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Proxemic maps for immersive visualization

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ABSTRACT
In human computer interaction, proxemics describes the ways that people use space to interact with other people or objects. We focus on proxemic maps, which are virtual maps in immersive environments that react to proxemic interaction. Proxemic maps take advantage of new opportunities brought about by immersive visualization, where virtual maps can be freely positioned in virtual or physical space and adapt themselves relative to the spatial position of the viewer. We discuss proxemic interactions that alter the content and type of maps, including changing scale, symbolization, type of visualization and geometry. We propose a novel transformation that changes the geometry of maps based on their proximity to users. Users move the map back and forth and the map transitions between ring, horizontal, vertical and cylindrical geometries. The ring geometry surrounds the user and aligns features on the map with features in the real world. We implemented the map transformation in virtual reality and conducted a user study to evaluate it. The results of the user study indicate that participants preferred the ring and horizontal geometries. The ring geometry is useful because it simplifies connecting virtual features on the map with real features in the landscape, while the horizontal geometry provides an overall view of the landscape. We further found that combination of different geometries helped the study participants to overcome the limitations of each geometry.

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Proxemic interaction; proxemics; immersive maps; situated visualization; augmented reality; virtual reality; map projection

1. Introduction

Commodity head-mounted displays for immersive visualization have opened up new opportunities to visualize and explore information with maps in virtual and augmented reality (Büschel et al., 2018). Previous studies have explored different interactions for manipulating immersive maps with handheld devices and hand and foot gestures (Austin et al., 2020; Giannopoulos et al., 2017; Newbury et al., 2021; Satriadi et al., 2019; Santos-Torres et al., 2020; Wagner et al., 2021a), however, proxemic interactions have not been systematically explored for maps and other types of geovisualization in immersive environments.

Proxemics, first introduced by Edward Hall, explains the spatial relationship between people and features (Hall, 1966). Hall's theory was later used by Greenberg et al. (2011) to introduce proxemic interactions which use various dimensions including distance and orientation between objects and users. Our motivation for proxemic interaction in geovisualization is that users can concentrate on data exploration rather than focusing on potentially complex gestures to manipulate a visualization (Lee et al., 2012). In addition, proxemic interaction with immersive maps enables behaviors that are impossible with physical maps or displays. For instance, in this paper we explore changing the geometry of the map based on the user's proximity.

We are interested in spatial position and orientation relationships between the user and the virtual map. Traditionally, proxemics deals with the situations where users move, however, we also consider the situation where users move the map. Figure 1 shows an example of proxemic interactions for adjusting a map. In this example, the zoom level of the virtual proxemic map changes based on the distance between the user and the virtual map. Figure 1, top shows the user moving toward the map, while Figure 1, bottom shows the user explicitly moving the map. In both cases, the map responds by adjusting its level of details based on the spatial relationship between the user and the map.

The goal of this paper is to design proxemic interaction techniques for maps in immersive environments, for example, for situated visualization with AR (Bressa et al., 2021; Willett et al., 2017), and explore potential applications of proxemic maps. This study focuses on proxemic immersive maps, that is, virtual maps that are viewed in immersive virtual reality (VR) or augmented reality (AR) environments and react to proxemic

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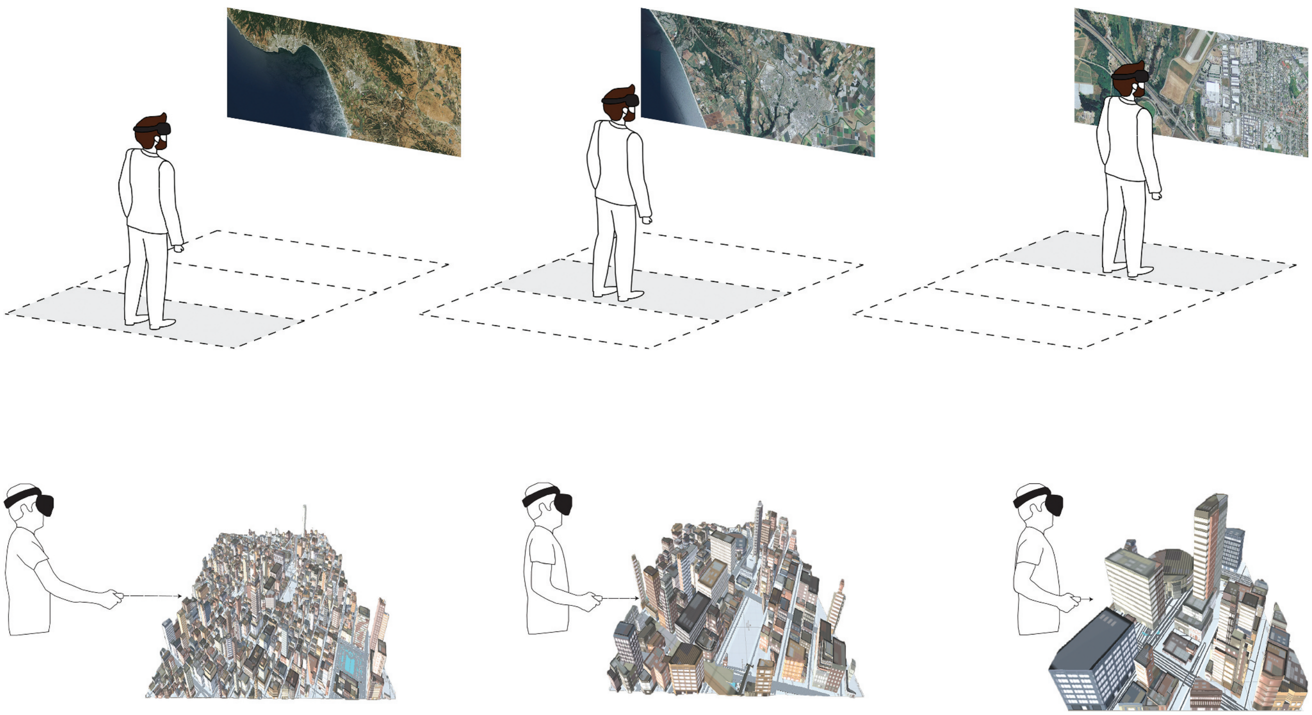


Figure 1. Changing zoom level from small scale (left) to large scale (right) based on the distance between the user and the immersive map. Either the user (top) or the map (bottom) change position.

interactions. We build on proxemic interactions that were developed for controlling large physical wall displays with user movement (Isenberg et al., 2013; Jakobsen & Hornbæk, 2012), however, we take advantage of the ability of freely moving and positioning virtual maps in immersive environments. We focus on altering the content and type of a map such as adjusting the zoom level, symbolization, type of visualization, information overlay, and map geometry.

Changing the map geometry with proxemics is a novel method that is explored in more detail in this study. With increasing distance, we transform the map geometry from a ring, to a horizontal rectangle, then to a vertical rectangle, and finally to a cylinder. Figure 2 shows an example of changing the map geometry based on the proximity to the user. An example use scenario of such a map is a group of hikers with a horizontal map in front of them. When they need an overview of the area and analyze the hiking path together, one hiker positions the map further away and they analyze the area in collaboration on a large vertical map. When they choose a direction at an intersection, they pull the map closer to see a ring-shaped map around them, which allows them to easily find the direction of features in the real world by following the line of sight from the ring map.

