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Designing Virtual Spaces for Immersive Visual Analytics

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Abstract

Modern virtual reality (VR) technology has garnered significant attention in the geographic visualization community for its ability to immerse users within geospatial data sets. While immersion within one-to-one models of reality offers unique and powerful perspectives from which to view spatial data, VR also allows users to transcend the physical limitations of the real world, thereby allowing them to visualize, experience, and interact with spatial data at any scale, in any virtual environment, at any time. This paper presents a collection of 3D data-driven geovisualization case studies, implemented in an immersive virtual GIScience data visualization space (IVEVA). IVEVA was purposefully designed and developed to highlight the differences in spatial data type, the challenges associated with spatial data visualization in an immersive virtual environment, and the importance of adhering to the established design heuristics of cartography, human–computer interaction, and extended reality (XR) development. Through this process, we offer our observations on how well each data type fits this medium of visualization and interpretation, and how the design heuristics play out for an immersive virtual environment that extends the practicable space in which GIScience and visual analytics are performed. Finally, we offer our perspectives, from designing and developing this prototype, on the future for immersive interface-based GIScience.

Keywords Geovisualization · Visual analytics · Virtual reality · Design heuristics · GIScience · 3D Data

Gestaltung virtueller Räume für immersive Visual Analytics

Zusammenfassung

Moderne Virtual Reality (VR)-Technologien haben in der geographischen Visualisierungsszene große Aufmerksamkeit erregt, da sie es den Nutzerinnen und Nutzern ermöglichen in georäumliche Datensätze einzutauchen. Während das Eintauchen in Eins-zu-Eins-Modelle der Realität einzigartige und leistungsstarke Perspektiven bietet, aus denen Geodaten betrachtet werden können, ermöglicht VR den Nutzerinnen und Nutzern auch, die physischen Beschränkungen der realen Welt zu überwinden, wodurch sie raumbezogene Daten in jedem Maßstab, in jeder virtuellen Umgebung und zu jeder Zeit visualisieren, erleben und mit ihnen interagieren können. In diesem Beitrag wird eine Sammlung von Fallstudien zur datengesteuerten 3D-Geovisualisierung vorgestellt, die in einem immersiven virtuellen GIScience-Datenvisualisierungsraum (IVEVA) implementiert wurden. IVEVA wurde gezielt entworfen und entwickelt, um die Unterschiede in der Art der räumlichen Daten, die Herausforderungen, die mit der Visualisierung räumlicher Daten in einer immersiven virtuellen Umgebung verbunden sind, und die Bedeutung der Einhaltung der etablierten Design-Heuristiken der Kartographie, der Mensch-Computer-Interaktion und der Entwicklung der erweiterten Realität (XR) hervorzuheben. Im Rahmen dieses Prozesses stellen wir unsere Beobachtungen darüber vor, wie gut jeder Datentyp für dieses Medium der Visualisierung und Interpretation geeignet ist und wie sich die Design-Heuristiken auf eine immersive virtuelle Umgebung auswirken, die den praktikablen Raum erweitert, in dem GIScience und visuelle Analysen durchgeführt werden. Abschließend geben wir einen

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Ausblick auf die Zukunft der immersive, oberflächenbasierte Geoinformationswissenschaften, die sich aus der Konzeption und Entwicklung dieses Prototyps ergibt.

1 Introduction

The potential of extended reality (XR) technology is becoming increasingly visible across a range of geographic information science (GIScience) domains. These technologies allow users to experience, interact with, and immerse themselves within geospatial data in a multitude of new ways, providing the opportunity for alternative perspectives from which to perform scientific inquiry. The value proposition for the future of XR and GIScience resonates deeply with the founding vision for GIScience; where the "S" signifies *science* and the field itself is legitimized and motivated by scientific questions, is a toolbox that supports scientific practice, and is a domain with an established scientific research agenda that addresses the relationship between GIScience and technology (Goodchild 1992). In its infancy, it was noted that geographic information systems (GISs) were at times driven by technology that was searching for an application. Today, where the cutting edge in GIScience is no longer defined by primitive 386-based personal computers with limited processing power, but by locationally and positionally aware handheld and wearable mobile computers and cloud computing, the relationship between the future of GIScience and XR technology is unclear. Will XR drive the future of GIScience? Could XR fundamentally change GIScience practice and our relationship and understanding of geographic space? As was the case in 1992, technology again appears to be driving current advances. Critical relationships between technology and spatial data collection, analysis, and display must be discussed and demonstrated to illuminate both the potential and implications of XR GIScience.

