Behind the Scenes: Adapting Cinematography and Editing Concepts to Navigation in Virtual Reality

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Figure 1: Two examples of applying editing rules to navigation in VR. Each example shows the scene before teleport (left), after teleport (middle) and after reframing by ACTIVE (right). Top row: the camera is repositioned using the 30 degree rule and reoriented using the rule of thirds. Bottom row: the camera position is unchanged, but the view has been panned to the right due to a graphic vector pointing into the scene and the rule of thirds acting on the statue.

ABSTRACT

Teleportation is a popular method of navigation in virtual reality (VR) because it does not induce symptoms of VR sickness, such as nausea and disorientation. However, teleportation may reduce spatial awareness, causing users to miss important aspects of their surroundings. We present ACTIVE, a novel approach to teleportation that uses techniques from cinematography to enhance the user experience of navigation in VR. ACTIVE adapts heuristics from continuity editing to dynamically reposition and reorient the camera after teleportation. This approach aims to improve the aesthetic quality of entities and environmental features while respecting users' intended trajectory through the virtual environment. In a user study, we found that even though ACTIVE did not improve users' recall of which entities were present in the environment, it increased engagement by significantly improving aesthetic appeal. Lastly, despite removing some agency from users, ACTIVE had no impact on presence or VR sickness compared to teleportation.

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CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Virtual reality**.

KEYWORDS

virtual reality, navigation, cinematography, multi-objective optimization, user engagement

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1 INTRODUCTION

Virtual reality (VR) is typically deployed in physical environments that are smaller than the virtual environments being explored [8]. Therefore, navigation in VR requires locomotion techniques where users can remain stationary (i.e. sitting or standing) or involves minimal movement (e.g. stepping to the side [20]). To address this issue, numerous continuous and discontinuous locomotion techniques have been developed. Continuous locomotion allows users to move smoothly through a virtual environment using joystick-based controls or by harnessing physical movements, such as walking-in-place [31], leaning [18] and arm cycling [11]. Discontinuous locomotion, however, is typically based on teleportation, where users select a target location and are instantaneously transported to that point [7, 28]. Teleportation is particularly useful for mitigating the symptoms of VR sickness [9, 11, 15] and, therefore, has been implemented in many commercial VR games (e.g. *Resident Evil 4 VR* includes teleporting under comfort options). Indeed, while various techniques have been proposed to reduce the severity of VR sickness in continuous locomotion, teleportation tends to be preferred by users [8].

Unfortunately, teleportation has the unintended consequence that it can lead to reduced spatial awareness compared to continuous locomotion. This reduced spatial awareness has been shown to cause users to miss task-specific details [9], sketch less accurate maps of the virtual environment [5] and increase task completion times as users need to look around to reorientate themselves after teleporting [6, 11]. While many studies have proposed enhancements to teleportation, their focus has primarily been on improving instrumental aspects of navigation, such as target selection accuracy [27] and task completion time, rather than the non-instrumental qualities that shape user experience [19, 43]. It is, therefore, crucial to explore how users' attention can be directed during navigation to create opportunities for engagement and enhance important visual aspects of the scene without compromising on users' sense of control or inducing symptoms of VR sickness.

In this article, we present ACTIVE, a novel approach to teleportation that uses techniques from cinematography and video editing to enhance the user experience of navigation in VR. We reconceptualize teleportation as a *cut* – an instantaneous transition between two shots in a movie – and apply the rules of continuity editing to reposition and reorientate the camera to improve the aesthetic quality of the scene. Indeed, ACTIVE aims to focus users' attention on important visual elements within the scene, while respecting their intended trajectory as they move through the space. Within the framework of continuity editing, these two goals are not independent, but follow naturally from maintaining spatial continuity before and after teleportation. However, as there are numerous editing rules that could be used to achieve continuity, we need to consider multiple optimization objectives simultaneously. For example, framing an entity with the *rule of thirds* has two optimal solutions (at one third and two thirds of the width of the frame), but only one of those solutions may be consistent with the user's current trajectory (that we implement using a rule called *cutting closer*). Furthermore, to provide a seamless experience, the optimization procedure needs to be sufficiently lightweight that it can be performed in a single update of the 3D engine used for rendering the scene.

In a user study, we compared our implementation of ACTIVE with traditional teleportation (i.e. translation on the *xz* plane without applying ACTIVE's repositioning and reframing objectives). We designed a between-subject experiment to investigate whether ACTIVE had an impact on: (i) user engagement with VR content as they freely explore a virtual environment, (ii) users' abilities to recall the contents of the scene due to the focusing of their attention towards specific entities; (iii) presence, in terms of whether users' sense of control was diminished, and (iv) VR sickness, as our repositioning and reorienting of the camera has the potential to increase disorientation. Our results show that ACTIVE significantly improves user engagement, which is driven by a dramatic increase in aesthetic appeal compared to the baseline teleportation method. While ACTIVE did not improve users' recall of which entities were present in the scene, there were also no statistically significant differences in presence or VR sickness between ACTIVE and teleportation. Source code for ACTIVE is available at https://github.com/ajm/active.

The main contributions of the research are:

(1) We reconceptualize teleportation as a cut, a cinematic transition between scenes, highlighting unexplored connections between VR and editing theory.
(2) We operationalize numerous rules from continuity editing as probability distributions on a circle, transforming camera reorientation into a multi-objective optimization problem.
(3) The design and implementation of ACTIVE, a teleportation-based VR navigation method inspired by cinematography and editing concepts,
(4) An empirical evaluation of ACTIVE compared to regular teleportation, demonstrating increased user engagement without negatively impacting users' sense of presence or symptoms of VR sickness.

2 RELATED WORK

In related work, we cover navigation in VR, with a particular focus on the properties and enhancements of teleportation, as well as editing theory and its application to 3D graphics and VR.