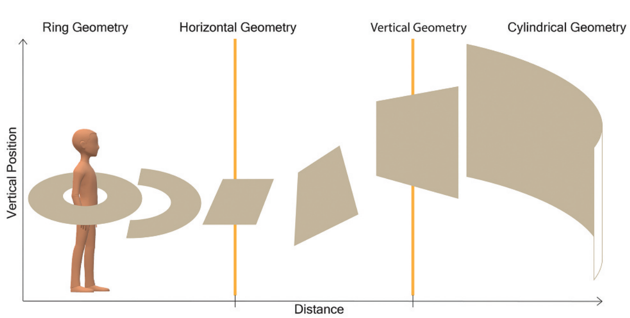


Figure 2. Map reprojection by moving the map. The geometry, size and tilt angle adapt as the user adjusts the distance of the map.

The transitions between these geometries happen seamlessly, and the size and tilt angle of the map are adjusted based on the proximity to the user. The user is not required to trigger the changes between the geometries, but the proxemic map adapts itself based on the distance to the user.

This paper is organized as follows. Section 2 reviews related work on immersive geovisualization, proxemic theory and proxemic interaction. Section 3 discusses the proxemic interactions for immersive environments. Section 4 details the transitions between different geometries for immersive maps. Section 5 presents a user study to identify the most favored geometries by participants and determine preferable parameters of each geometry. Section 6 discusses the study results and section 7 presents conclusion and future work.

2. Related work

This section discusses the advantages of immersive geovisualization as well as the background of proxemic interaction and its application to wall displays. We also review previous studies focusing on interaction for immersive geovisualization and identify a small number of studies on proxemic manipulation for non-geographical immersive visualization.

2.1. Immersive geovisualization

Immersive geovisualization brought about new opportunities to explore and present geospatial data in 2D and 3D interactive environments using head-mounted VR and AR displays (Dwyer et al., 2020; Satriadi, 2021). It also enables the users to explore data with egocentric (viewer stands inside the visualization) and exocentric (viewer stands outside the visualization) views to take advantage of both views in 3D scenes and at different scales (Wagner et al., 2021b). Example applications of immersive geovisualization include simulating ecosystems (Chandler et al., 2021; Hruby et al., 2019), teaching of landscape design (Carbonell-Carrera et al., 2021), visualizing geological data (Engelke et al., 2019), exploring geo-temporal marine trajectories (Ssin et al., 2019), visualizing forestry data (Nam et al., 2019), navigating through virtual cities (Gardony et al., 2021), and visualizing and interacting with globes in virtual reality (Yang et al., 2018). Immersive environments enable users to create any number of virtual maps and globes, position and resize them at will, and view them from various perspectives (Satriadi et al., 2020). Prior studies compared immersive visualization and desktop visualization and found that interacting with three-dimensional maps is faster with immersive visualization (Zhang et al., 2018), requires fewer interactions (Nguyen et al., 2017), and increases user engagement (Bach et al., 2018). Immersive maps also help users to better perceive 3D content in comparison to desktop visualization (Mendes et al., 2019). However, standard interaction methods for manipulating immersive maps are still missing (Satriadi et al., 2019).

2.2. Proxemics and proxemic interaction

The term proxemics, first introduced by Hall (1966), indicates the interpersonal spatial relationship between people and features. He defines four different zones: intimate, personal, social and public and describes how these zones affect people's relationship to other people and features in surrounding spaces. Hall's theory of proxemics later influenced research in human computer interaction. Greenberg et al. (2011) introduced proxemic interaction among people and features based on Hall's theory of proxemics. They identified five dimensions of proxemic interaction: distance between people and digital and non-digital features; orientation between entities; identity, which helps to distinguish entities from each other; movement, which describes the distance and orientation over time; and the location of entities. Previous research used proxemic interaction for large wall displays (as explained in the next section); however, using proxemics to perform new interactions in an immersive environment has not been systematically explored.

2.3. Proxemic interaction with large wall displays

Prior studies have shown the advantages of proxemics for interacting with visualizations on large wall displays. The scale of visualization, type of visualization, level of details and amount of information have been controlled by changes of the user position in relation to the display. Harrison and Dey (2008) magnified the on-screen content based on the distance between the user and the display. Jakobsen and Hornbæk (2012) and Jakobsen et al. (2013) designed interactions to zoom, pan, filter, sort and select visualizations based on the user's distance, orientation, movement and location relative to wall displays. Isenberg et al. (2013) changed the information density of the image based on the distance to the display. Dostal et al. (2014) proposed a collaborative framework for altering the level of details, symbolization and type of visualization based on the users' distance. Badam et al. (2017) suggested a design space for changing the visualization based on the gestures and the proximity to the display. Chulpongsatorn et al. (2020) introduced a design space for transitioning between visualizations and changing the level of details based on the distance to the display. They altered the level of aggregation in choropleth maps and scale of bar charts based on user proximity to the display.

In summary, previous studies on proxemic interaction for wall displays resulted in more effective visualization especially for changing the zoom level (Jakobsen et al., 2013), or user performance improvement in data manipulation when combining gesture and proxemic interaction (Badam et al., 2017). We extend these studies on proxemics for large wall displays to maps in immersive environments.

2.4. Proxemic interaction in immersive environments

Previous studies have explored interactions for manipulating maps based on handheld devices, as well as hand and foot gestures (Austin et al., 2020; Giannopoulos et al., 2017; Satriadi et al., 2019; Wagner et al., 2021a), but few studies used proxemics to interact with immersive visualizations. Aseniero et al. (2013) adjusted the amount of AR information based on the user's distance to products in a supermarket. Hurter et al. (2017) changed immersive 2D graphs, 3D scans and 3D trajectory visualizations based on user movement and showed that freely moving in space produces less fatigue than using hand gestures. Hubenschmid et al. (2021) modified visualizations based on user's proximity; the amount of information was adjusted based on the user's distance, and the text, labels and icons oriented themselves toward the user.

In summary, different types of interactions for immersive maps have been introduced recently based on gestures and hand-held devices, but there is only a limited number of previously published works using proxemic interaction with immersive maps in AR or VR.

3. Designing proxemic interaction for immersive maps

We go beyond proxemic interaction with physical wall displays and focus on new opportunities brought about by immersive visualization, where maps can be moved and freely positioned and adapt themselves based on their position. We are interested in how immersive maps respond to the distance and orientation relationship between the map and the user.

We use a taxonomy of basic interactions in cartography and geovisualization proposed by Roth (2013), and consider his "work operator primitives" for proxemic interaction with immersive maps. Roth identified 12 work operators for manipulating maps, of which the *Zoom and Pan*, *Resymbolize*, *Reexpress*, *Overlay*, and *Reproject* operators are related to the type and design of the map. Below we explore how these six operators can be controlled with proxemic interaction.

The **zoom and pan** operators change the scale and the geographic center of a map. Research in interaction techniques usually considers zoom and pan as a single operation (Bourgeois & Guiard, 2002; Nancel et al., 2011), because they commonly are required concurrently. For proxemic interaction with immersive maps, either the user (Figure 1, top row) or the map (Figure 1, bottom row) can change position, and the distance between them can control the zoom level. When the user is close to the map, the zoom factor is increased and a smaller area with more detail is displayed. When the distance increases, the map displays a larger geographic area with generalized features (Dostal et al., 2014; Jakobsen et al., 2013).

