Exploration of Large Omnidirectional Images in Immersive Environments

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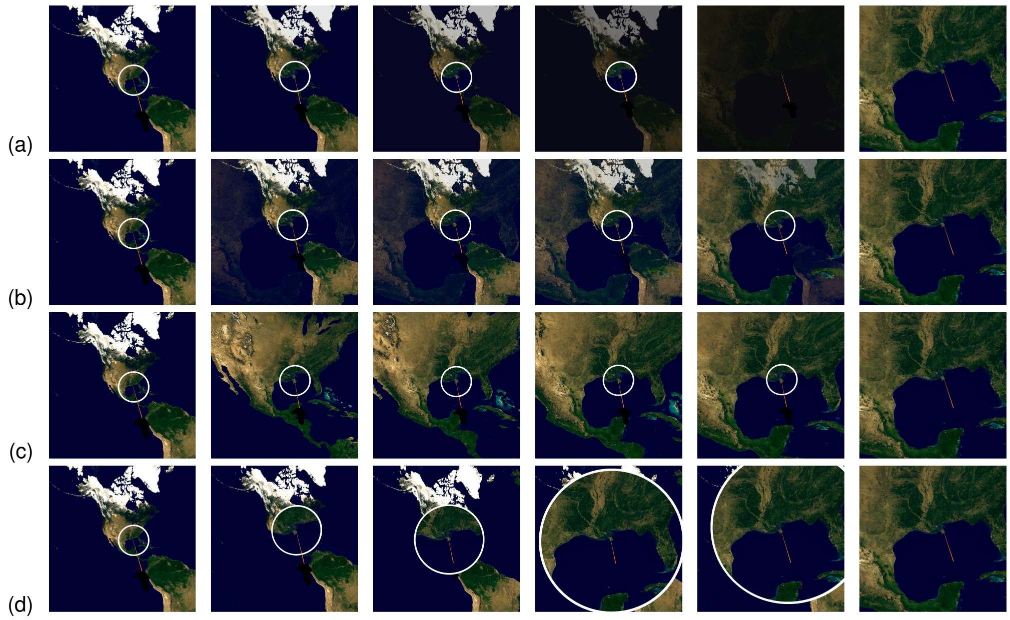

Figure 1: Four teleportation methods through the zoom lens, including a view of the start location, four intermediate steps, and the destination location: (a) *Fade*, (b) *Blend*, (c) *Animate*, and (d) our introduced *Envelop* method.

Abstract

Navigation is a major challenge in exploring data within immersive environments, especially of large omnidirectional spherical images. We propose a method of auto-scaling to allow users to navigate using teleportation within the safe boundary of their physical environment with different levels of focus. Our method combines physical navigation with virtual teleportation. We also propose a ”peek then warp” behavior when using a zoom lens and evaluate our system in conjunction with different teleportation transitions, including a proposed transition for exploration of omnidirectional and 360-degree panoramic imagery, termed *Envelop*, wherein the destination view expands out from the zoom lens to completely envelop the user. In this work, we focus on visualizing and navigating large omnidirectional or panoramic images with application to GIS visualization as an inside-out omnidirectional image of the earth. We conducted two user studies to evaluate our techniques over a search and comparison task. Our results illustrate the advantages of our techniques for navigation and exploration of omnidirectional images in an immersive environment.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Visualization—Visualization application domains—Geographic visualization;

1 Introduction

One of the major challenges of exploration in virtual environments is navigation, especially of large panoramic or omnidirectional spherical 360-degree image data. Most navigation methods rely on some form of virtual camera movement, which can cause nausea and cybersickness. As a result, teleportation is commonly used in many applications. Teleportation is navigation from one point to another in a virtual environment by means of pointing in the direction of the destination, pressing the trigger, and leaping to the destination by warping the view to that of the destination with minimal discomfort. While it does not require camera movement, teleportation can hamper a user's understanding of the path taken and spatial awareness. Significant benefits of kinematic movement during travel-maneuvering have been previously highlighted in work on locomotion and hierarchical physical navigation [11, 46]. However, locomotion as a sole method of navigation is not be feasible for larger scenes such as gigapixel spherical or panoramic imagery, geographic information system (GIS) visualization or astronomical data visualization.

We propose a new method combining the scalability of teleportation with the benefits of locomotion on user's sense of presence. Our method automatically scales the visualized model based on the user's distance from an area of focus. The user simply walks around within the safe boundary of his/her physical environment and explores the surrounding areas with different levels of focus.

Moreover, instead of naïve teleportation, we propose a "peek then warp" behavior. The user simply points (e.g., a wand controller) towards the area of focus, similar to a virtual lantern [31], and previews a magnified view (closer visualization) of this region [12].

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Upon tapping on the selection, the user's view is moved to this region. We propose a new transition for teleportation, *Envelop* (which is also used in a new VR game "Budget Cut VR"[1]), and evaluate it with three other camera view teleportation methods (Figure 1):

- *Fade* out to black and back in at the new camera position
- *Animate* the virtual camera between the two positions
- *Blend* between the view from both camera positions
- *Envelop* the user by increasing the frustum of the virtual lantern widget until it completely surrounds the user

Omnidirectional and 360-degree panoramic imagery can capture an environment surrounding a viewpoint from all angles and can be produced by stitching a set of images [3, 22] or directly captured through spherical cameras [17, 26]. This is used in a variety of applications such as virtual [8] and tele-immersive tours [16]. This type of media provides a 360-degree field of view (FoV), hence, it is more suitable to be explored within immersive environments with 360 field of regard (FoR). Many streaming platforms such as YouTube focus on making 360-degree content available to a wider audience through commodity HMDs.

Navigation paradigms proposed in this work are applicable to all immersive environment with positional tracking, such as HMDs, CAVEs, and immersive tiled displays. In this work, we evaluate our system using HTC Vive commodity VR HMD and controllers.

We have chosen a GIS application for our case study since GIS inherently has a very large scale and high information density, going beyond gigapixel images. Our system is designed for egocentric visualization and immersive systems that surround the user. The first step to such a GIS application is a shift from the typical exocentric view of the earth to an inside-out visualization, creating an omnidirectional spherical image of the earth.

The main contributions of this work are as follows:

- A navigation method in large-scale omnidirectional or 360 panoramic images
- A method for automatically scaling the data to deliver a method for hierarchical physical navigation
- Combining zoom as a peek view before teleportation
- A pipeline combining scaling and teleportation for automatic navigation and exploration (replacing traditional warp, lens zoom, and scale)
- A comparison of teleportation transitions: *Fade*, *Animate*, *Blend*, and *Envelop*.
- An inside-out projection of the earth to deliver a truly immersive GIS visualization in an omnidirectional image

The paper is organized as follows. We cover related work in Sec. 2 and introduce our auto-scaling in Sec. 3. We discuss our teleportation method and how auto-scaling affects the teleportation transitions in Sec. 4. We describe the system evaluation in Sec. 5, and our two user studies in Sec. 6 and 7. We conclude in Sec. 8.