2.1 Navigation in Virtual Reality

Navigation in virtual reality is challenging for several reasons. First, wired connections can restrict users' physical movements and prevents them from turning their bodies to face different directions [16]. Second, VR experiences can be based on large virtual environments, but are generally used in smaller, room-scale settings [8]. Lastly, locomotion can exacerbate symptoms of VR sickness, such as nausea and disorientation [13, 23].

VR sickness is thought to be caused by sensory conflicts between visual stimuli and the body's vestibular (balance and spatial orientation) and proprioceptive (bodily position) senses [13, 34]. While it is difficult to estimate the prevalence of VR sickness in the general population, a recent meta-analysis by Saredakis et al. found that VR experiments have an average dropout rate of ~15% due to participants experiencing symptoms of VR sickness, suggesting a higher incidence of mild to moderate symptoms otherwise [34]. Furthermore, the increased availability of consumer VR headsets has created renewed interest in how different locomotion methods affect VR sickness [8, 9, 11, 15, 39]. While teleportation has been found to induce lower levels of VR sickness than, for example, joystick-based locomotion [9, 11, 15], this is at the cost of other aspects of task performance and user experience. In Christou and Aristidou, for example, using teleportation resulted in users missing task-specific environmental details [9]. Coomer et al. also showed that teleportation can increase spatial disorientation, causing users to spend more time looking around to reorientate themselves [11]. Other studies identified additional benefits of teleportation: Frommel et al. found that teleportation resulted in higher presence [15] and Vlahovic et al. found it to have the best overall user experience for navigation [39]. Lastly, Bozgeyikli et al. found that users preferred teleportation over seven other locomotion methods in terms of ease of use, enjoyment, and required physical effort [8].

As teleportation has been shown to mitigate the effects of VR sickness, it forms the basis of numerous approaches to improve the user experience of navigation. Most related to our study, there have been several attempts to reduce users' sense of disorientation by allowing them to pre-specify what their orientation will be after teleportation [7, 16, 29, 42]. Funk et al. showed that allowing users to change their orientation slowed down the process of teleporting, but decreased the need for users to reorient themselves (an important consideration for wired headsets) [16]. Wolf et al. allowed users to select their target orientation over fixed discrete intervals (i.e. not a continuous angle), which decreased disorientation [42]. Conversely, Bozgeyikli et al. found that allowing users to change their orientation degraded user experience as it increased cognitive load in addition to several symptoms of VR sickness [7]. Most recently, Mori et al. revisited the issue of cognitive load by allowing users to specify their post-teleportation forward vector rather than an angle of rotation [29]. Lastly, there have been numerous methods proposed to extend the functionality of teleportation by, for example, making the process hands-free (e.g. [5, 25, 40]), adapting it to a given scene [24], larger city-scale environments [37], and 3D scenes [27].

In our work, the primary focus is on improving user engagement rather than instrumental aspects of navigation. Unlike previous approaches we want to influence the composition and framing of VR content, which is achieved by reducing the level of control users have of their position and orientation when teleporting.

2.2 Film and Editing Theory

Editing is the process of combining segments of film, or *shots*, in sequential order to maintain the logical coherence of a movie's narrative [14, 30]. The rules that filmmakers follow to smooth the instantaneous transitions (called *cuts*) between shots are collectively referred to as *continuity editing* [14]. The goal of continuity editing is to maintain viewers attention across cuts that might be otherwise disconnected in terms of time (temporal continuity) and space (spatial continuity). Early on, Arnheim used Gestalt psychology and principles from art theory to develop the concept of *screen space* to understand how continuity editing supports narrative. Screen space considers each frame to be a two-dimensional image that is simultaneously a representation of the scene (and, therefore, subject to the rules of composition and continuity) in addition to being a window through which viewers are witnessing the scene [2, 3]. Later, Zettl took the idea of screen space further, conceptualizing film as having a three dimensional structure (with x and y axes on the bottom and left edges of the frame, respectively, and the z axis going into the frame) to define *vectors* describing the directionality and magnitude of forces leading the viewer from shot to shot [44]. These vectors could follow architectural features, the eye-line of a character or the motion of an object to enforce continuity across shots. We describe numerous editing rules and vectors in detail throughout Section 3, but for a more formal treatment of the topic we recommend the work of Frierson [14].

While continuity editing has been explored in computer graphics [21] and 3D animation [17], very few studies have used it in VR. Serrano et al. found that continuity editing was successfully used in narrative VR content, but that misaligned regions of interest between cuts took viewers longer to converge on a focal point compared to non-VR content [36]. These results were replicated in a larger study by Marañes et al. using more advanced saliency estimation techniques [26]. Husung and Langbehn investigated techniques for VR scene transition and found that traditional transition methods, such as cuts, fades and dissolves, were outperformed in terms of presence and continuity by interactive transitions designed specifically for VR [20].

To the best of our knowledge, no studies have attempted to use continuity editing in an interactive VR task like navigation. Our work addresses this gap in the literature, opening up the possibility of novel engaging VR experiences.

3 CONTINUITY EDITING FOR NAVIGATION IN VIRTUAL REALITY

3.1 Rationale: Teleport as Cut

Zettl proposed three approaches for representing reality in film: *looking at an event* (the camera follows the point of view of someone present in the scene), *looking into an event* (a focus on psychological and emotional outcomes to intensify the story) and *creating an event* (exploiting the nature of the medium, e.g. using special effects, causing the viewer to suspend disbelief) [14]. While VR has potential in all these approaches, looking at an event is the most natural from an interaction standpoint as the VR camera follows user head movements giving them control over tilting and panning. Teleporting is, therefore, equivalent to a cut between shots in film because it too is an instantaneous transition between two camera positions. Such transitions have negative implications in both film and VR. In film, jump cuts can break temporal and spatial continuity, causing viewers to experience a jump forward in time or become disorientated in terms of how visual elements relate to one another on screen [30]. Similarly in VR, prior work has suggested that teleportation can decrease spatial awareness, causing users to miss the presence of entities within a scene and experience momentary disorientation [6, 9, 11].