Resymbolization changes the design parameters of the map (Edsall et al., 2009; Roth, 2013). The size of the symbol and the distance of the viewer's eye affect the perception of the symbol on maps (McCready, 1985). With immersive geovisualization, map symbols can dynamically adjust for best readability depending on the proxemic distance between the user and the map. When a proxemic map is close to the user, additional information is visualized and symbolization is adjusted, for example, by using smaller symbols or less details. When the map is far from the user, simplified symbology is used that is easier to read, for example, larger symbols or increased generalization (Figure 3).

The **reexpress** operator alters the map presentation, for example, transitioning between isopleth, choropleth, and dot maps (Dykes, 1997; Roth, 2013; Shepherd, 1995). The reexpress operator was explored for virtual reality maps by Yang et al. (2021), who used the tilt angle of a virtual reality map to transition between choropleth, prism and bar charts to overcome the limitation of each map type. The transitions between maps occur at key angles within 90 degrees: at a vertical orientation it is a choropleth map, at an intermediate

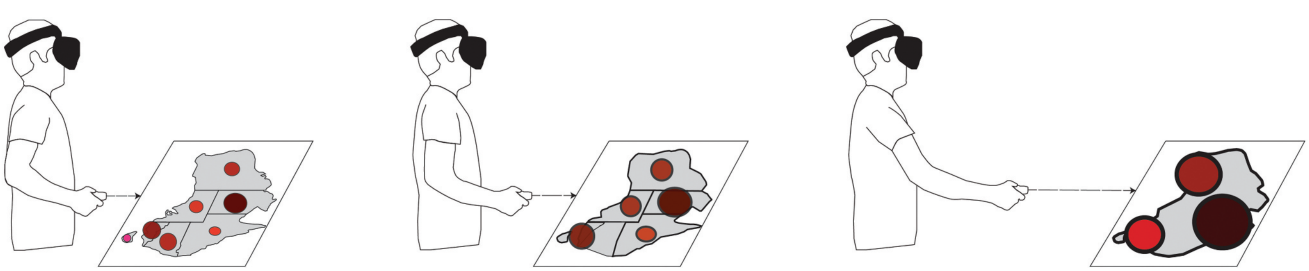


Figure 3. Proxemic interaction for controlling the resymbolization operator: The symbology and generalization vary with the distance between the map and the user.

tilt angle it is a prism map, and at a horizontal orientation it is a geographically sorted bar chart. The map smoothly transitions between these three different visualizations. Although, Yang et al. (2021) did not explicitly use the term proxemics in their work, they used the rotation dimension of proxemic interaction to control their immersive map. Their example (Yang et al., 2021) is outstanding and we are not aware of any related proposals for transitioning with proxemics between different cartographic expressions in immersive maps.

Spatial **overlay** of data layers has been used in previous studies to superimpose different layers and information in immersive environments. Veas et al. (2013) designed an AR mobile application for environmental monitoring and overlaid contour lines and polygons on real terrain. In other studies, geological maps were displayed over the real landscape using AR (Mathiesen et al., 2012; Westhead et al., 2013). With proxemic maps, layers can be added or removed based on the proximity of a map to an embodied overlay. Map layers are superimposed on a map based on proxemic interaction and enable users to find the spatial relationship between entities on different layers (Figure 4). When the user moves a map toward a set of symbols embodying different layers, the closest layer snaps onto the map and is shown as an overlay on the map. When the map is then moved away from the symbol, the layer disappears from the map. This is similar to the brushing and linking interaction in the immersive analytics framework *ImAxes* for non-geographic immersive visualization (Cordeil et al., 2017), where users move embodied axes toward each other and see ephemeral visualization created between close axes.

In cartography, a **reprojection** operator changes the projective transformation between a globe surface and a flat plane (Roth, 2013; Snyder, 1997). In immersive visualization a map can be projected onto non-planar surfaces, and the surface geometry can change dynamically. The reprojection operator in the context of this paper therefore translates map coordinates between different geometries. In the example in Figure 5, the map transitions between different geometries as the map is moved away or toward the user. The map changes from a ring segment (Figure 5a) to a cylindrical geometry (Figure 5b) as the distance increases.

Adapting the geometry of maps to user interaction in real-time has been proposed before. Pasewaldt et al. (2014) created multi-perspective 3D panoramas for 2D displays that bend parts of a 3D virtual world toward the viewer to tackle occlusion and perspective distortion issues.

4. Reprojection based on proxemic distance

We are not aware of any previous work exploring proxemic transformations of the geometry and projection of maps. Our motivation is that such transformations may result in maps that are engaging, help users to overcome the limitations of each geometry by transferring to another one and facilitate the linking of virtual map features with the corresponding objects in the surrounding world. An example application is a proxemic hiking map (Figure 6). When the user is on the way with no turning path or intersection (Figure 6a), an overview of the area is visualized on a rectangular map with an oblique orientation that is convenient to read. When the user is to choose a path near an intersection (Figure 6b),

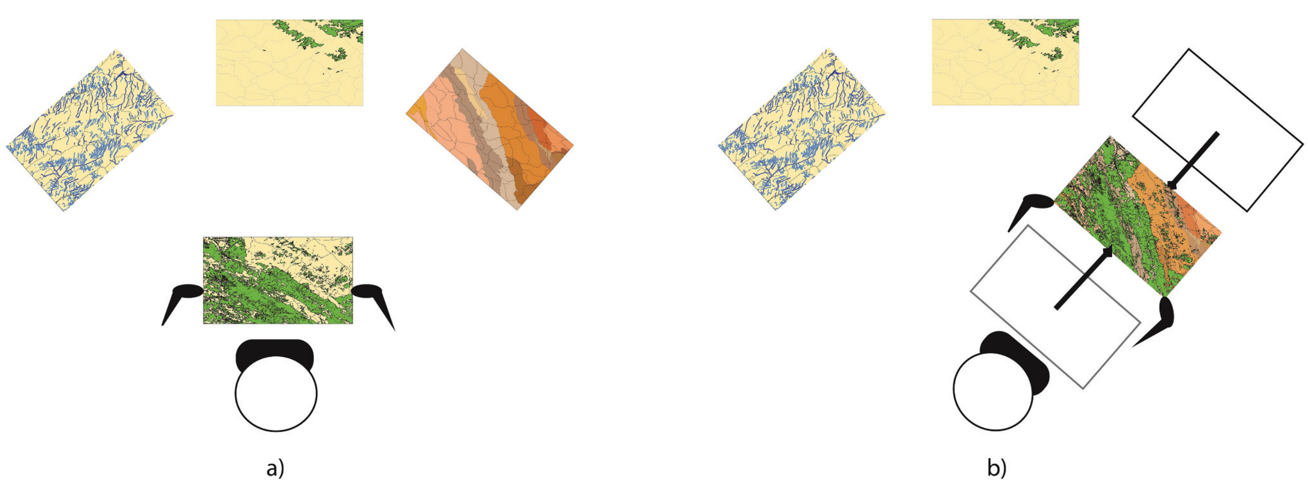


Figure 4. Overlaying different layers based on the proximity between an immersive map and layer symbols. In the example, a) three map layers are placed around an immersive map. b) When the user moves the map toward a layer, the layer snaps onto the map. When the map is later moved away, the layer is taken off the map.