2 Related Work

There have been many recent advancements for capturing and displaying large-scale datasets, including a pipeline for capturing and viewing gigapixel images [25] and a scale-independent method for modeling and rendering large-scale astronomical models [15]. Spatio-temporal large-scale datasets can be displayed using a 'mashup' approach to flexibly combine multiple data sources in a single visualization [48]. A pipeline was developed for out-of-core rendering for interactive visualization and exploration of aggregated data from dynamic, streamed, and offline sources [7]. There have been further developments in a distributed out-of-core pipeline for producing gigapixel panoramas [37], and gigapixel microscopy images can be explored and interacted with [23]. Large high-resolution displays have been shown to be useful for GIS visualization [13]. High-resolution images can be interactively rendered and explored on high resolution tiled display walls using out-of-core acuity driven rendering with support for focus-and-context lenses [33].

While capturing and displaying large-scale data presents technical challenges, appropriate techniques for exploration, user interaction, and physical navigation are also necessary. Various immersive visualization environments deliver a physical space for users to navigate in, including CAVE systems [14], tiled displays such as the Reality Deck [34], or commodity VR HMDs such as the HTC Vive[2]. It has been shown that a higher degree of physical immersion can improve user performance, especially in combination with head tracking [43]. Automatically adjusting movement speed based on the distance from the point of interest can also be beneficial [28]. Look-and-fly, a multiscale 3D navigation for use on 2D desktop displays, relies on automatic scale detection based on the distance of the closest visible object to the camera [30]. Congruent mapping of the control and display space can improve user experience and performance on optical see-through HMDs [44].

Physical navigation can be less frustrating compared to virtual navigation through a pan+zoom pipeline [4, 5] and can result in higher spatial understanding [6]. An infinite canvas was proposed to map large data to a smaller immersive environment and utilize physical navigation for exploration across one dimension [34]. Combining head tracking and stereo improves performance [41], and this motivates our work to utilize the benefits of immersive environments in a much larger virtual environment, such as GIS visualizations.

While previous work has focused on expanding redirected walking to larger applications [36], our work aims to combine virtual and physical navigation to provide multi-scale exploration. Other work has focused on combining body gestures in a tracked environment for navigation and fly-through using head-mounted displays and large tiled displays [39]. Empty spaces can be utilized in urban visualization to expand points of interest, such as paths and landmarks, and perform occlusion-free route visualization [40]; Such a technique can be combined with other visualization methods and is similarly usable in our visualization method.

Animation during zooming has been found to improve user performance and experience [45], and increase spatial awareness [42]. The choice of animation can impact the feeling of movement and movement profile [29]. A study comparing a zoomable interface with and without overview has been conducted [19], and the results show that users preferred the option overviews, though they performed better without the overview in datasets with rich visual cues. A hybrid navigation method combining virtual portals and redirected navigation for large-scale architectural exploration has been proposed [10].

World-in-Miniature (WIM) uses a small hand-held model of a virtual environment as a map [35]. The user can move inside the environment by moving a small avatar inside this miniaturized model. To solve the problem with spatial conflict, upon the user moving the avatar the miniaturized model expands to encompass them, giving the feeling of being moved into the new position without a fly-through path. This behavior influenced our design and is similar to the *Envelop* transition proposed in our technique.

A scalable WIM model was used for improved physical navigation and better understanding of visualization context in exploring large-scale astronomical models in virtual environments with multiple scaling cues [27]. Our method focuses on omnidirectional and 360 panoramic images with a single surface, solving the problem with a navigation path constrained by automatic scaling based on camera position relative to a sphere/cylinder center. We propose zoom lenses to peek before teleportation to solve the problem of loss of spatial context. Furthermore, our system tries to solve the problem of smoothly transitioning between various zoom levels without

[1]Budget Cuts VR. http://www.neatcorporation.com/BudgetCuts/

[2]HTC VIVE. https://www.vive.com

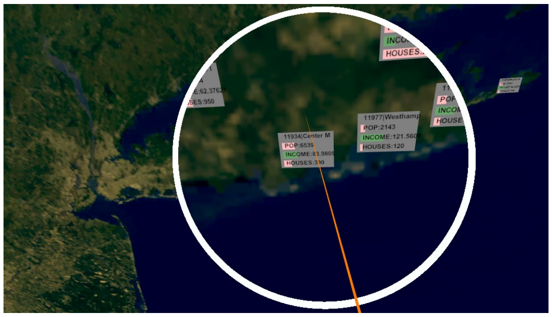


Figure 2: The Vive controller is used to magnify over a specific region (Long Island, New York in this case). The projection FoV can be changed with swipe gestures on the controller's trackpad.

causing offsets between the lens and actual visualization.

3 AUTO-SCALING

Our system combines both physical and virtual navigation. The user can explore by simply walking around in the physical space. For further exploration or repositioning, the user can choose an area of the surface using the input device and teleport to that location. The user begins the process by pressing the button to turn on the magnification lens for observation of the area (Figure 2). The user can change the zoom level by swiping up and down across a touchpad, or change the point of interest by simply moving the lens around. A second button press initiates the teleportation transition, moving the camera as if the environment surrounding the user was moved to the new point. Auto-scaling can be performed to adapt the scale of the model and surrounding environment for improved physical navigation and easier exploration. Without proper scale adjustment, physical movement would result in minimal virtual navigation, yielding negligible benefit and reducing the user's exploration ability. In our system, auto-scaling is only performed during each virtual teleportation.

We have developed a method for auto-scaling which changes the radius of the sphere model based on the user's virtual position inside the sphere. The scaling is done by keeping the center of the virtual room at a constant distance k from the sphere surface. This constraint allows for physical navigation within the spherical model. By limiting the equations to a 2D plane and circles, this technique can also be applied to cylinders for 360-degree panoramic images.

While inspecting the image information of a certain area of the sphere surface, the user may choose to move closer or further away by clicking the trigger on the controller. The camera will translate along the vector joining the camera position to the point of intersection of the ray cast by the controller and the sphere surface. We define an absolute room space in which we always keep track of the absolute camera position vector ($\vec{c}$). We define the new radius $R = ||\vec{c}|| + k$ as the sum of the magnitude of the camera's position and the constant distance we prefer the camera to be at from the earth's surface. The scaling factor is defined as $scale = R/k$.

3.1 Scaling the Sphere Model

When scaling, it is necessary to create a new sphere to contain the omnidirectional image, which is positioned and scaled appropriately in relation to the current sphere for the desired zoom amount. We refer to the current sphere as the first sphere S_1 which is centered at c_1, and the new sphere model we wish to compute as the second sphere S_2 centered at c_2. The user is contained within a virtual room sphere S_R which is centered at c_R and has a radius of 1 unit.