The proliferation of complex three-dimensional (3D) data sets within modern GIScience requires interfaces that preserve the native dimensionality of spatial data, allowing GIScientists and other stakeholders to visualize, experience, query, and interact with morphological and topological representations that are inherently 3D in analytical visualization environments that can support 3D analyses in space and through time (4D). While conventional GISs do include 3D functionality, the 2D displays and graphical UI metaphors used to overcome the limits of 2D displays add cognitive overhead and prohibit natural physical interactions. As we navigate the transition into increasingly 3D data and displays (and commensurate transducers), it is vital that we address the persistent challenges that plague geovisualization: from the interdisciplinary challenges facing geovisualization and its relationship with other domains, to the human factor challenges driving cognitive processing and knowledge transfer, and the contextual challenges that must be overcome to develop geovisualizations that match users and use (Çöltekin et al. 2017).

The primary objective of this paper is to explore some of these issues, presenting and discussing the development of an immersive virtual reality (VR)-based virtual environment (VE) prototype designed as a multifunctional environment for geospatial visual analytics (VA) and interpretation of (3D) spatial data sets. This work is informed by design heuristics from cartography, human–computer interaction (HCI), and XR. This multidisciplinary design and development approach accounts for the unique design challenges associated with the VE, the user interface (UI), the user experience (UX), and the representation of geospatial data in VR. While the relationship between XR and GIScience is not new, the democratization of the enabling technologies has presented new opportunities for widespread adoption beyond specialized research laboratories and could represent a new normal for VA and spatial data science. However, without a practicable set of guidelines from which to base visualization design, inconsistencies between applications and the use/user relationship may hinder the extraction of knowledge from such applications. Here, we use five case studies—glass sponge morphometry, human movement, urban development, resource management, and flood risk governance—to highlight how different geospatial phenomena, different data types, scales, and resolutions, and different objectives and analyses demand different design considerations. From these, we discuss a set of design guidelines to support the development of immersive VR-based analytical VEs.

In the following section, we provide a brief introduction to geovisualization, XR, and design heuristics from cartography, HCI, and XR development. In "Design and Development of IVEVA" we outline the development of *IVEVA*, a prototype for an immersive VR-based VE for geospatial VA, focusing on the design of the virtual space, the UI and UX, and the presentation of geospatial data within immersive VEs. In "Discussion" we discuss the affordances and limitations of IVEVA, discuss its use in an applied context, and discuss the design heuristics for VR-based VA design. We conclude with some thoughts on the future role of XR in GIScience and the power of XR technology to advance GIScience.

2 Background

2.1 Geovisualization and Visual Analytics

Geographic visualization, or geovisualization, integrates the approaches from multiple disciplines, cartographic and otherwise, "to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data" (MacEachren and Kraak 2001). Geovisualization, much like scientific visualization, relies on technology to facilitate the development of visualizations that support cognitive processes and knowledge formation (MacEachren and Kraak 1997). For some time, a community of spatial information visualization researchers have been increasingly exploring the capabilities and potential of immersive and interactive technologies for geographic characterization, interpretation, and communication. This has produced evolving perspectives on these technologies as more than new ways to see, but perhaps new ways to experience; and because of this, new relationships with geographic space mediated by data and interfaces have emerged. A good example of these expert groups, evolving perspectives, and theorizations of emerging interface technologies are the commissions established by the International Cartographic Association (ICA).