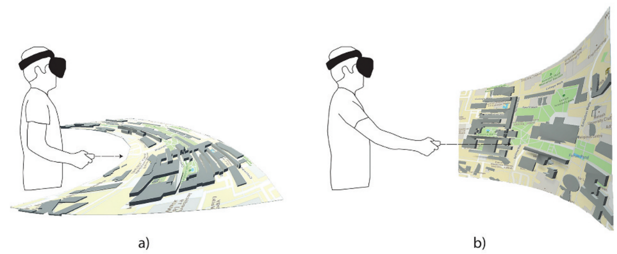


Figure 5. Proxemic geometry transition between a) a near ring segment and b) a far cylindrical geometry.

the map morphs into a ring geometry, so the user can find the direction of features by following the line of sight from the ring map.

We therefore designed and implemented a virtual reality prototype to explore transitions between different map geometries and evaluated the different geometries in a user study. The geometries include a horizontal ring, a horizontal rectangle, a vertical rectangle, and a vertical cylinder (Figure 2). The horizontal and vertical rectangles use a conventional map projection, the ring geometry is a type of azimuthal projection as it preserves direction from a central point, and the cylindrical map bends the map into a semi-open cylinder. In our implementation, the map shows a three-dimensional terrain surface, but flat maps can be visualized in a similar way.

The geometry, size and orientation of the map vary with proximity to the user. As illustrated in Figure 2, when the map is moved toward the user, the geometry changes from a horizontal rectangle to a ring segment and when the map is close to the user, it transitions to a ring. When the user pushes the map away, the orientation of the map gradually changes from horizontal to vertical. At the furthest distance, the geometry can change to a vertical rectangle or a vertical cylinder. The transition between different geometries occurs seamlessly between different zones, which is inspired by the way a person moves seamlessly through Hall's (1966) proxemic zones during routine interactions with people or objects. Similar to this concept of zones, the map changes its geometry as it moves toward or away from the user.

When transitioning from the horizontal rectangle to the ring, users pull the map toward themselves and the map gradually morphs into a ring segment while the size of the map and the radius of the ring increase simultaneously. The final map geometry is a ring which surrounds the user, and the center of the ring is the location of the user. Figure 7 demonstrates the transition from a rectangle to the ring. Features on the ring map are aligned with the direction of the corresponding features in the surrounding landscape (Quach & Jenny, 2020). This enables users to easily find the direction of real-world features by following the line of sight from the map to the surrounding world (Figure 8).

The conversion from a rectangular map to a ring map applies a transformation to each geometry vertex of the map. This transformation uses polar coordinates with the user positioned at the center of the coordinate system and the polar axis aiming at the center of the map at the start of the transformation. The transformation is applied before each new animation frame is rendered. As the user pulls the map closer, each vertex is moved toward the pole of the coordinate system, hence the radial distance r is reduced to r'. We also change the corresponding polar angle θ. The polar angle θ is scaled by a parameter k that varies with the distance between the user and the center of the map: $\theta' = \theta \times k$. For

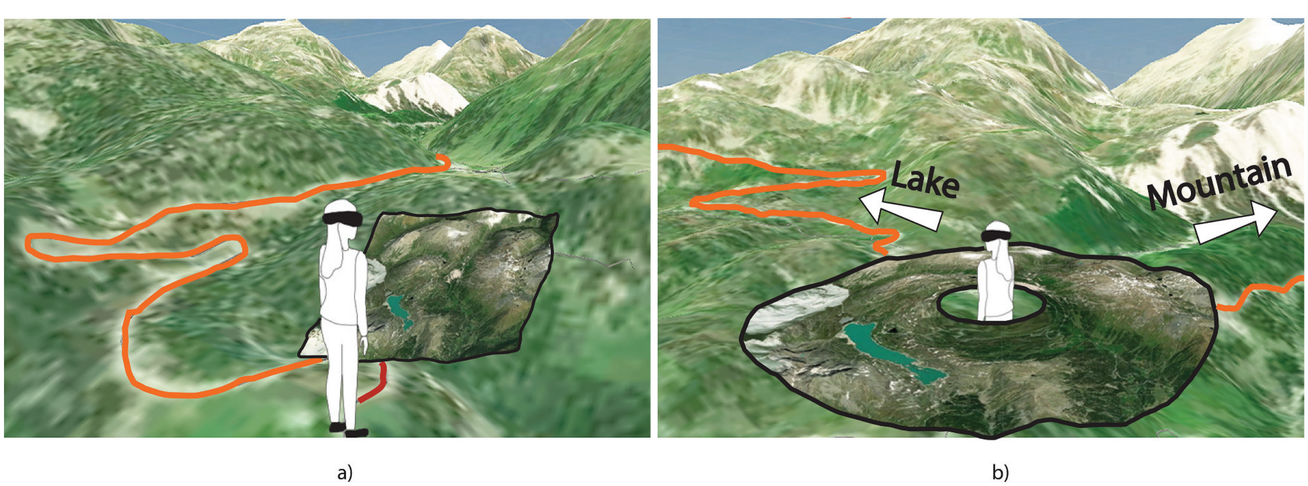


Figure 6. A morphing proxemic hiking map: a) a rectangular map is visualized along the path, and b) near an intersection, the map morphs into a ring to help the user to select the desired path.