The room sphere S_R is tangent to the mesh model sphere S_1 containing the omnidirectional image. This tangency constraint ensures a constant distance between the room center and the closest point of the omnidirectional image. The following three conditions must be satisfied:

- S_2 must be tangent to S_R, maintaining the constraint that the closest point on the model sphere is a fixed distance (1 unit) from the center of the room sphere.
- The location on S_1 at which the wand is aimed must be the same location on S_2, ensuring that the same location is in focus.
- The focus point over the S_2 must be scaled (i.e., larger or smaller) than on S_1.

The creation of S_2 is accomplished in three parts. First, the smallest possible sphere S_S is found that satisfies the three conditions listed above. Then, S_1 is parameterized against S_S to generate the zoom level. Finally, this parameterization is used to generate the final model for S_2.

3.2 Compute Smallest Sphere.

The wand the user is holding within the virtual room S_R is located at position w_{xyz} with a direction vector of $\overrightarrow{w}$; and the ray formed by this pair is W. We first find the front and back intersections of the wand ray with both the room sphere (x_{Ra}, x_{Rb}) and the first model sphere (x_{1a}, x_{1b}):

$$x_{Ra} = S_R \cap W, \quad x_{Rb} = S_R \cap \text{-}W, \quad x_{1a} = S_1 \cap W, \quad x_{1b} = S_1 \cap \text{-}W$$

We also calculate the midpoint m of the intersections with the room sphere, which is used throughout the later calculations:

$$m = \frac{(x_{Ra} + x_{Rb})}{2}$$

The angle between $\overrightarrow{w}$ and the vector formed by $(x_{1a} - c_1)$ is given as θ. The normal $\overrightarrow{p}$ of the plane which will contain the center of the smallest sphere is calculated as:

$$\overrightarrow{p} = \overrightarrow{w} \times (c_1 - w_{xyz})$$

The perpendicular bisector B is then created which passes through the midpoint m in the orientation given by of $\overrightarrow{w} \times \overrightarrow{p}$. The two possible tangent points for the two possible smallest sphere options are then calculated as:

$$t_a = S_R \cap B, \quad t_b = S_R \cap B$$

A 2D diagram showing the creation of the two possible smallest sphere candidates is shown in Figure 3a. The smallest sphere S_S is chosen from these two possibilities. Of the two possible smallest spheres, one will be within the room sphere, and the other will contain the room sphere. The two possible radius values corresponding to the two possible smallest spheres are calculated as follows:

$$r_{ta} = \frac{\|t_a - m\|}{1 + \sin(\theta)}, \quad r_{tb} = \frac{\|t_b - m\|}{1 - \sin(\theta)}$$

Since we want the data to surround the user, the larger of these two possible spheres is the correct smallest sphere for our purpose:

$$\overrightarrow{d} = \begin{cases} m - t_a, & \text{if } r_{ta} > r_{tb} \\ m - t_b, & \text{otherwise} \end{cases}$$

$$c_S = \begin{cases} \hat{d} \cdot r_{ta} + t_a, & \text{if } r_{ta} > r_{tb} \\ \hat{d} \cdot r_{tb} + t_b, & \text{otherwise} \end{cases}$$

$$r_S = \begin{cases} r_{ta}, & \text{if } r_{ta} > r_{tb} \\ r_{tb}, & \text{otherwise} \end{cases}$$

After this, the smallest sphere S_S has been created, centered at c_S and with radius r_S, which satisfies the constraints described above.

3.3 Parameterize First Model

We calculate the front and back intersections (x_{Sa}, x_{Sb}) of the wand ray with the smallest sphere:

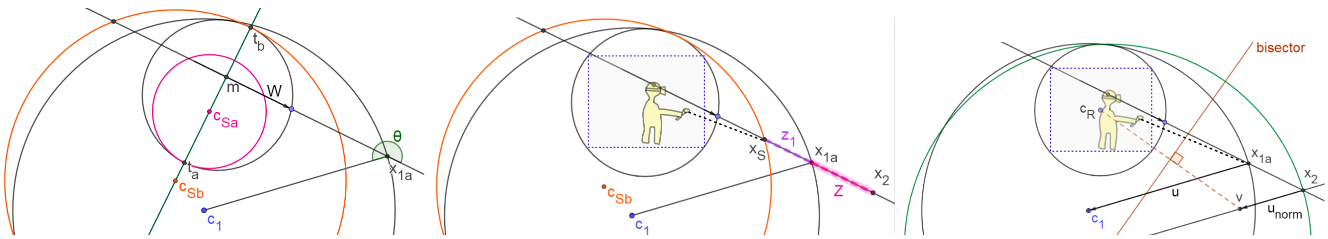
$$x_{Sa} = S_S \cap W, \quad x_{Sb} = S_S \cap \text{-}W$$

We also calculate the distance from the first model intersections to the midpoint, as well as the distance from the smallest sphere front intersection to the midpoint:

$$d_{1a} = \|x_{1a} - m\|, \quad d_{1b} = \|x_{1b} - m\|, \quad d_{Sa} = \|x_{Sa} - m\|$$

To parametrize the first model sphere S_1 against the smallest sphere S_S, we compute the zoom level of the first model with respect to the smallest sphere as shown in Figure 3b:

$$z_1 = \begin{cases} d_{1a} - d_{Sa}, & \text{if } d_{1a} > d_{Sa} \\ d_{Sa} - d_{1b}, & \text{otherwise} \end{cases}$$



(a) (b) (c)

Figure 3: User and their surrounding room is represented with yellow stick figure and the gray box. The direction of the wand is shown by the dotted line. (a) Example in 2D of computing the smallest sphere. Of the two possible smallest spheres, the larger of the two (in orange) is selected, as the room sphere must be contained within the chosen smallest sphere. (b) Example in 2D of parameterizing the zoom level of the first sphere model with respect to the smallest sphere. (c) Example in 2D of computing the second sphere based on the parameterization of the first sphere.

3.4 Compute New Sphere Model

We calculate the zoom level for the second sphere using the zoom coefficient $z_2 = z_1 + z$, show in Figure 3b. From this we calculate the projection of the point which will be the intersection of the wand ray with the second sphere:

$$x_2 = m + ((\operatorname{sgn}(z_2) \cdot (|z_2| + d_{Sa})) \cdot \overrightarrow{w})$$

We create a temporary point v one unit from x_2 in the direction towards what will be the center of S_2:

$$\overrightarrow{u} = \begin{cases} c_1 - x_{1a}, & \text{if } z_2 \geq 0 \\ c_1 - x_{1b}, & \text{otherwise} \end{cases}$$

$$v = x_2 + \hat{u}$$

A perpendicular bisector that goes through the middle of the line segment connecting c_R and v is created, and we determine the center c_2 of the second sphere model S_2 as the intersection of this bisector and the line passing through v and x_2. A 2D diagram illustrating the creation of the second sphere is shown in Figure 3c.

4 TELEPORTATION

Panning, tilting, and zooming are the three main methods of interaction in 2D environments, such as desktop monitors. Interaction in a VR environment differs in that panning and tilting are implicitly incorporated with the user's head movement. To round out the possible interactions in VR, we have added controller-based zooming in combination with four methods of transition during teleportation.