In film, the rules of continuity editing were developed to make instantaneous transitions between shots appear seamless to the viewer and not distract from the content in each shot. In this article, we extend these concepts to VR navigation based on the idea that teleportation is a kind of cut and that continuity editing could also improve user experience by encouraging users to focus on the contents of a virtual environment. However, adapting continuity editing to VR presents numerous challenges. First, multiple editing rules can apply in a given scene and, therefore, must be considered simultaneously to identify the optimal framing. Second, while many editing rules only require reorienting the camera, others need the camera to be repositioned as well. This has the potential to massively increase the state-space of possible solutions for framing the scene. Last, despite removing some of the user's agency, they still need to feel in control. This means that the change in orientation must be subtle and that we cannot force users to look up or down

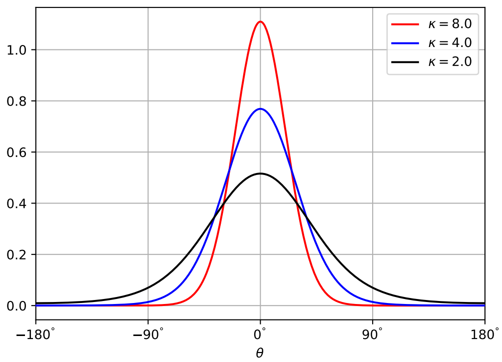

Figure 2: Editing rules were transformed into objectives using a probability distribution on a circle. We used a von Mises distribution with different values of κ to indicate the importance of the optimal rotation angle.

as the orientation of the virtual camera and the user's physical head would become misaligned.

3.2 Transforming Cuts into Objectives

We transform editing rules into objectives by representing them as probability distributions on a circle. This allows us to apply multi-objective optimization over editing rules in all directions the user could be facing after teleportation. The probability distribution associated with each editing rule is used to define a utility function in terms of the optimally of the angle of rotation with respect to entities and environmental features. For this, we use a von Mises distribution, which is an approximation of the wrapped normal distribution (see Figure 2). The probability density function for the von Mises distribution is given by:

$$vonMises(\theta \mid \mu, \kappa) = \frac{\exp(\kappa \cos(\theta - \mu))}{2\pi I_0(\kappa)}, \quad (1)$$

where θ is an angle in degrees, μ is the mean, κ is the concentration parameter (equivalent to $1/\sigma^2$ in the normal distribution), and $I_0(\kappa)$ is the modified Bessel function of order 0.

For each editing rule, we set $\mu = 0$ and set κ with respect to how far away from the optimal angle we judged the rule to be broken. For example, we set κ highest for the rule of thirds as it only applies to the single, closest entity (see Section 3.5.1), whereas we use a lower value of κ for the establishing shot as the entities tend to be further away (see Section 3.5.2). In our current implementation, all values of κ were set by manual inspection.

3.3 ACTIVE

We designed ACTIVE – Adaptive Cinematic Teleportation In Virtual Environments – using the concepts of teleportation as a cut and transforming editing rules into objectives using probability distributions on a circle. Our approach assumes that entities for which editing rules should be applied are tagged as entities of interest by the designer of the virtual environment. We also assume that the environment is annotated to indicate the designer's intended flow of movement through environmental features, such as narrow passages and walkways. For concision, we refer to entities of interest as *entities* and environmental annotations as *vectors*[1].

ACTIVE can be broken down into three steps: (i) select target position and teleport, (ii) reposition camera and (iii) reorient camera. We expand on each step below and further enumerate how we adapted specific editing rules in Sections 3.4 and 3.5.

- **Step 1 - Select target position and teleport:** The user picks a target position by pointing with a controller or using hand-tracking. Once teleportation is initiated, the user's position is changed to the target position.
- **Step 2 - Reposition camera:** We reposition the camera based on two deterministic rules: *the 30 degree rule* and *headroom*. These rules change the position of the camera with respect to the closest entity.
- **Step 3 - Reorient camera:** We reorient the camera by considering all possible rotations, θ, from 0-359° (as we do not control the tilt of the camera, we only consider the xz plane). At each θ, we calculate a utility function over all editing rules. We select the θ with the highest utility and reorient the camera to that angle.

As this procedure needs to complete before the next frame is rendered, the optimization procedure needs to be as lightweight as possible. Therefore, we considered it too costly to jointly optimize position and orientation. The optimization problem we need to solve in step 3 is:

$$\underset{\theta}{\operatorname{argmax}} \prod_{i=1}^{R} f_i(\theta, a, \vec{v}, b, E) \quad (2)$$

where a is the user's starting position, $\vec{v}$ is the user's forward vector at a, b is the target position for teleporting, E is the set of entities visible to the user immediately pre-teleport, R is the set of editing rules described in Section 3.5 and θ is the angle of rotation under consideration with respect to $\vec{v}$. If multiple θ's are Pareto optimal, then the smallest angle is used.

3.4 Repositioning the Camera

We apply two deterministic rules to reposition the camera with respect to the closest entity: *the 30 degree rule* and *headroom*.

3.4.1 30 Degree Rule: The 30 degree rule states that if two shots have the same subject, the angle between the two camera positions must be at least 30 degrees. The goal is to ensure that the image seen immediately after a cut is sufficiently different that viewers are forced to reevaluate the new image as a different context. If the difference is too slight, then the transition is perceived as a jump cut [30]. Figure 4 (top row) shows both scenarios: transitioning from the left image to the middle image is a jump cut, but transitioning from the left image to the right image respects the 30 degree rule.

We implement the 30 degree rule using basic trigonometry and linear algebra. In the following equations, a and b are the user's starting and target positions, respectively. c and c' are valid post-teleport positions, and e is the position of the closest entity (see

[1] In our implementation in Unity, entities of interest are represented as tagged game objects, whereas vectors are represented as empty game objects, i.e. objects with only a position and a forward vector.