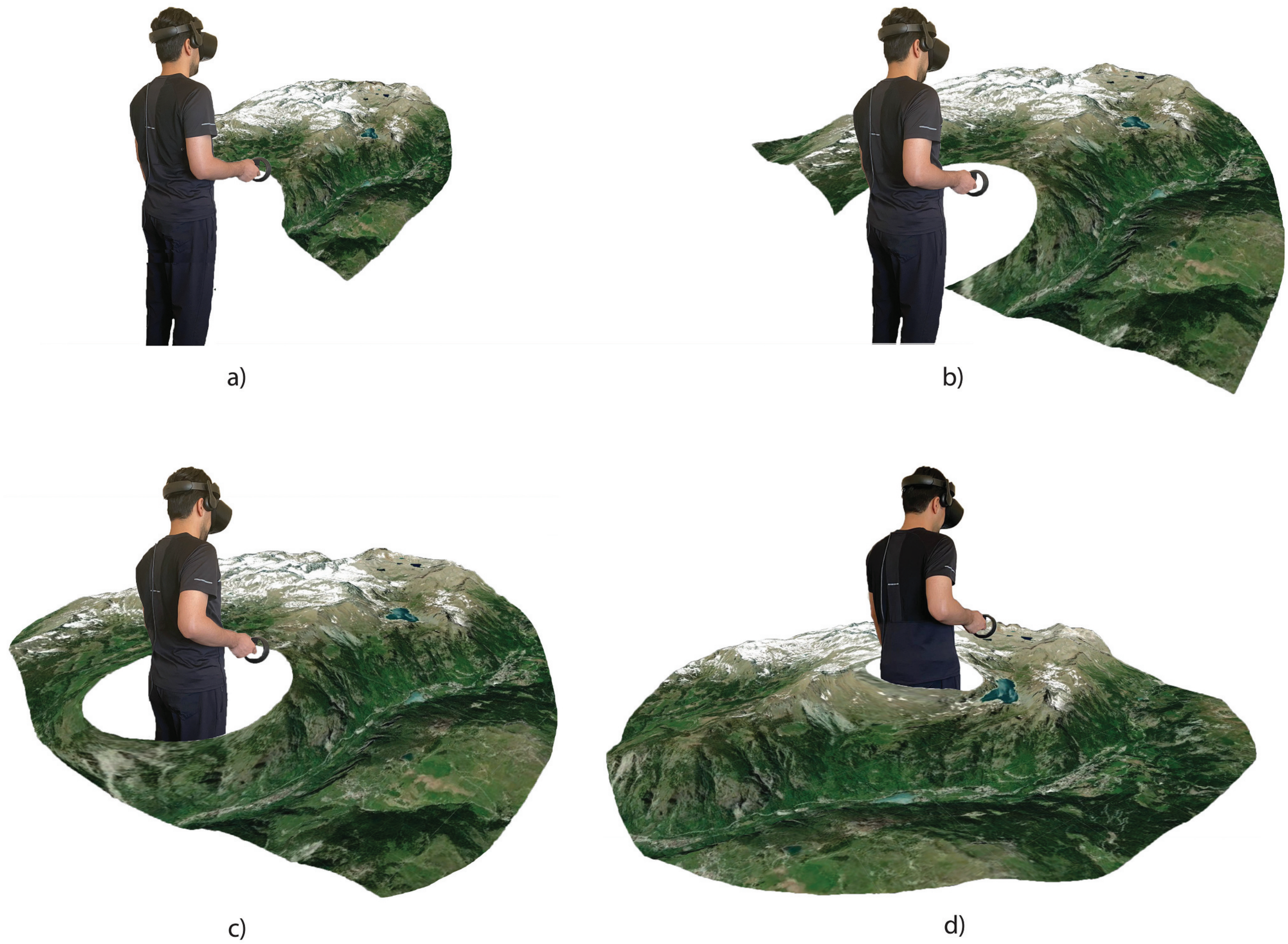


Figure 7. Transition from a) a rectangular geometry, b) to a ring segment, c) to a partial ring, d) to a ring geometry.

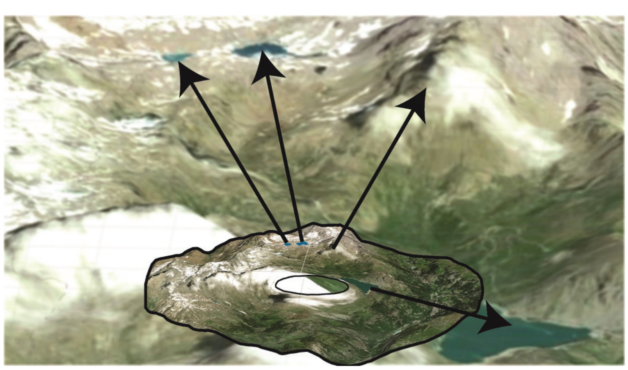


Figure 8. A ring geometry aligns features on the map with their real-world referent location.

rendering the geometry vertex, the transformed polar coordinate (r', θ') is converted to a Cartesian coordinate system.

The transition from a horizontal rectangle to a vertical rectangle or a vertical cylinder occurs when the map is pushed away. The map gradually rotates around the pitch axis to a vertical orientation as the distance increases (Figure 9). At the same time, the size of the map increases to make it easier for the user to read the map at farther distances. When transitioning to a cylinder, the map in addition starts to curve to a cylindrical geometry. The size of the cylinder is increasing while the distance between the map and the user is growing.

5. User study

We conducted a user study in virtual reality to evaluate transitions between the ring, horizontal rectangle, vertical rectangle and cylinder map geometries. We aimed at identifying user preferences and ideal parameters for each map geometry. We created a VR application with the Unity 2018.4.2 game engine (https://unity.com) and the Mapbox SDK for Unity (https://www.mapbox.com/unity). In this study, we used a Samsung Odyssey mixed reality headset with a field of view of 110°. The application showed maps of natural environments with three-dimensional terrain and draped aerial imagery, and the

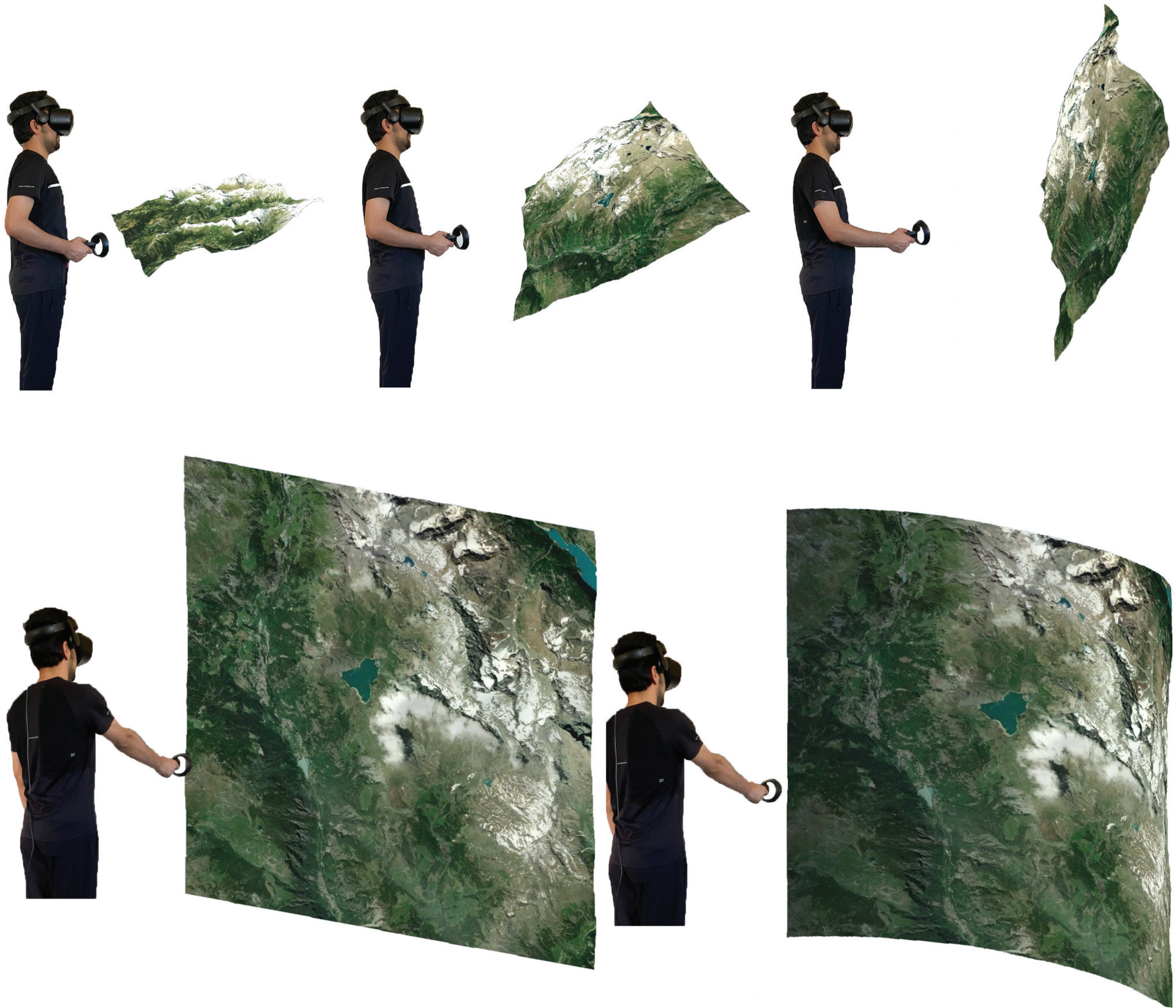
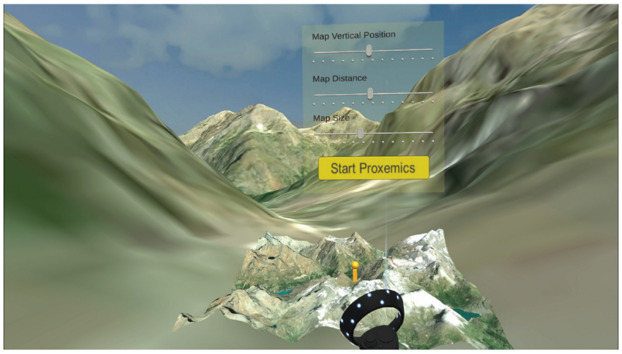