Rather than a naïve zooming when the user chooses a location, we introduce a "peek then warp" approach. The user is able to first preview the location of interest within a zoom lens, allowing for focus on this area while maintaining the context of the surrounding scene. If further inspection is desired, the user can teleport towards that location. This zoom gesture is initiated via a button click on the wand controller's trackpad. An upwards swiping motion over the trackpad increases the zoom level, while a downwards swipe decreases the zoom level. A second button click is used to complete the transition and teleport the user to the selected zoom level.

Our implementation contains two identically textured spheres. The first sphere is the current view, while the second sphere is the zoom result. A button click enables the second sphere to zoom and auto-scale depending upon the extent of the swipe over the trackpad. As shown in Figure 2, only the region of the second sphere within the field of view of the projector cast by the controller is visible (within the white circle), while the first sphere takes up the remainder of the field of view. The second button click sets the transform of the first sphere to that of the second sphere. Four transitions are evaluated with our auto-scaling technique :

1. *Fade*: The current view transitions to black. Transform of first sphere is set to that of the second sphere, and finally the opacity value transitions back to one (transparent). The second sphere is disabled at the end of the sequence.
2. *Animate*: The position and scale of the first sphere are animated to that of the second sphere. Since the camera is inside the sphere, this gives the impression of animating the camera to the position from which the zoomed region was being previewed.
3. *Blend*: Similar to *Fade*, except that instead of fading out to black and fading back in, the user gets the impression that both of these processes are happening simultaneously (i.e., there is a blending in of the destination position over the initial location).
4. *Envelop*: This last technique transitions the FoV of the projector viewing the second sphere from the initial value (lens) to a sphere surrounding the user. This enables a smooth transition as the new scaled sphere will completely envelop the user.

A recent game, Budget Cut VR, uses a similar concept of a window/lens during their teleportation which also quickly envelops the user during the teleportation. While our work also uses a lens in conjunction with teleportation, we use the lens for better selection of the teleportation destination and as a magnification lens for better exploration. The Budget Cut VR lens is used for observing the surrounding area and verification of the destination, since the destination itself is chosen by throwing a teleportation device.

We expect *Envelop* to produce a dynamic transition that enables the user to view the spatial connection between the source and destination, which is lost in *Fade* and *Blend*. In some sense, this "movement" as the destination view encompasses the user is similar to *Animate*, while having reduced impact on motion sickness due to no camera motion throughout the transition.

5 EVALUATION

We have evaluated the impact of our scaling on a user's experience within the virtual environment by conducting two user studies using GIS data, which are detailed in Sections 6 and 7. The first study focuses on evaluating the impact of automatic scaling on the user experience, while the second study analyzes the effect of the proposed teleportation transitions on the user experience. In both studies the user's performance is evaluated using a search and comparison task. The user must find the ZIP code with the highest or lowest value along one of the visualized parameters (e.g., income), select the identified widget, and press a button to finish the task.

5.1 GIS Data

We used the Planet Earth HD 64K[3] asset as the baseline for our visualization. The model of earth is flipped against its own rotational axis to maintain a familiar orientation when observed from inside, resulting in an inside-out omnidirectional image of the Earth. We also use a dataset containing over 24,000 postal codes in the United States with their population, average income, and number of taxpayers. Glyphs show the name and statistics of each town superimposed

[3]Earth HD 64K. https://assetstore.unity.com/packages/3d/environments/sci-fi/earth-hd-64k-53113

Table 1: Participants' previous experience for User Study I.

Experience level	Visualization	GIS	VR
1 (no experience)	3	2	5
2	0	7	2
3	2	4	2
4	6	0	2
5 (very experienced)	2	0	2

upon a bar. The colors of the bars are chosen from a color-blind safe ColorBrewer [9] diverging color set. The widgets have a uniform size and are not overlapping (Figure 2).

Each dataset contains a subset of cities corresponding to a local position on earth. Through a preliminary study we found that locating inland cites was too challenging, and thus the coastal regions of New York and California were chosen for the studies. Each dataset contains a randomized subset of cities in New York or California with the size limited to a maximum of 30 square miles.

5.2 Apparatus

This work was developed in C# using the Unity®Game Engine[4] and was designed to run on various VR and immersive tiled display hardware. The studies were conducted on the HTC Vive headset and a VR-ready workstation. We have used a room setup to provide positional and rotational tracking in a space of 2.5 square meters. Two HTC Vive controllers were used, one to enable participants to select the goal and navigate throughout the experience and the second as a clicker to perform the tapping test.

5.3 Questionnaire and Measurements

We are interested in evaluating the effect of our scaling and transition on the user's sense of presence, mental and cognitive load, and task performance. Since our method features a difference in motion and navigation behavior, we are also interested in observing the impact of our system on motion sickness. We evaluate motion sickness through the use of the Simulator Sickness Questionnaire (SSQ) [24]. We use raw NASA-TLX [18] as a form of subjective measurement for mental load, and use a presence questionnaire (PQ) [47] for evaluating the user's sense of presence.

During our preliminary evaluation, we found the combination of all these questionnaires to be overwhelming and necessitated a simplification. Examining our goals, we found that we are focused on evaluating the two factors of *possibility to act* and *possibility to examine* defined by the Cyberpsychology Lab at the Université du Québec en Outaouais (UQO) [1]. *Possibility to examine* contains questions regarding visual fidelity that evaluate distraction caused by the mechanism proposed for performing a task. *Possibility to act* contains four questions regarding major factors of immersion and involvement defined by the presence questionnaire [47] that focus on user control of actions. The final questionnaire contained SSQ, raw TLX, *possibility to examine*, and *possibility to act* questions.

The data obtained from the SSQ and TLX questionnaires were treated as single scores to evaluate simulator sickness and mental load, respectively. The PQ results were treated as two separate dependent variables of *possibility to act* and *possibility to examine*. NASA-TLX scores were treated as a single dependent variable and RANOVA was used to evaluate the effect of the scaling and transition methods on each of these variables. In all cases transformation was applied for normalization where needed. Data transformation was performed based on the application of Tukey's ladder of power. Unless otherwise mentioned, normality of the transformed data was confirmed with the Shapiro-Wilk test at 0.05 significance.

[4]Unity game engine. https://unity3d.com

6 User Study I: Scaling

6.1 Task

This study consists of focus and a context tasks in two modes: scaling on and scaling off. In the focus task, users must navigate toward a known part of the planet, and then explore within that region of focus. For example, the user is asked to find highest income house in New York. The context task consists of 20 widgets that are uniformly distributed across the surface of the planet, and the user is asked to search anywhere. These widgets are scaled so they can be viewed with slight virtual navigation or, in the case of auto-scaling, by simply walking toward them. During our preliminary examination, we found that observing widgets at a latitude higher or lower than 60 degrees to be too challenging. As a result, the widgets are limited to within the window of -60 to 60 degrees. Also based on this preliminary examination, we decided to set the radius of the earth to 150 meters for the unscaled models in the first study, which is the smallest radius that enables users to comfortably read the widget and information visualized. Larger sizes resulted in more difficult navigation, and reduced the effect of motion parallax.