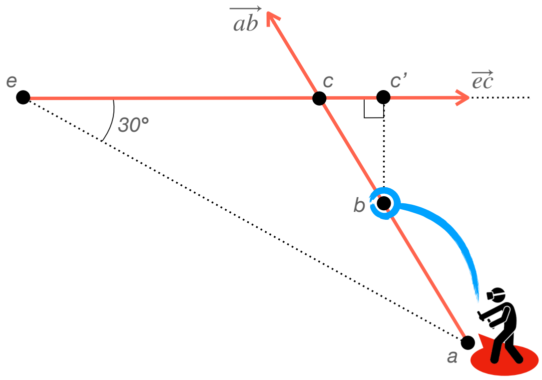

Figure 3: The 30 degree rule requires the angle between an entity and two consecutive camera positions is at least 30 degrees. The target position, b, is repositioned to c', the closest point to b that obeys the rule.

Figure 3 for a graphical representation). The 30 degree rule only applies if the closest entity is the same at both a and b, otherwise b is a valid target position. First, we use the law of sines to identify position c, where vectors $\vec{ab}$ and $\vec{ec}$ intersect:

$$Dist(a, c) = \frac{Dist(a, e) \cdot \sin(30)}{\sin(180 - 30 - \angle eab)}, \tag{3}$$

where $Dist(\cdot)$ is the Euclidean distance between two points, and $\angle eab = \angle eac$ as a, b and c are colinear. c is found with:

$$c = (\vec{ab} \cdot Dist(a, c)) + a, \tag{4}$$

where $\vec{ab}$ is normalized. While c is a position that obeys the 30 degree rule, we can find a better position, c', that is closer to b, the user's intended target position:

$$c' = (\vec{ec} \cdot Dist(e, b) \cdot \cos(\angle bec)) + e, \tag{5}$$

where, $\vec{ec}$ is normalized and $\angle bec = \angle bec'$ as e, c and c' are colinear.

Lastly, we perform a collision detection by firing a ray along $\vec{ec'}$ to test whether it intersects with the environment before reaching c' and, if it does, we move c' closer to e back along the vector $\vec{ec'}$.

3.4.2 Headroom: The headroom rule relates to how the subject should be positioned vertically within the frame to improve the composition of the image. As we have constrained ourselves from altering the tilt of the camera, we instead clamp the minimum distance between the camera and the closest entity. In our experiments, the minimum distance was set to perform well across the range of entities in our scene.

3.5 Reorienting the Camera

After the camera has been repositioned, we perform multi-objective optimization using the procedure described at the end of Section 3.3 to identify the optimal camera orientation, θ. Below, we describe the intuition behind each rule and the probability distributions used for optimization. These rules can be divided into three categories: entities, user intent and environment. The rules for entities are intended to focus users' attention on entities of interest. Nearby entities are framed using the *rule of thirds* and those further away are centered using the *establishing shot* rule. The rules for user intent ensure that ACTIVE respects the user's current trajectory through the virtual space: *cutting closer* explicitly considers the user's forward direction, whereas the *180 degree rule* prevents the user from being oriented in the opposite direction, which could cause disorientation (without the 180 degree rule, the user could be forced to face an entity they would expect to be behind them given their current trajectory). The environment rules encode the designer's intended flow of movement through the virtual space, causing users to look straight down corridors and between buildings. The final camera orientation is optimized jointly over all editing rules.

3.5.1 Rule of Thirds: The rule of thirds works by composing an image using two equally spaced vertical lines and two equally spaced horizontal lines, creating a 3×3 grid [38]. However, as we are constrained to the xz plane, we only consider the vertical grid lines in VR (see Figure 4, bottom row, left image).

We implement the rule of thirds by calculating two angles, τ_1 and τ_2, where $\tau_i = \angle ept_i$: the angle between the closest entity, e, the camera position, p, and the i^{th} grid line in screen space transformed on to the camera's near clipping plane in world space[2], t_i. Each camera orientation, θ, is scored as the maximum probability from two von Mises distributions where $\mu = 0$ and $\kappa = 8$.

$$f(\theta, \cdot) = max(vonMises(\theta - \tau_1 \mid \mu, \kappa), vonMises(\theta - \tau_2 \mid \mu, \kappa)). \tag{6}$$

Intuitively, this equation gives the highest probability when $\theta = \tau_i$, where the closest entity is positioned at either the 1/3 or 2/3 positions in screen space.

3.5.2 Establishing Shot: An establishing shot is a wide shot intended to frame multiple entities, highlighting their spatial positions with respect to one another and the environment (see Figure 4, bottom row, right image). We implement the establishing shot rule by calculating the angle, τ, between the camera's forward vector and the vector between the camera's origin and the average position of all entities visible on screen. Each camera orientation is scored by $vonMises(\tau \mid \mu, \kappa)$, where $\mu = 0$ and $\kappa = 2$.

3.5.3 Cutting Closer: Cutting closer refers to a cut to a narrower shot, e.g. zooming in on a subject's face. In VR, we treat the user's intended teleportation trajectory as them "zooming in" on the scene. We implement cutting closer by calculating the angle, τ, between the camera's forward vector and the vector passing through the pre- and post-teleport positions. Each camera orientation is scored by $vonMises(\tau \mid \mu, \kappa)$, where $\mu = 0$ and $\kappa = 4$.

3.5.4 180 Degree Rule: The 180 degree rule states that two or more subjects in a scene should always have the same left/right relationship with respect to one another, e.g. in a conversation, as it becomes confusing if their relative position changes. In VR, we use this rule to prevent users from being turned around after teleportation, e.g. due to moving past an entity. Namely, we score θ using the following step function:

$$f(\theta, \cdot) = \begin{cases} 1, & \text{if } |\theta| < 90 \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

[2]The grid lines only exist in *screen space*, but we need an equivalent coordinate in *world space* where our camera and entities are defined.