Figure 9. Transition from the horizontal to the vertical rectangle and cylinder using proxemic interaction. The map rotates from a horizontal orientation to a vertical orientation as the distance increases (top), then transitions to vertical and cylindrical geometries (bottom).

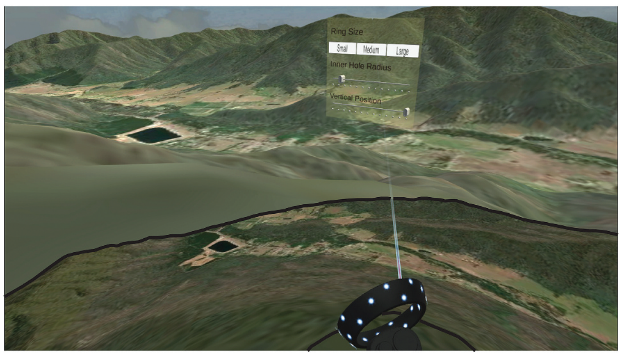
map was rendered at a rate of 90 frames per second. We recruited 12 participants (3 female and 9 male), within an age range of 20–40 years. Six participants self-declared as experts and six as non-experts in VR and AR. Three participants were experts in mapping and geovisualization.

For this exploratory study, participants were asked to adjust the parameters of each map geometry, imagining that they were hiking while using each of the different geometries for wayfinding using an imagined augmented reality interface. We designed three simulated scenes with different landscape types to check if the surrounding landscape affects the parameter selection or the preferred geometry. The scenes included a valley, where participants were surrounded by mountains (Figure 10a), a mountain peak, where users had a wide view over a mountainous landscape (Figure 10b), and a plain with fewer terrain features (Figure 10c). In total there were 3 scenes × 12 parameters = 36 parameter settings per participants. We used Latin square design to balance the order of the scenes.

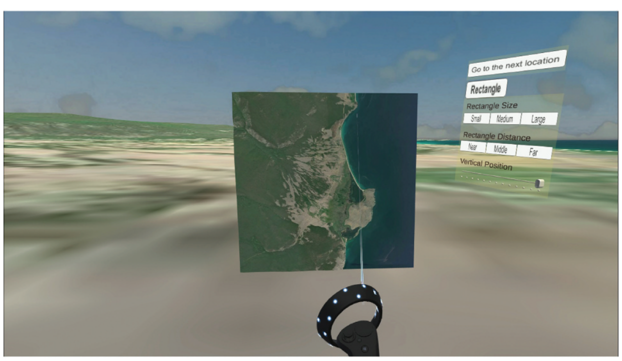
The user study consisted of the following tasks: first, participants were asked to modify the parameters of the horizontal map geometry including the distance between themselves and the map, the vertical position of the map, and the size of the map (Figure 10a). Then, they started moving the map back and forth to transition to other geometries and modify parameters for each geometry. Participants used the left or right VR controller to move the map and change the parameters. For each geometry, a control panel was shown (Figure 10) and participants changed the parameters related to the



a)



b)



c)

Figure 10. a) The Valley scene with a) horizontal rectangle geometry, b) the mountain scene with ring geometry and c) the plain scene with vertical rectangle geometry of the user study with the VR controller and the interface elements to select geometry parameters.

geometry using sliders and buttons. For the ring geometry, users could change the outer ring radius, the radius of the inner hole and the vertical position of the ring (Figure 10b). For the vertical rectangle and cylinder, they were asked to modify the size, distance and vertical position (Figure 10c). Table 1 lists the eight parameters that participants adjusted, along with the possible parameter values. For selecting the dimension of the ring map, participants chose a value between 0 and 1 meter for the inner hole radius, and then selected the outer ring radius from three predefined values (*small* = 1 m, *medium* = 3 m, *large* = 5 m). For selecting the dimensions of the horizontal, vertical, and cylindrical maps, participants selected from three predefined sizes (*small, medium, large*). For selecting the distances of the maps, participants first selected the initial distance to the center of the horizontal rectangular map between 0.5 and 2 m, then selected from three predefined offset distances (*near* = 3 m, *middle* = 5 m, *far* = 7 m) to position the vertical rectangular map and the cylindrical map. For all geometries, participants could adjust the vertical position of the map centers between 0 and 2 meters.

Tables 2 and 3 show the angular sizes of the vertical rectangle and cylindrical geometries, respectively. Angular size is defined by the size of the map and its distance from the eye, which determine how many degrees the map covers in the viewer's field of view. The angular size of the vertical rectangle and cylindrical geometries are important as they are placed in front of users and occlude a portion of their view.

5.1. Procedure

We first introduced participants to the project, the different map geometries and their parameters. An initial training helped the participants to become familiar with proxemic interaction and transitions between different geometries. After the training, we asked participants to adjust the parameters of all geometries and finally rank

Table 1. Size and distance parameters of the four map geometries. All values are in meters.

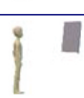
Geometry		Parameters			
Ring		Inner hole radius	0–1	Ring radius	Small: 1 Medium: 3 Large: 5
Horizontal Rectangle		Size	Small: 1 × 1 Medium: 1.5 × 1.5 Large: 2 × 2	Initial distance	0.5–2
Vertical Rectangle		Size	Small: 1.2 × 1.2 Medium: 2.4 × 2.4 Large: 4.2 × 4.2	Offset	Near: +3 Middle: +5 Far: +7
Cylinder		Size	Small: 1.8 × 1.8 Medium: 3 × 3 Large: 6 × 6	Offset	Near: +3 Middle: +5 Far: +7

Table 2. The angular size at the horizontal center of the vertical geometry.

	Near	Middle	Far
Small	19°	12°	9°
Medium	38°	25°	18°
Large	62°	42°	31°

Table 3. The angular size at the horizontal center of the cylindrical geometry.

	Near	Middle	Far
Small	21°	14°	11°
Medium	33°	23°	17°
Large	57°	40°	29°

the geometries based on their preference in each scene. During the study, we asked users to think loudly and explain what they liked and disliked about each geometry, parameter and scene. After completing the tasks, a post-hoc questionnaire recorded feedback on: (1) background information about the participant; (2) System Usability Scale (SUS) (Brooke, 1996) of the system with a five-point Likert scale; (3) preference ranking of geometries in terms of ease of use and effectiveness for hiking and way finding; and (4) perceived advantages and disadvantages of each geometry.