Each user first freely explores the system during a training trial. Then they evaluated the system through four trials in a randomized order of four combinations of task type (focus, context) and scaling modality (auto-scaling, fixed scaling). The order of exposure to dataset, goals, and modality were also randomized. After each trial, the users were asked to fill out the post-trial questionnaire. At the end of the study participants were asked to highlight their favorite method of scaling during each task (focus, context).

We used the tapping test [2] as a method of task overload to directly evaluate the impact of our proposed methods on mental load. The tapping test relies on task overload by imposing a secondary load on the user [32]. Participants were instructed to use their non-dominant hand to press the button on the secondary Vive controller, similar to a clicker, at a constant rate of once per second.

6.2 Data Collection

Participant Demographics. A total of 13 graduate and undergraduate students (10 male, 3 female) voluntarily participated in our study, with age ranging from 18 to 40 and average of 27. Their self ratings of previous experience in visualization, GIS, and VR on a scale of 1 (no experience) to 5 (very experienced) are shown in Table 1. All tasks were completed without interruption.

The data gathered from the tapping test was evaluated to extract the standard deviation of the tapping sequence for each user. The cases that users forgot to tap throughout were removed from our analysis. The position of the user was used to calculate the overall distance traveled normalized by time (speed). We also evaluate the standard deviation of the user's positions through the trial.

A two-way repeated measures ANOVA (RANOVA) was used to determine a significant difference in simulator sickness from both the type of task (context, focus) and the method of navigation (auto-scaling and constant scaling). Two-way RANOVA was chosen because of the existence of two independent variables and since measurements were taken on the subjects of the same group in different conditions. Gathered data including standard deviation of positions, speed of movement, and elapsed time were treated as dependent variables, and were analyzed through a RANOVA test.

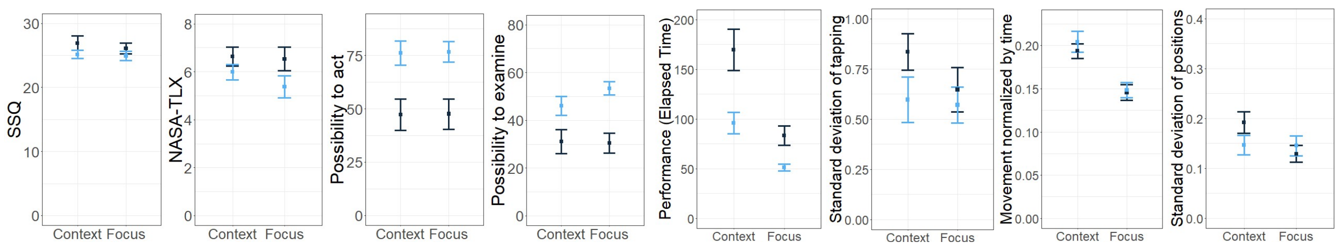
6.3 Results

The mean and standard deviation of the values discussed below are shown in Table 2 and interaction plots are shown in Figure 4.

SSQ. No possible transformation was found to normalize the data. Hence, comparison of the repeated measures was performed using one-way Friedmans test for each of the groups for each of the task types (Focus, Context). There was no significant main effect of scaling modality on the total SSQ scores ($\chi^2(1) = 3.5714, p = 0.05878$) in context task, and ($\chi^2(1) = 2, p = 0.1573$) in focus task.

Table 2: Mean and standard deviation of results for scaling modality.

	No Scaling			Auto-Scaling		
	Context Task	Focus Task	Overall	Context Task	Focus Task	Overall
Time	169.61 (74.87)	83.36 (31.78)	130.08 (72.74)	95.92 (38.55)	51.08 (12.37)	73.5 (36.19)
Speed	0.19 (0.03)	0.15 (0.033)	0.17 (0.04)	0.2 (0.04)	0.15 (0.03)	0.17 (0.05)
$\text{Positions}_{\text{STD}}$	0.19 (0.07)	0.13 (0.06)	0.16 (0.07)	0.15 (0.07)	0.14 (0.07)	0.15 (0.07)
Possibility to act	47.18 (26.59)	47.59 (25.6)	47.39 (25.57)	76.09 (20.73)	76.6 (17.38)	76.34 (18.74)
Possibility to examine	31.01 (18.16)	30.42 (14.8)	30.72 (16.23)	46.09 (14.18)	53.35 (10.01)	49.72 (12.58)
SSQ	26.92 (3.95)	26.08 (3.12)	26.5 (3.51)	25.15 (2.37)	24.92 (2.56)	25.04 (2.42)
NASA-TLX	6.64 (1.42)	6.53 (1.77)	6.59 (1.57)	5.99 (1.16)	5.38 (1.68)	5.68 (1.45)
$\text{Tapping}_{\text{STD}}$	0.84 (0.31)	0.65 (0.35)	0.75 (0.34)	0.6 (0.32)	0.57 (0.3)	0.58 (0.3)



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 4: Interaction plots for two-way ANOVA for auto-scaling (blue) and no scaling (black). The square points represent means for groups, and error bars indicate standard errors of the mean. (a) SSQ; (b) NASA-TLX; (c) Possibility to act; (d) Possibility to examine; (e) Performance (elapsed time); (f) Standard deviation of tapping; (g) Movement normalized by time; and (h) Standard deviation of positions.

NASA-TLX. The data was transformed with $\sqrt{(k+x)}$. The mean TLX score is consistently lower during the scaled environment, and higher difference is observed during the Focus task. There was a significant main effect of scaling modality on the total TLX scores ($F_{(1,48)} = 4.55, p = 0.038$), and no significant interaction between scaling modality and task type ($F_{(1,48)} = 0.353, p = 0.555$).

Presence. The data was transformed with $(k+x)^3$ for *possibility to act* and $(k+x)^2$ for *possibility to examine*. The *possibility to act* scores reject the null hypothesis during normality testing ($W = 0.95, p = 0.04$). The mean presence scores were consistently higher during the scaled environment. While the difference in *possibility to act* was constant between the Focus and Context tasks, a higher difference in *possibility to examine* was observed during the Focus task. There was a significant main effect of scaling modality on total *possibility to act* ($F_{(1,48)} = 20.824, p = 0.000035$) and *possibility to examine* ($F_{(1,48)} = 22.084, p = 0.000022$) scores, and no significant interaction between scaling modality and type of task over either score ($F_{(1,48)} = 0.0, p = 0.99$), ($F_{(1,48)} = 0.94, p = 0.33$).

Performance. The mean elapsed time is consistently lower during the scaled environment. To achieve normal distributions, we removed the *scaling off* result from the two worst performing users during the Focus task. Removal of these two data points did not increase the significance reported by the further ANOVA test. There was a significant main effect of scaling modality on elapsed time ($F_{(1,46)} = 18.94, p = 0.00007$), and no significant effect on interaction between scaling and type of task ($F_{(1,46)} = 2.52, p = 0.12$).

