements removed the ability to rely solely on realigning the environment with a single degree of freedom. Instead, completing the pointing task with a translational update requires first approximating the viewpoint change and then triangulating the position of the missing objects from the new location.

We also note that *rotation only* changes were only significantly better than *both translation and rotation* for spatial awareness in Experiment 4, so it is not definitively clear when translation is more difficult. Across all techniques (Experiment 4), the studies provide empirical evidence of the added difficulty in spatial tracking with view changes that involve *both translational and rotational* updates, which agrees with the subjective results from Klatzky [31].

In terms of the comparison of different transition types from Experiment 4, *animated* interpolations enabled the best spatial awareness. This result supports our hypothesis that animating the viewpoint movement would make it easier to understand the change. The advantage of *animated* was most notable for viewpoint changes that include translational updates, though no significant interaction was detected between technique and viewpoint change. Of the three techniques in Experiment 4, note that the animated technique allowed participants the longest amount of transition time, which likely made it easier to track the target object. However, Experiments 2 and 3 also compared variations with different transition times, since different speeds of *animated* transitions and numbers of intermediate points in *pulsed* transitions affect total time. Since these experiments did not detect significant differences among the techniques with different durations, we do not have evidence supporting that transition time was the determining factor. The study of Bowman et al. [9] also failed to detect an impact of travel speeds for spatial awareness. Therefore, we hypothesize that the speed of the transition is not of primary importance for maintaining orientation during spatial changes as long as visual cues are available to sufficiently show the change, which teleportation does not. Further experimentation would be needed to specifically address this hypothesis, and it would be important to also consider response time as a measure in addition to spatial judgment error, as response latency can reflect the difficulty in spatial updating.

As shown in Experiment 4, the spatial task was more difficult with the *teleportation* technique than the *animated* version. This is not surprising, as numerous studies have contributed evidence of disorientation problems associated with *teleportation* (e.g., [9], [52]). Unlike the prior studies, our work demonstrates the same effect without user initiation of the view change. The instant change of *teleportation* does not allow users time to observe the path of motion for the viewpoint change, while the more gradual *animated* and *pulsed* transitions provide intermediate cues to aid prediction. It is logical that *animated* transitions support better spatial awareness given the highest amount of transition cues among the three techniques for indicating the direction and type of viewpoint change. Though the *pulsed* technique provides greater indication of the change than *teleportation*, the results suggest it was not enough to yield significant improvements in the spatial task.

8.2 Limitations

When interpreting the results or the presented experiments on transitions and spatial understanding, it is important to note two main limitations. First, our method evaluated spatial awareness based solely on judgment error as the measure for the pointing task. Our studies did not account for response time (i.e., latency) for the pointing task, which other researchers have demonstrated as a valuable measure that corresponds to ease of maintaining or interpreting orientation (e.g., [21], [32], [36]). While participants were instructed to provide responses immediately after the transition, variations in response times were possible. Thus, even in cases from our studies where the results did not exhibit significant differences for pointing errors, it is possible that response latencies may have differed. Second, our studies did not evaluate the effect of the magnitude of the rotational and translational viewpoint changes used in the task. The degree of distance or angular chance can influence the difficulty of spatial judgment tasks (e.g., [32], [53]). Though we varied the magnitude of change to prevent learning effects during the repeated trials, the values were randomized. While the range of possible magnitudes were controlled, we are unable to assess possible influence of specific magnitudes from these experiments.

8.3 Sickness and Preference

Reported sickness effects were relatively low in all four experiments, as demonstrated by the low SSQ scores. Only minor discomfort was reported. When interpreting sickness ratings for the relative ratings using the 1–10 scales, it is important to note the relative nature of the ratings, which means that a high or low score on this scale might not necessarily correspond to high or low sickness on an objective scale. These ratings should not be used to compare scores across experiments since the ratings were made at the same time relative to the available options. The clearest result from the sickness ratings indicate that participants were bothered by the *animated* transitions in comparison to the *teleportation* and *pulsed* techniques, which verifies that designers should have concerns about *animated* transitions despite their benefits for spatial awareness. More specifically, participants reported discomfort with rotation with the *animated* technique. Such feedback was not surprising since head tracking was enabled, and forced camera rotations mean a certain mismatch between physical head and virtual view adjustments. If anything, we suggest using *animated* transitions rarely, as alternative methods can still allow sufficient understanding of scene changes. And, if *animated* transitions are used, we suggest avoiding animated rotations—especially since our results show *teleportation* with *rotation only* works well for tracking scene changes.

It is interesting that, despite the sickness problems, some participants (7 of 16) preferred *animated interpolations* over the *pulsed* and *teleportation* techniques in Experiment 4. This may have to do with the ease of the spatial awareness task, as people prefer to perform well, so participants might have been more inclined to rate the *animated* technique higher due to the ease of the pointing task. However, we would expect sickness to be more important for continued use in real applications. The disparity of ratings (in all experiments) also points to the high level of variability in individual differences and preferences.

The effects of different types or modified rotations relate to interesting questions about how different types of rotational changes might influence sickness or sensitivity to changes, as studied by others (e.g., [4], [54]). For example, Jerald et al. [54] found forced rotations to be more acceptable when the view was rotated in the direction of physical movement, and Sargunam et al. [4] similarly found amplified rotation to be less problematic than reorientation adjustments that were applied independently of physical turning. Other factors could likely influence sickness effects associated with rotational adjustments, and further assessment of such factors would be useful for understanding how to design scene transitions.

Finally, we note that the results of the last experiment did show that the *pulsed* technique generally served its purpose as a middle ground between the *animated* and *teleportation* techniques. Pulsed transitions had better results than *teleportation* for spatial awareness but it caused more sickness, and it had better results than *animated* for sickness but was not as good for spatial awareness. Therefore, we conclude the *pulsed* technique can be useful in some scenarios where the goal is for the viewer to be able to keep track of changes in the scene while not getting sick by the movements and transitions. For future research, rather than rely on intermediate points at equal intervals between the start and end point, it might be beneficial to consider the different choice of intermediate points that might be most helpful for a given viewpoint change.

It would also be interesting to considering additional types of techniques that might better manage the benefits of spatial awareness and sickness. For instance, other researchers have considered methods such as reducing the field of view (e.g., [55]) or providing a stable reference frame during movement (e.g., [56]), but additional studies are needed to understand whether it is possible to evaluate the balance among sickness and spatial awareness, as well as preference and disruption during immersive experiences.

9 Conclusion

From four experiments with scene transitions in VR with tracked HMDs, we summarize our key findings as follows:

- Participants could most easily track scene changes with *rotation only* transitions using using *teleportation*.
- Across techniques, viewpoint changes involving *both translation and rotation* were more difficult to track than either individual type of change.

- *Animated interpolations* allowed significantly better spatial awareness of the three tested techniques.
- *Animated interpolation* was rated worst in terms of sickness, with animated rotations being especially problematic.

It would be beneficial to use a combination of different techniques based on the scene, the viewer's vantage point, and the importance of tracking dynamic scene changes. For practical purposes, our experiments tested a limited number of variations of transition techniques and environments. Naturally, our results are not guaranteed to be true for all possible variations of techniques. Other types of transition techniques are also possible, and the interplay of other interaction and environmental factors are also important.

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