5.2. Results

The average score of 71.4 for the SUS shows a good usability performance of the system. The reliability of the SUS responses was evaluated using Cronbach's alpha with the result of 0.71. According to George and Mallery (2019), Cronbach's alpha value above 0.70 is acceptable.

Figure 11 shows the participants' ranking of the geometries aggregated for the three scenes. The ring and horizontal rectangle were generally the two preferred geometries with 17 and 14 rankings as the most preferred geometries respectively. However, the ring geometry received 11 ranking as the least preferred geometry while the horizontal rectangle received only one least ranking. The cylindrical map was the least preferred. Figures 12–15 show the suggested parameters for each geometry aggregated for all three scenes. We used Wilcoxon signed rank test to check if there was a significant difference between parameter selection for different scenes. We applied the test on both geometries and scenes. The results showed no significance difference between parameter selection on different scenes (for the results of each geometry refer to Supplementary Materials). Because we could not find a significant influence of the three different scenes on geometry preference or suggested parameters, from here onwards we discuss the results without any specific analysis of the three scenes.

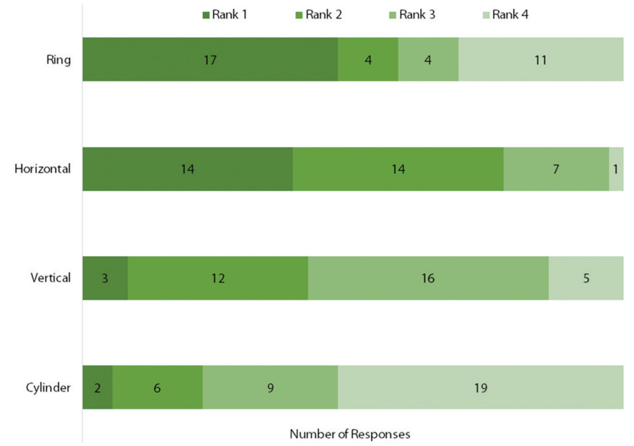


Figure 11. Preference ranking for the four geometries aggregated for the three scenes.

The ring map was positioned at waist height in 25 responses (Figure 12). A majority of participants commented that waist height results in less fatigue and causes less motion sickness. An inner hole radius of less than 0.5 meter or zero was selected in 29 responses (Figure 13). There were different reasons for selecting the size of the ring radius. A small ring size was selected in 16 responses to avoid occlusion of the area by a large ring. On the other hand, a large ring size was selected in 14 responses to allow detailed features to be more easily seen on the map (Figure 14).

For the horizontal geometry, most participants (28 responses) preferred a distance of less than one meter (Figure 15). In 19 of the responses, participants positioned the horizontal geometry at chest height

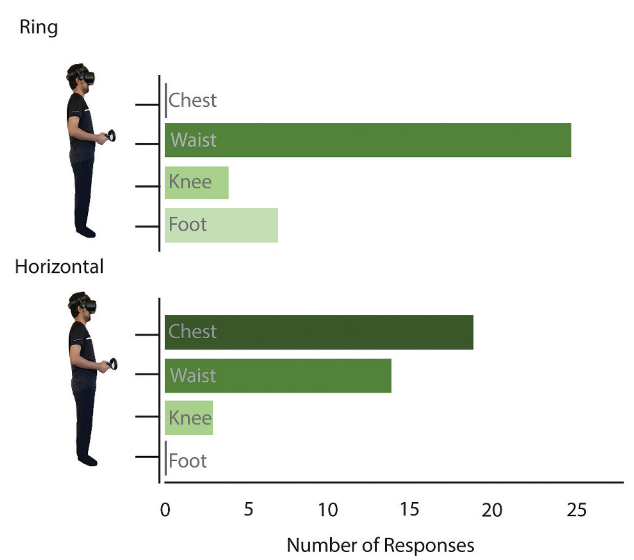


Figure 12. Suggested vertical position for the ring and horizontal rectangle geometries aggregated for all three scenes (classified to four heights).

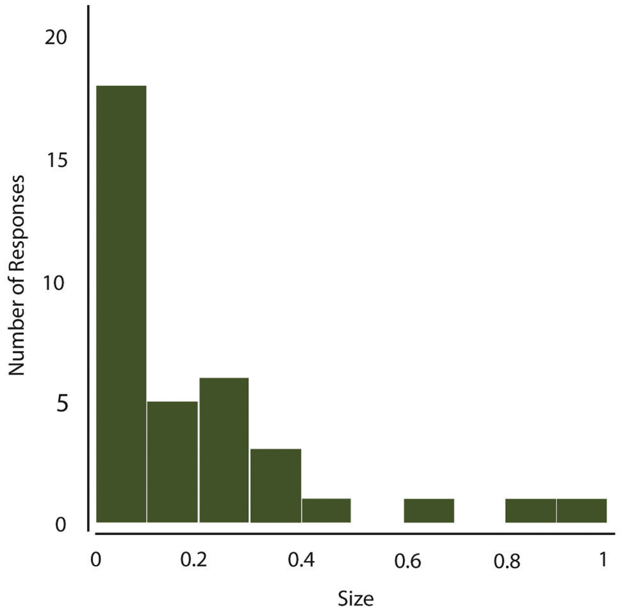


Figure 13. Suggested size (m) for the inner hole radius of the ring geometry aggregated for all three scenes (histogram with 0.1 m interval).

(Figure 12), because they wanted to have an overall view of the map without large neck movement. However, horizontal geometry was positioned at waist height in 14 responses to reduce occlusion on the map.

For the vertical rectangle and cylinder geometries, all participants preferred the vertical position at head-height to align the center of the map with eye level. Participants rarely chose the large size for the vertical rectangle and cylindrical geometries, which would have blocked a large portion of their field of view (Figure 14). Based on Tables 2 and 3, a large vertical rectangle and cylinder at near distance cover 62° and 57° out of 110° of users' field of view respectively. A distance of almost four meters was selected for the vertical and cylindrical geometries in 26 and 23 responses (Figure 15).

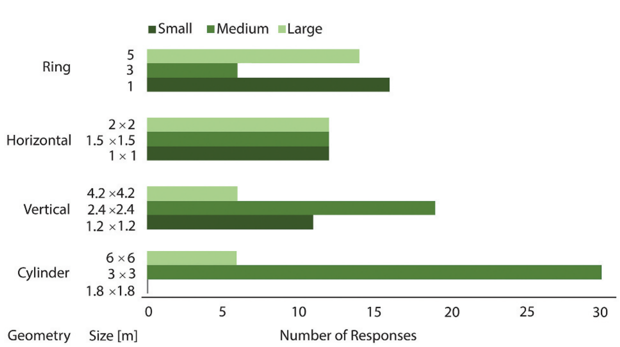


Figure 14. Suggested size for the four geometries aggregated for all three scenes. Dimensions are indicated in meters.

5.3. *Participants' feedback*

During the study, we asked users to explain the pros and cons of each geometry in each scene. Participants could also give general feedback at the end of the study. Qualitative analysis of participant feedback revealed the following.