Figure 4: Examples of applying editing rules to teleportation. Top row: before teleportation (left), after teleportation (middle), and after reframing (right). The 30 degree rule has moved the camera's position to the right and the rule of thirds has panned the view to the left. Bottom row: examples of the rule of thirds (left), graphic vectors (middle), and the establishing shot rule (right).

Clearly, the 180 degree rule halves the state space, so in reality we simply do not test the θs that would be zero. However, we describe it here for completeness.

3.5.5 Graphic Vectors and Index Vectors: Graphic vectors indicate the directionality implied by the environment, e.g. looking down a corridor emphasizes a direction into the screen (see Figure 4, bottom row, middle image), whereas index vectors indicate the directionality implied by other entities in the scene, such as a hand pointing or eyes looking in a given direction (in this case it is often referred to as *cutting on eyes*). We implement both graphic and index vectors as vectors on the xz plane that we annotate the environment and entities with, respectively. Each camera orientation is scored by calculating the angle, τ, between the camera's forward vector and the closest graphic/index vector: $vonMises(\tau \mid \mu, \kappa)$, where $\mu = 0$ and $\kappa = 4$.

4 EVALUATION

In this work, we investigated whether techniques from cinematography can improve user engagement when navigating through a virtual environment. The introduction of cinematic techniques is intended to give designers a means to influence user experience in terms of how players move through a virtual space (e.g. using graphic vectors to encourage forward movement) and engage with VR content (e.g. framing an entity using the rule of thirds). Of course, taking too much control away from users can negatively impact their sense of agency and, therefore, reduce their feeling of presence. Furthermore, altering users' orientation and position may increase disorientation and other symptoms of VR sickness. Lastly, we hypothesized that user engagement would be positively correlated with memory recall, increasing users' abilities to identify the entities present in the scene.

We designed a controlled laboratory study to compare ACTIVE with regular teleportation to understand whether our navigation approach increases user engagement without negatively impacting aspects of well-being and presence. Our study used various measures to answer the following research questions:

- RQ1: How does ACTIVE affect user engagement in virtual environments?
- RQ2: How does ACTIVE affect user recall of the contents of the virtual environment?
- RQ3: How does ACTIVE affect symptoms of VR sickness compared to teleportation?
- RQ4: How does ACTIVE affect user perception of involvement/control in virtual reality?

4.1 Participants

Forty participants (22 female, 15 male, 3 non-binary) were recruited for our study. Participants were recruited using posters in several local universities, email lists and via social media. The median age of participants was 22, ranging from 19 to 55. A majority of participants had prior experience with VR (33/40), including games (26/40), movies (10/40), stereoscopic images (10/40) and other VR experiments (11/40). However, VR use among participants was generally low. For example, of those who had played VR games, none do so frequently. Indeed, a majority of participants do not own a VR headset (37/40).

4.2 Study Design

We designed a between-subject study to compare ACTIVE and teleportation. Participants used hand-tracking to navigate through a virtual environment that contained various entities that influence their orientation and position. As we wanted participants to be able to freely turn their bodies during navigation, we used a Meta Quest 2 headset because it is not tethered to a host PC. Throughout the experiment, participants were standing.

4.2.1 Virtual Environment. We wanted to have a virtual environment that contained a combination of open spaces and narrower corridors between buildings to provide a variety of spaces for entities and vectors. We used Map 2 from Kutcenko Dmitry's Industrial Set v3.0 from the Unity Asset Store[3]. We added graphic vectors to the environment to indicate the directionality of narrow passages and suspended walkways. The map was approximately 120m^2. Figures 1 and 4 show the variety of environmental features in the scene.

4.2.2 Entities. For entities, we used public domain 3D models by Harald Wraunek of monuments from Lower Austria[4]. We included statues of Greek gods/goddesses, philosophers, lions and centaurs. In total, the virtual environment contained 20 statues and they were all marked as entities of interest. Figure 4 shows several of the statues used in our study.

4.2.3 Teleportation. We implemented teleportation using hand-tracking in the Meta Quest 2 headset. Participants would see a parabolic line extending from their right hand to a reticle on the ground indicating where they would teleport (similar to [16]). Participants used a pinching gesture with their thumb and fingers to initiate teleportation. The color of the line changed from white to blue if the target position was valid (this check was to prevent users from teleporting over walls and outside of the map, or onto a wall or rooftop). The maximum distance that could be traversed in a single teleport was approximately 27m.

The baseline performed teleportation by translating the position of the user to the target position selected by the user. ACTIVE took the participant's starting position, forward vector and target position, and applied multi-objective optimization based on heuristics from continuity editing as described in Secion 3.3.

4.3 Task

Participants were given a navigation task where their goal was to explore a virtual environment by teleporting. Participants were instructed to be observant of their surroundings and to remember the details of entities in the virtual environment. As participants would be exploring a previously unseen virtual environment, we decided to add optional visual cues that could be used to mark where they had already been in the scene. We used floating white cubes as visual cues that turned red when activated. Participants could use a ray emitted from their left hand to active a cube. In total, 20 cubes were spread evenly throughout the environment. Each participant used the marker cubes to a greater or lesser degree, with the number of activated cubes ranging from 14 to 20.

4.4 Measures

We used standardized questionnaires to measure user engagement and to assess VR sickness and presence. We created our own cued recall questionnaire based on images of the statues in the virtual environment.