Tapping Test. The data was transformed with $\sqrt{(x)}$. There was no significant main effect from scaling modality on the standard deviation of the tapping intervals ($F_{(1,49)} = 2.81, p = 0.102$). The trend from this result follows the mental load trend from TLX, though the non-significant result might be caused by varying sensitivity between the two tests.

Movement. The speed data was transformed with $\sqrt{(x)}$ and the position data already had a normal distribution. There was no significant main effect of scaling modality on movement speed ($F_{(1,48)} = 0.48, p = 0.49$) or standard deviation of positions ($F_{(1,48)} = 0.54, p = 0.46$).

Post-study User Feedback. After the trials, participants chose their favorite modality during each task. Most participants chose Scaling regardless of the task type. We found that Scaling was more preferred by more participants during the Focus task (12) than the Context task (10). We observed that participants who preferred scaling off were more likely to deploy a strategy of keeping the zoom lens on throughout the search task, while users that preferred scaling on were more likely to physically navigate to investigate.

6.4 Discussion

We evaluated the automatic scaling against a fixed scale mode for both the context and focus search tasks. We observed a significant difference in user performance and mental load based on NASA-TLX, confirming the trend observed by previous studies [6, 46] of the benefit of physical navigation when used with large tiled displays over virtual navigation. Automatic scaling can be used to bring a similar benefit to physical navigation in large-scale datasets with different levels of information (focus and context). However, the results showed no significant effect on physical movement, which might be due to two possible reasons. The first is that users would navigate to the room boundary in the non-scaled environment, even though the information gain from it is minimal. Secondly, the physical space in our study is limited and the same size in both modes, while in previous VR studies the physical space for tiled displays has been necessarily larger. While our system did not increase physical movement itself, it possibly enabled users to utilize the surrounding environment to more efficiently explore the data.

From the results of ANOVA over the presence questionnaire, we observed that participants found it easier to control navigation and examine the data during automatic scaling in comparison to the fixed scale model. The SSQ results showed no significant effect of scaling on simulator sickness for the users; this might be due to either lack of rotational movement during the scaling phase (there is no twisting or rotating while scaling) or the limited size of the zoom lens.

Other conditions of our user study include limiting widgets to range of -60 to 60 degrees, and comparing against a model with size of 150m. Putting widgets in areas closer to the poles can reduce both observability and readability of widgets hampering overall user performance, and possibly reducing the benefits observed through

Table 3: Mean and standard deviation of results for teleportation transition method.

	Blend	Animate	Envelop	Fade
Time	111.16 (34.06)	115.48 (37.67)	102.71 (41.42)	105.05 (33.31)
Possibility to act	21.92 (3.65)	22.28 (3.79)	21.96 (3.79)	22.4 (3.76)
Possibility to examine	41.19 (23.61)	40.31 (23.49)	38.50 (21.64)	42.89 (19.76)
SSQ	3.24 (0.17)	3.24 (0.16)	3.22 (0.14)	3.23 (0.14)
NASA-TLX	2.15 (0.17)	2.17 (0.17)	2.17 (0.19)	2.16 (0.14)
$Tapping_{STD}$	0.44 (0.1)	0.44 (0.11)	0.41 (0.07)	0.42 (0.09)

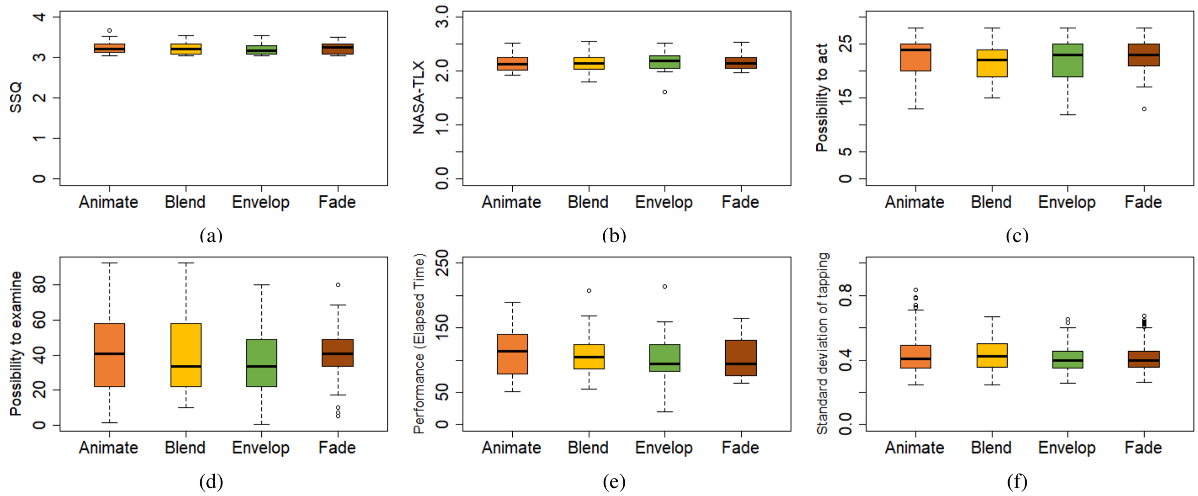


Figure 5: Box plots from the interaction user study. (a) SSQ; (b) NASA-TLX; (c) Possibility to act; (d) Possibility to examine; (e) Performance (elapsed time); (f) Standard deviation of tapping.

scaling. Furthermore, we believe benefit of automatic scaling can improve with even larger models, since in larger models the need for navigation and exploration of data at various level would scale (with size of model and resolution of data), which can further benefit from a hierarchal navigation. As seen in Table 2, while Focus task and Context task require searching for widgets for different sizes, user performance was improved regardless of widget size during auto-scaling. However, further studies can be conducted to evaluate scalability of the benefits from auto-scaling.

7 User Study II: Transitions

7.1 Task

In this study, users perform search and comparison task twice: users must navigate toward the first known region and find a widget within it. Then they are shown the name of the second region where they have to navigate and repeat the task.

This study consisted of five trials. During the training phase, each user explores the system and can switch between these different transitions. In each of the first four trials, participants would use a different teleportation transition to fly through an automatically scaled model of the earth performing the tasks. After each of these four trials participants are asked to fill out the post-trial questionnaire. During the fifth trial, participants can switch between teleportation modalities using a button and compare them. Afterward they are asked to rank the modalities in order of their preference.

We focused on the effect of our system on the user's ability to examine and ability to act inside the experience. We also measured participants' position and navigation throughout the study as well as the time taken to achieve the goal. Moreover, we used the tapping test [2] as a method of task overload to directly evaluate the impact of our proposed methods on mental load.

7.2 Data Collection

Participant Demographics. A total of 25 graduate and undergraduate students (19 male, 6 female) voluntarily participated in our study, with age ranging from 19 to 40 and average of 27. Their self ratings of previous experience in visualization, GIS, and VR on a scale of 1 (no experience) to 5 (very experienced) are shown in Table 4. All tasks were completed without interruption.