Seven participants found the ring geometry to be a "*unique experience and engaging*" and thought it would be "*really useful in navigation and finding direction.*" Some commented that "*everything is around me*," "*I just need to turn around to find features*," or "*the actual view is perfectly aligned with the real world, which is great.*" Some participants, on the other hand, mentioned difficulties using the ring geometry as four of them mentioned that they could "*only see a portion of the map*" and two reported experiencing motion sickness when surrounded by the ring geometry.

For the horizontal rectangle geometry, eight participants commented that they liked it as it provided "*an overall view*" and did not require participants "*to learn a lot to use it.*" Four participants mentioned that "*finding the direction of the features in real world is still difficult with the horizontal geometry*" (or similar).

Four out of 12 participants found the vertical rectangle geometry to be easy to read, but five participants commented they did not want to block their view using vertical maps, and one participant commented that "*it covers my view, so I would probably look at it for a moment then hide it.*" Moreover, with the vertical rectangle geometry, five participants commented that they could not easily see the third dimension of the terrain map, which is essential for route planning in mountainous areas.

Similar to the vertical rectangle geometry, the cylindrical geometry was criticized by five participants for "*blocking the view*" and resulting in "*invisible depth information.*" Additionally, five participants found "*the curvature of cylindrical geometry useless*" because they could not see the information clearly on the sides of the open cylinder.

6. Discussion and design recommendations

The main finding of the user study was that most participants valued the combination of different geometries for hiking and exploring the landscape. Eight participants commented that they preferred the horizontal geometry for an overview of the area and the ring geometry to find the direction of a target, or they preferred the horizontal geometry while walking and the vertical geometry while standing. The combination of multiple geometries provided the participants with complementary views and enabled them to overcome the limitation of one geometry

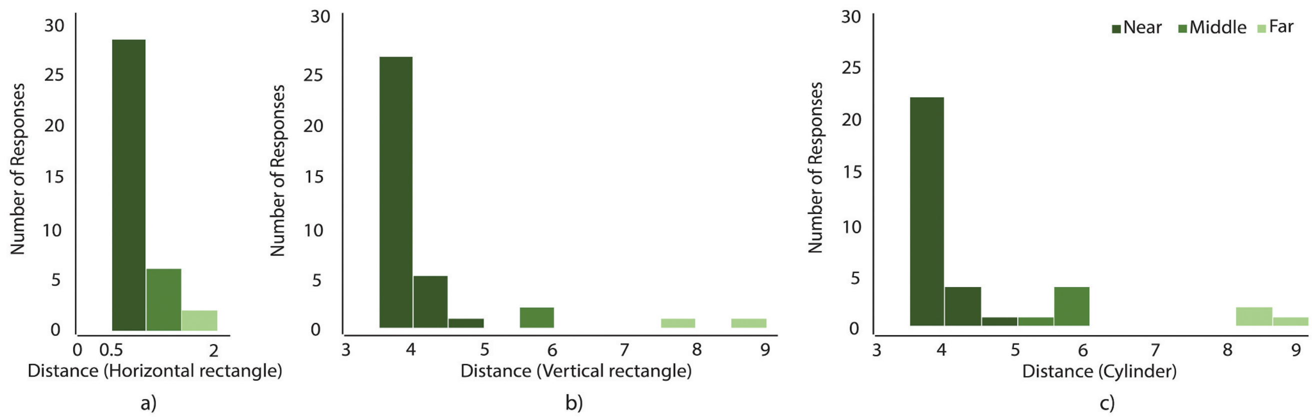


Figure 15. Suggested distance in meters for a) the horizontal rectangle, b) vertical rectangle and c) cylinder aggregated for all three scenes (histograms with 0.5 and 1 meter interval).

by transitioning to another one. For instance, users could obtain an overall view of the landscape with the horizontal map geometry as they found it simple, easy to use and similar to the maps used in their daily life, while they found the ring geometry to be useful to link features on the map with features in the landscape.

All participants were satisfied with the transitions between geometries and commented positively on the seamless morphing between the geometries. Users preferred the horizontal rectangle and ring geometries, while the cylindrical geometry was the least preferred due to difficulty in reading information on the curved edges. Most of the participants positioned the ring around the waist to reduce occlusion on the map. Most participants set the inner hole radius of the ring to zero, presumably because in our VR application the participants could not see their own body. If we used avatars to simulate users with a full body in VR or implemented the ring geometry in AR such that users could see their real body, they would likely choose an inner hole radius greater than zero to avoid intersections of the map with their body. Some participants felt motion sickness when surrounded by the ring, which is likely due to the landscape in the background being rendered similar to the ring geometry in VR. We presume it was difficult for some participants to distinguish the ring map from the virtual background (see Figure 10b). This issue is unlikely to occur in AR where users see the real physical world instead of a virtual environment. Participants rarely chose large vertical rectangle and cylinder geometries because they did not want to block their view with a large map. All participants positioned the vertical rectangle and cylinder at eye-level, because this arrangement results in minimum head and neck movement. For the cylinder geometry, the study participants were not always at the center of the cylinder, because they could choose the distance to the cylinder.

Based on the results of our user study conducted with three different landscape scenes, we recommend transitioning between the ring, horizontal rectangle and vertical rectangle geometries. The ring geometry is best placed at waist height. The horizontal geometry should be used at approximately one meter from the user and be positioned at chest height. The vertical rectangle should be placed at about 3 to 4 meters from the user and have a maximum size of 3 × 3 meters. The vertical position should be such that the center of the vertical rectangle aligns with the user's eye level. However, in our study, we only considered natural environments and not built environments, where other geometry dimensions might be preferred. A limitation of our study is the relatively small number of participants, which may affect the reliability and generalizability of our study results. Also, "imagining" a wayfinding scenario might be very different from a real wayfinding scenario and might affect the geometry and parameter selection.

7. Conclusion and future work

This paper introduces the application of proxemics to interactive immersive maps. We briefly discuss how the six working operators zoom and pan, resymbolize, reexpress, overlay, and reproject can be controlled by proxemic interaction for immersive maps. Focusing on the reproject operator we then introduce a novel type of proxemic transitions between different map geometries that is controlled by the distance between the user and the map. In our design, the map seamlessly transitions between a ring surrounding the user, a horizontal rectangle, a vertical rectangle and a cylinder. The users do not primarily select a map geometry, but they change the distance to the map, which changes and controls the morphing of the map to different geometric shapes. The user study showed that most users ranked the ring and horizonal rectangle as the most preferred geometries. The ring geometry simplifies linking features on the map with the features in the landscape, and the horizontal rectangle geometry shows a clear overview of the landscape. Study participants valued using the combination of different geometries. Transitioning between different map geometries seems to have helped them to overcome the disadvantages of each geometry and better explore the surrounding environment.

Proxemic interaction for immersive maps is not limited to the operators discussed in this paper and future work could explore other operators for manipulating immersive maps based on proxemics. Future research also could explore proxemic adjustment of content, symbolization and generalization of maps.

Future work could also focus on collaborative immersive map manipulation. In this study, we considered spatial relationship between a single user and one map, but proxemic interaction of multiple users with multiple maps can also be explored. The opportunities offered by immersive environments for collaborative data analysis (Lee et al., 2021) could be reinforced with proxemic interaction to provide more efficient immersive collaboration.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are openly available in Zenodo at DOI https://doi.org/10.5281/zenodo.5242049

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