- **User Engagement:** We used the User Engagement Scale (UES) to assess user engagement [32]. UES consists of 30 items across four dimensions of engagement: focused attention (7 items), perceived usability (8 items), aesthetic appeal (5 items) and reward (10 items). Each item uses a 5-point scale from strongly disagree to strongly agree. To address RQ1, UES was administered and scored using the procedure outlined in the original article for both total scores and individual subscale scores [32].
- **Cued Recall:** To assess recall, we developed a 25 item survey consisting of images of statues where respondents could indicate whether they were present (15 statues) or absent (10 statues) from the scene. Users were only shown one question at a time on screen, the question ordering was randomized and users were not permitted to change their answers to previously answered questions. The cued recall survey addresses RQ2.
- **VR Sickness:** We used the Simulator Sickness Questionnaire (SSQ) to assess VR sickness [33]. SSQ measures three dimensions of VR sickness: nausea, oculomotor disturbance and disorientation using 16 items on a 4-point scale. To address RQ3, we administered SSQ both prior to the experiment and after the experiment to assess the degree to which each navigation method impacted symptoms associated with VR sickness.
- **Presence:** We used the Presence Questionnaire (PQ) to answer RQ4 [41]. While PQ assesses five dimensions of presence, we only included the 12 items from the involvement/control subscale. Each item uses a 7-point scale with item-specific endpoint labels. We did not include the other dimensions for the following reasons: natural (the virtual environment and interaction method were the same for both navigation methods), auditory (there was no audio in our study), haptic (there was no haptic feedback in our study), resolution and interface quality (both navigation methods used the same headset). We did not assess participants' immersive tendencies as this is not common practice (e.g. [7, 10]) and should be unnecessary due to the random assignment of participants to experimental conditions.

4.5 Procedure

We conducted a between-subject study where users navigated a virtual environment using either ACTIVE or teleportation. The selection of navigation method was alternated as the order of participants was assumed to be random. At the time the study was conducted there were no longer any restrictions nor experimental guidelines related to the COVID-19 pandemic at our university. The VR headset was wiped down prior to the start of each experiment.

After providing informed consent, participants filled in a demographics questionnaire and the pre-experiment SSQ questionnaire. Next, participants were shown an instructional video where they were told that their goal was to explore a virtual environment by teleporting. The video explained how to teleport using hand-tracking and that the environment also contained floating cubes that could be activated as a marker of where they had been in the environment. Participants were explicitly told to be observant of their surroundings and to remember the contents of the virtual environment.

After watching the instructional video, the VR headset was fitted to the participant's head to ensure it was comfortable. Prior to the main experiment, participants were allowed to familiarize themselves with the hand-tracking based target selection for both cubes and for navigation in a smaller virtual environment. During this brief tutorial, all participants used the baseline teleportation

[3]https://assetstore.unity.com/packages/3d/environments/industrial/rpg-fps-game-assets-for-pc-mobile-industrial-set-v3-0-101429
[4]https://noe-3d.at/

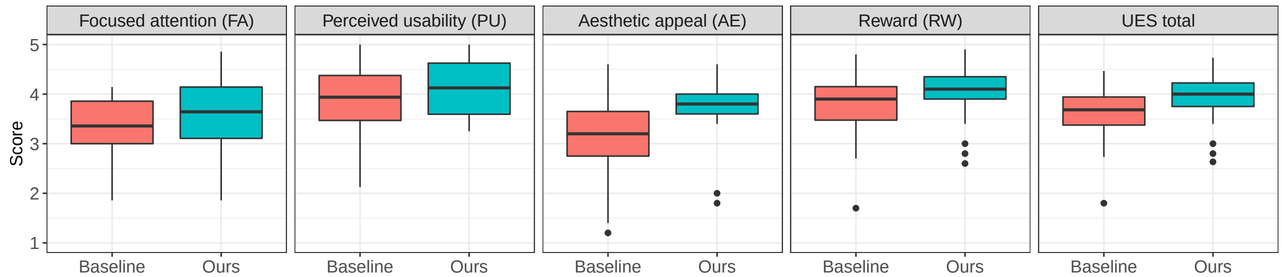

Figure 5: Boxplots of UES subscales and total score. There was a statistically significant difference between systems for aesthetic appeal and the total score. Baseline refers to teleporting and Ours refers to ACTIVE.

method. When users indicated that they were comfortable with the setup or after 5 minutes had elapsed (whichever came first), they were moved on to the main experiment. The main experiment lasted 15 minutes and participants were told verbally when they had 5 minutes and 1 minute remaining for exploration.

After the experiment, participants filled in the post-experiment SSQ questionnaire, followed by UES, cued recall and PQ questionnaires. Each complete study lasted a maximum of 40 minutes. Participants were compensated for their time with a book voucher.

5 RESULTS

We analyzed the data from the UES, SSQ, PQ and cued recall questionnaires. We checked the normality assumption of the data from each scale and subscale used in our study. With the exception of *focused attention* and *perceived usability* from UES, all other scales were statistically significant according to the Shapiro-Wilk test, leading us to reject the null hypothesis that the data is normally distributed. Therefore, throughout this section we used the non-parametric Wilcoxon rank sum test to compare the differences between systems (for consistency, we used the same statistical test for all UES subscales[5]). Lastly, we used the point-biserial correlation coefficient (i.e. the correlation between a continuous and a dichotomous variable) to calculate effect sizes and their associated 95% confidence intervals. An overview of our main results is shown in Table 1.

5.1 User Engagement

The primary goal of our work was to increase user engagement while navigating around virtual environments (RQ1), which we assessed using UES. Figure 5 shows boxplots of responses for the four subscales and the UES total score. ACTIVE increased user engagement by an average of 8.6% compared to teleporting in terms of UES total score (W=118.5, p=0.028). This difference was driven by the *aesthetic appeal* subscale, where our system scored 17.6% higher than the baseline (W=103.0, p=0.009). There was no statistically significant differences between systems for any of the other UES subscales (*focused attention, perceived usability* and *reward*).

[5]This does not affect our conclusions as there were no statistically significant differences in *focused attention* or *perceived usability* between systems, irrespective of whether the Wilcoxon rank sum test or t-test was used.