Table 4: Participants' previous experience for User Study II.

Experience level	Visualization	GIS	VR
1 (no experience)	7	4	7
2	1	7	8
3	9	10	4
4	7	3	4
5 (very experienced)	1	1	2

The tapping results were analyzed within five second windows around each transition. This five second window was chosen to isolate the impact of the transition on mental load, while being long enough that users that are tapping as slow as once every 2 seconds would produce enough datapoints to allow for calculation of the standard deviation. The standard deviation was calculated from the mean of intervals in a 20 second window of time transition. The window of 20 seconds was chosen empirically to be long enough to produce a robust mean even when users are tapping slowly, while not being too long to encapsulate multiple transitions. During the transition study, intervals where the user has forgotten to tap, resulting in less than two taps in a 20 second window, were also removed from the analysis. Since the tapping test scores were evaluated per teleportation, this study produced more than 600 data points. This was performed to evaluate the mental load of the transition and the connection of destination and source in the transition. A one-way RANOVA was used to determine a significant difference in simulator sickness from the type of transition used for teleportation. When RANOVA has determined a significant effect, a post hoc test of multiple contrasts was used to determine the source of significance.

7.3 Results

The mean and standard deviation of the values discussed below are shown in Table 3 and box plots are shown in Figure 5.

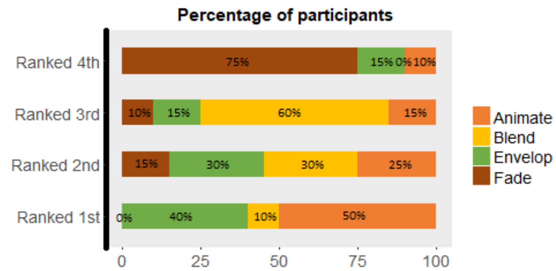


Figure 6: User preference of transition methods.

SSQ. The data was transformed with $(k+x)^2$. There was no significant main effect of navigation mode on the total SSQ scores ($F_{(3,96)} = 0.126, p = 0.94$).

NASA-TLX. The data was transformed with $(k+x)^2$. There was no significant main effect of navigation mode on the total TLX scores ($F_{(3,96)} = 0.227, p = 0.877$).

Presence. The data was transformed with $(k+x)^3$ for *possibility to act* and $(k+x)^2$ for *possibility to examine*. There was no significant main effect of navigation mode on neither *possibility to act* ($F_{(3,96)} = 0.1, p = 0.96$) nor *possibility to examine* ($F_{(3,96)} = 0.17, p = 0.92$).

Performance. There was no significant main effect of navigation mode on the total elapsed time ($F_{(3,96)} = 0.627, p = 0.599$).

Tapping test. The data was transformed by $-\frac{1}{\sqrt{x}}$ and normality was confirmed with the Kolmogorov-Smirnov test. There was a significant main effect of navigation mode on cognitive load during teleportation ($F_{(3,639)} = 3.06, p = 0.0277$). Pairwise t-tests show statistically significant differences between pairs of *Envelop/Blend* ($p = 0.039$), *Envelop/Animate* ($p = 0.015$), and *Blend/Fade* ($p = 0.03$). Tukey's HSD test showed no significance pairwise difference. This discrepancy is because Tukey's HSD multiple comparison corrects for family-wise error rate.

Post-study User Feedback. Participants had trouble remembering the different models evaluated after four separate trials, so we added a fifth trial. During this fifth trial participants were given the ability to switch between different navigation modalities, enabling them to evaluate all modes together and afterward rank their preferences (Figure 6). Most participants ranked *Animate* as their favorite method of navigation, followed closely by *Envelop*. Almost three quarters (70%) of participants ranked *Envelop* as one of their top two preferred methods, which is a very favorable result for our proposed Envelop method. No participant chose *Fade* as their favorite method. Some participants could not distinguish between *Fade* and *Blend* modes. Participants that ranked these modes as their least favorite listed discontinuity between source and origin of navigation as their reason. Participants that ranked *Animate* poorly were concerned with camera movement, especially during longer distances. Participants that disliked *Envelop* were mostly concerned with the aggravated effect of wand movement during the increase of the size of the zoomed in view (during the transition). This issue would arise when the user is zoomed in too high, and their hand is shaking.

7.4 Discussion

We evaluated our proposed method of teleportation (*Envelop*) against the de facto standard models of virtual movement (*Fade*, *Animate*, and *Blend*). The results from the ANOVA test on subjective measurements (SSQ, PQ, TLX) and user performance showed no significant result from the method of teleportation on users' sense of presence, simulator sickness, mental load, and performance. ANOVA on the tapping test results showed a significant result of transition method over mental load during the teleportation. However, a significant difference was not shown during the Tukey HSD multiple compassion test, and this discrepancy can be studied in further research.

Based on post-study user feedback, we found that half of the participants ranked the *Animate* method as their favorite, with *Envelop* being a close contender. A heavy preference was shown towards *Envelop* and *Animate* compared to the less dynamic *Blend* and *Fade*. While *Animate* is chosen as the preferred method by the users, *Envelop* come as a close second without the need for virtual camera movements. *Envelop* also has a more flexible nature than *Animate*. *Animate* is only feasible for transitions with relatively short camera or geometry movement, while *Envelop* can be used with long distance teleportation and with any change, such as change of modality during rendering. This combination of less mental load and greater flexibility supports the potential of *Envelop* not only for large omnidirectional images, but also as a candidate for applications and use cases. The major concern with *Envelop* among participants who disliked this method was the aggravated effect of movement during the transition over large magnification levels caused by shaking of the hand holding the controller. Performing stabilization and smoothing over the hand shake in high zoom level would likely improve this. This stabilization could be accomplished by performing Kalman filtering over the wand when the zoom is above a certain threshold.

Our study is limited to the scope of search and comparison tasks. Teleportation methods such as *Envelop* and *Animate* might perform better in tasks that require a higher level of spatial understanding or path tracing. In which, the more highlighted connection between source and destination can be beneficial.

8 Conclusion And Future Work

We have presented new techniques for navigation and exploration of large omnidirectional spherical images within immersive environments, with a focus on inside-out omnidirectional GIS image. We developed a method of auto-scaling to deliver natural hierarchical physical navigation. We also proposed a new method for zoom lens teleportation and evaluated the usability of multiple transition methods. The results of our two user studies support the use of these navigation methods for improved exploration within immersive data.

Our work has applications to other immersive content such as 360-degree panoramic imagery. While our evaluation focuses on omnidirectional images based on a spherical model, the proposed auto-scaling method is also applicable to cylindrical models by limiting the equations to two-dimensional space and circular models. Since our system relies on lenses as a method for peeking and navigation, we plan to complement our work by combining it with techniques that rely on lenses for visualizing added information in large interactive visualization and exploration [20], and for a complete interactive GIS visualization exploration pipeline in VR environments. Another extension of our work would be together with other navigation methods for navigating landmarks [38], wherein our method can be used for general navigation and exploration of the earth, and a secondary model used for exploration of landmarks in a more surround setup. The lens view for navigation also enables augmenting a new view upon the previous, enabling the user to move between different projections of the same data based on distance. Our work can be combined with adaptive projection methods [21] to show a more suitable projection of data upon movement.