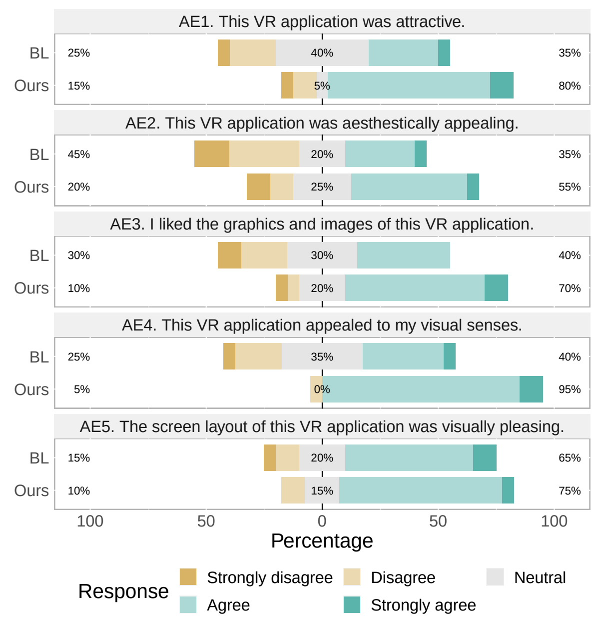

Figure 6: Distributions of responses to individual items from the UES aesthetic appeal subscale. BL refers to the baseline (teleportation), and Ours refers to ACTIVE.

We inspected the responses to individual items from the *aesthetic appeal* subscale (see Figure 6). After using our system, the proportion of participants who agreed or strongly agreed with statements related to aesthetic quality exceeded the baseline by an absolute difference of 10-55 percentage points. For example, there was almost unanimous agreement with the statement *"this VR application appealed to my visual senses"* (AE4) among participants that used our system (95%) compared to a far more moderate agreement from participants that used the baseline (40%).

5.2 Cued Recall

The secondary goal of our work was to improve user recall of entities within the virtual environment (RQ2). On average, participants using our system answered more cued recall questions correctly (M=19.2, SD=1.91) compared to participants who used the baseline

Questionnaire	Baseline		Ours		Test	P-value	Effect	Confidence
	Mean	SD	Mean	SD	stat. (W)		size (r)	interval (95%)
SSQ-Nausea	0.95	17.75	4.52	20.94	167.0	0.514	0.121	[-0.234, 0.463]
SSQ-Oculomotor disturbance	10.99	30.57	7.18	21.51	187.5	0.955	0.013	[-0.366, 0.379]
SSQ-Disorientation	16.01	48.91	13.92	36.54	174.0	0.660	0.084	[-0.281, 0.458]
SSQ-Total score	10.01	33.59	9.05	25.80	172.5	0.632	0.092	[-0.294, 0.458]
PQ-Control	5.01	0.67	5.10	0.59	163.0	0.455	0.142	[-0.242, 0.494]
UES-Focused attention	3.38	0.58	3.59	0.77	159.0	0.272	0.205	[-0.167, 0.571]
UES-Perceived usability	3.87	0.75	4.15	0.58	162.5	0.315	0.188	[-0.235, 0.527]
UES-Aesthetic appeal	3.12	0.87	3.67	0.66	103.0	0.009**	0.485	[0.135, 0.818]
UES-Reward	3.73	0.67	4.01	0.63	145.0	0.139	0.275	[-0.073, 0.614]
UES-Total score	3.58	0.58	3.89	0.56	118.5	0.028*	0.407	[0.045, 0.717]
Cued recall	18.9	2.55	19.2	1.91	201.0	0.989	0.005	[-0.354, 0.349]

Table 1: Descriptive and test statistics for SSQ, PQ, UES and cued recall questionnaires (∗ = statistically significant).

system (M=18.9, SD=2.55). However, the difference was not statistically significant (W=201.0, p=0.989). We also reanalyzed the cued recall responses using a mixed-effects logistic regression model to account for the repeated measured per participant (modelling each participant as a random effect). However, the difference between systems was not statistically significant.

5.3 VR Sickness

SSQ was administered before and after the experiment to assess whether participants experienced any of the symptoms of VR sickness using either system and, furthermore, whether our system adversely affected participants' level of VR sickness compared to the baseline (RQ3). Participants using regular teleportation to navigate through a virtual environment did not experience VR sickness during the experiment (SSQ total score, W=183, p=0.654), nor did they experience any of the individual symptoms of VR sickness: nausea (W=215, p=0.686), oculomotor disturbance (W=172, p=0.451), and disorientation (W=167, p=0.353). Similarly, participants using ACTIVE did not experience VR sickness (SSQ total score, W=137.5, p=0.212), nor any of the symptoms of VR sickness: nausea (W=151.5, p=0.392), oculomotor disturbance (W=141, p=0.2413), and disorientation (W=134, p=0.169).

More importantly, there were no statistically significant differences in SSQ total score between systems (W=172.5, p=0.632), nor in any of the three symptoms associated with VR sickness (see Table 1). While ACTIVE appears to increase nausea compared to the baseline, this difference is dwarfed by the standard deviations of both nausea symptom scores (see Table 1).

5.4 Presence

As stated previously, we only administered the involvement/control subscale from PQ to assess whether participants felt that ACTIVE diminished their perception of control relative to the baseline (RQ4). However, there was no statistically significant difference in perceived involvement/control between systems (W=163.0, p=0.455).

6 DISCUSSION AND FUTURE WORK

The main goal of this research was to investigate whether cinematography techniques could be used to enhance the user experience of navigation in VR. We developed ACTIVE by adapting editing rules from continuity editing to VR. These rules were used to dynamically reposition and reorient the camera at the moment of teleportation to direct user attention and enhance the visual aspects of the scene. We evaluated our approach in a between-subject study (N=40). Our results showed that ACTIVE increased user engagement compared to teleportation, but failed to improve user recall. Despite removing some agency from users, ACTIVE had no impact on presence or symptoms of VR sickness compared with regular teleportation. We discuss the implications of these results in the following subsections.