Since our method of navigation relies on automatically scaling the environment, an interesting challenge would be to adapt the existing method for collaborative environments and evaluating such a setup. Since our method of navigation is currently limited to a single surface dataset, this work could be extended for exploring large-scale data with complex geometries. Another extension could be evaluating a method for dynamic projection in combination with scaling to better adapt the geometry for user observation.

Acknowledgments

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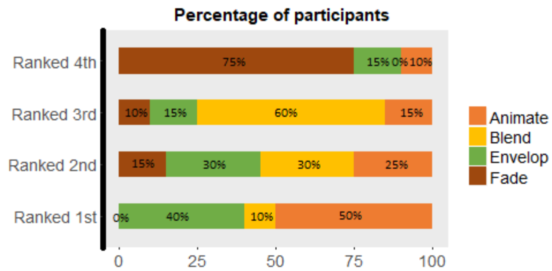

Figure 6: User preference of transition methods.

SSQ. The data was transformed with $(k+x)^2$. There was no significant main effect of navigation mode on the total SSQ scores ($F_{(3,96)} = 0.126, p = 0.94$).

NASA-TLX. The data was transformed with $(k+x)^2$. There was no significant main effect of navigation mode on the total TLX scores ($F_{(3,96)} = 0.227, p = 0.877$).

Presence. The data was transformed with $(k+x)^3$ for *possibility to act* and $(k+x)^2$ for *possibility to examine*. There was no significant main effect of navigation mode on neither *possibility to act* ($F_{(3,96)} = 0.1, p = 0.96$) nor *possibility to examine* ($F_{(3,96)} = 0.17, p = 0.92$).

Performance. There was no significant main effect of navigation mode on the total elapsed time ($F_{(3,96)} = 0.627, p = 0.599$).

Tapping test. The data was transformed by $-\frac{1}{\sqrt{x}}$ and normality was confirmed with the Kolmogorov-Smirnov test. There was a significant main effect of navigation mode on cognitive load during teleportation ($F_{(3,639)} = 3.06, p = 0.0277$). Pairwise t-tests show statistically significant differences between pairs of *Envelop/Blend* ($p = 0.039$), *Envelop/Animate* ($p = 0.015$), and *Blend/Fade* ($p = 0.03$). Tukey's HSD test showed no significance pairwise difference. This discrepancy is because Tukey's HSD multiple comparison corrects for family-wise error rate.

Post-study User Feedback. Participants had trouble remembering the different models evaluated after four separate trials, so we added a fifth trial. During this fifth trial participants were given the ability to switch between different navigation modalities, enabling them to evaluate all modes together and afterward rank their preferences (Figure 6). Most participants ranked *Animate* as their favorite method of navigation, followed closely by *Envelop*. Almost three quarters (70%) of participants ranked *Envelop* as one of their top two preferred methods, which is a very favorable result for our proposed Envelop method. No participant chose *Fade* as their favorite method. Some participants could not distinguish between *Fade* and *Blend* modes. Participants that ranked these modes as their least favorite listed discontinuity between source and origin of navigation as their reason. Participants that ranked *Animate* poorly were concerned with camera movement, especially during longer distances. Participants that disliked *Envelop* were mostly concerned with the aggravated effect of wand movement during the increase of the size of the zoomed in view (during the transition). This issue would arise when the user is zoomed in too high, and their hand is shaking.

7.4 Discussion

We evaluated our proposed method of teleportation (*Envelop*) against the de facto standard models of virtual movement (*Fade*, *Animate*, and *Blend*). The results from the ANOVA test on subjective measurements (SSQ, PQ, TLX) and user performance showed no significant result from the method of teleportation on users' sense of presence, simulator sickness, mental load, and performance. ANOVA on the tapping test results showed a significant result of transition method over mental load during the teleportation. However, a significant difference was not shown during the Tukey HSD multiple compassion test, and this discrepancy can be studied in further research.

Based on post-study user feedback, we found that half of the participants ranked the *Animate* method as their favorite, with *Envelop* being a close contender. A heavy preference was shown towards *Envelop* and *Animate* compared to the less dynamic *Blend* and *Fade*. While *Animate* is chosen as the preferred method by the users, *Envelop* come as a close second without the need for virtual camera movements. *Envelop* also has a more flexible nature than *Animate*. *Animate* is only feasible for transitions with relatively short camera or geometry movement, while *Envelop* can be used with long distance teleportation and with any change, such as change of modality during rendering. This combination of less mental load and greater flexibility supports the potential of *Envelop* not only for large omnidirectional images, but also as a candidate for applications and use cases. The major concern with *Envelop* among participants who disliked this method was the aggravated effect of movement during the transition over large magnification levels caused by shaking of the hand holding the controller. Performing stabilization and smoothing over the hand shake in high zoom level would likely improve this. This stabilization could be accomplished by performing Kalman filtering over the wand when the zoom is above a certain threshold.

Our study is limited to the scope of search and comparison tasks. Teleportation methods such as *Envelop* and *Animate* might perform better in tasks that require a higher level of spatial understanding or path tracing. In which, the more highlighted connection between source and destination can be beneficial.

8 Conclusion And Future Work

We have presented new techniques for navigation and exploration of large omnidirectional spherical images within immersive environments, with a focus on inside-out omnidirectional GIS image. We developed a method of auto-scaling to deliver natural hierarchical physical navigation. We also proposed a new method for zoom lens teleportation and evaluated the usability of multiple transition methods. The results of our two user studies support the use of these navigation methods for improved exploration within immersive data.

Our work has applications to other immersive content such as 360-degree panoramic imagery. While our evaluation focuses on omnidirectional images based on a spherical model, the proposed auto-scaling method is also applicable to cylindrical models by limiting the equations to two-dimensional space and circular models. Since our system relies on lenses as a method for peeking and navigation, we plan to complement our work by combining it with techniques that rely on lenses for visualizing added information in large interactive visualization and exploration [20], and for a complete interactive GIS visualization exploration pipeline in VR environments. Another extension of our work would be together with other navigation methods for navigating landmarks [38], wherein our method can be used for general navigation and exploration of the earth, and a secondary model used for exploration of landmarks in a more surround setup. The lens view for navigation also enables augmenting a new view upon the previous, enabling the user to move between different projections of the same data based on distance. Our work can be combined with adaptive projection methods [21] to show a more suitable projection of data upon movement.

Since our method of navigation relies on automatically scaling the environment, an interesting challenge would be to adapt the existing method for collaborative environments and evaluating such a setup. Since our method of navigation is currently limited to a single surface dataset, this work could be extended for exploring large-scale data with complex geometries. Another extension could be evaluating a method for dynamic projection in combination with scaling to better adapt the geometry for user observation.

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