6.1 Continuity Editing makes VR more Engaging

ACTIVE increased user engagement by significantly increasing the perceived aesthetic appeal of the environment. This finding is particularly striking because we used an identical environment for both experimental conditions and, moreover, users of the baseline had complete control over the orientation of the camera by moving their heads. Furthermore, there is suggestive evidence that ACTIVE may improve other aspects of user engagement: ACTIVE had higher median responses (see Figure 5) and positive effect size estimates (see Table 1) across all UES subscales. We also note that the spread of UES responses were generally narrower for ACTIVE compared to teleporting (see Figure 5). We believe this is due to the framing of entities and environmental features producing a more consistent viewing experience, whereas regular teleporting results in situations where users need to constantly reorient themselves to navigate in VR, e.g. after teleporting towards a wall or other environmental features.

In future work, we plan to expand our analysis to understand how users' attention is impacted by ACTIVE and, in particular, whether the improvements in user experience come from the instant of teleportation or whether it has a broader impact on users' appreciation of the scene. While the Meta Quest 2 does not have eye tracking, newer VR headsets, such as the Meta Quest Pro and Varjo headsets, allow for the collection fine-grained attention data. Other studies have also used head orientation as a proxy for gaze data in VR (e.g. [26]).

6.2 Increased User Engagement in VR does not Improve Recall

While ACTIVE succeeded at increasing user engagement, this did not translate into improvements in memory recall. However, there were several experimental factors that may have influenced this result. While our virtual environment was relatively large by experimental standards, it was still possible for users to visit every statue several times within the time limit. A larger map with more elements to remember or a stricter time limit might have increased our discriminative power. An alternative approach could also be to design a free recall task, where users need to describe the contents of the scene without prompting, or a different cued recall task, where they need to reconstruct the scene by placing statues in an empty environment. Furthermore, our decision to use 3D models of statues in an industrial setting might have made the test items particularly memorable. In general, there are mixed results on the impact of VR on recall. While numerous studies have found VR can be used to aid recall [22], others have found no improvement compared to traditional desktop environments [12]. Indeed, several studies have identified a negative correlation between presence and performance on cued recall tasks in VR [1, 4].

6.3 No Loss of Presence, No VR Sickness

There were no significant differences in terms of presence or symptoms of VR sickness between ACTIVE and teleportation. When we were developing ACTIVE, we noticed that even comparatively extreme repositioning and reorienting did not always feel disorientating, unless it resulted in being very close to an entity or turned around 180 degrees[6]. We speculate that this may be due to the ambiguity of the target position. When placing the reticle farther away, small differences in wrist orientation can result in large differences in the target position. Furthermore, the act of pressing a button or performing a gesture can also result in the target position changing. In future work, we want to investigate how noticeable deviations from the requested target position are in teleportation. A better understanding of users' tolerance for where they are being teleported could enable novel navigation methods that have greater latitude to influence user experience.

6.4 Application Domains

There are three application domains that we see as potential use cases for ACTIVE: games, cultural heritage and immersive movies. First, cinematic techniques have long been used in video games to frame visuals and enhance narrative. As teleporting is available in a majority of even fast-paced VR games (e.g. *Residential Evil 4 VR* and *Half Life: Alyx*), ACTIVE could be used in any game that supports teleporting where entities of interest and environment features have also been annotated. However, games that focus on narrative and exploration, such as so-called "walking simulators" like *Everybody's Gone to the Rapture*, could use ACTIVE to even greater effect to create more aesthetic immersive experiences. Second, VR is already widely used in the exhibiting arts and cultural heritage sectors within existing museums [35] and fully virtual museums (e.g. Museum of Other Realities[7]). ACTIVE could be used to highlight the contents of a virtual museum using the rules of framing and composition, while allowing users to freely explore the exhibition space. Lastly, while there is prior work on the use of continuity in immersive movies, scenes are often observed from a fixed position (e.g. [36]). ACTIVE could enable users to move around as a story is unfolding, while keeping the various characters appropriately framed after teleporting.

[6]We note that neither of these things happened in experiments due to the headroom and 180 degree rules, but were experienced by one of the authors during the development of our implementation.

7 LIMITATIONS

There were several limitations with both the design of ACTIVE and our evaluation with teleporting. First, ACTIVE relies on the manual annotation of entities and vectors within the virtual environment. While this additional work is minimal compared to the creation of the environment itself, annotation requires an understanding of where, for example, vectors should be placed with respect to other features and each annotation needs to be tested to ensure it has the desired effect. It is also likely that annotation could be automated, but we leave this for future work. Second, our evaluation was based on only a single environment and placement of entities. While this was necessary to ensure invariance between experimental conditions, a different environment and placement of entities could create pathological scenarios where editing rules are of little use or even degrade user experience. Furthermore, virtual environments used in games often feature a linear path through the environment, leaving fewer opportunities to use editing rules and making more conventional scripted events more appropriate. Third, our evaluation did not consider where users' attention was focused during experiments. Gaze data would have helped us to understand how users perceived the environment and whether there were any behavioral differences between users of different systems. As stated in the discussion, we plan to investigate this in future work. Lastly, our study design could not reveal the degree to which each editing rule contributed to the final results. While we focused on adapting common editing rules, similar improvements could be achieved with a more limited set of rules.

8 CONCLUSIONS

In this article, we proposed ACTIVE, a VR navigation approach that combines teleportation with techniques from cinematography and video editing. ACTIVE reconceptualizes teleportation as a cut, applying the rules of continuity editing to reposition and reorient the camera after teleportation. To investigate whether ACTIVE improves the user experience of teleporting in VR, we conducted a controlled laboratory study where users were tasked with exploring a virtual environment. While ACTIVE did not improve user recall of entities in the scene, it increased user engagement by significantly

[7]https://www.museumor.com/

improving aesthetic appeal. Finally, despite taking some control away from users, there was no statistically significant impact on users' sense of control or symptoms of VR sickness compared with teleportation.

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