Launched in 1995, the Commission on Visualization strived to understand the expanding role of maps (particularly dynamic maps) as decision support tools, and to facilitate the exchange of visualization concepts between disciplines (MacEachren and Kraak 1997). In 1999, the commission extended its focus to include VEs, as maps were no longer restricted to static, 2D mediums and new challenges emerged for spatial data representation, visualization-computation integration, interfaces, and cognition and usability (MacEachren and Kraak 2001). By 2007, the ICA pivoted to establish the Commission on Geovisualization, focusing on the use of interactive maps supporting visual analyses of complex, voluminous, and heterogenous data across space and time (Dykes et al. 2010). Finally, in 2015 the ICA formed the Commission on Visual Analytics to address the challenges presented by massive spatio-temporal data sets and to encourage the advancement of visual analytics— "the science of analytical reasoning supported by interactive visual interfaces" (Thomas and Cook 2005)—in cartography (International Cartographic Association 2015). Over time, the ICA has shifted its focus to adapt to changes introduced by technology, data, and the use and users of geospatial data products. The democratization of XR technologies and the emergence of unconventional workflows, such as those using game engines, has enabled new opportunities for explorative visual analyses and has created a new set of challenges for VA.

2.2 XR Technology

XR has recently gained traction as a moniker encapsulating all VR, augmented reality (AR), and mixed reality (MR) technologies and experiences. We have, rather reluctantly, adopted 'extended' as the definition for "X" in this manuscript, while others suggest that "X" (or perhaps "x") is simply an undefined variable that could stand for virtual, augmented, or mixed, or that "X" signifies 'cross' reality. Regardless of what "X" represents, XR summarizes a range of emerging technologies under one umbrella. While this may be convenient, there are unequivocal differences between the constituent technologies, how they are used, what they allow users to see, and how they allow them to see it. We reluctantly accepted *extended* rather than *undefined variable* or *cross* as the definition for "X," not because of preference, but because we question the need to amalgamate VR, AR, and MR at the risk of suggesting they are one and the same. There is little doubt that XR technologies are inextricably linked, and there is no harm in referring to them en masse, so long as we recognize, understand, and account for the differences in "X" when designing VA applications.

Conceptualization and differentiation of a range of interface technologies that connect real and virtual worlds have existed for several decades. One that continues to inform developers of VR, AR, and MR (despite the noise created by XR popularity) is the *virtuality continuum* (Milgram and Kishino 1994) introduced as a taxonomy for the growing collection of display devices that are now commonly referred to as XR. The continuum extends from entirely real (reality) to entirely virtual (VR), with everything in between the two identified as MR. MR displays combine both virtual and real content, the proportions of which characterized MR displays as being either AR (reality augmented with virtual content) or augmented virtuality (AV) (virtuality augmented with real content). While the continuum considers AR a form of MR, modern discourse views both AR and MR as displays that augment reality with virtual content; where AR simply places virtual content in reality and MR combines virtual content with reality, thereby enabling meaningful interactions between the real and virtual content (Hedley 2017; Çöltekin et al. 2020b). The capacity for XR technologies to connect users, data, and space is transforming how we visualize, interact with, and comprehend geospatial data, both within GIScience and beyond.

2.3 XR in VA

The objective of VA is to combine the powers of human and computer data processing, utilizing visualizations and interactive visual interfaces to establish new approaches tackling the complex spatial problems facing modern society (Gennady Andrienko et al. 2011; Thomas and Cook 2005). In the simplest sense, XR technologies play into the strengths of visualization, providing additional methods of data visualization and new opportunities for users to detect patterns and anomalies within the data (Çöltekin et al. 2020a). At a higher level, XR technologies provide unmatched levels of immersion, presence, and interaction, the benefits of which to human perceptual and cognitive abilities may yet fully be realized.

User studies represent a significant and important piece of the XR research conducted by the geospatial community. The various ICA commissions have regularly identified the major research challenges and set research agendas based on the state of the discipline (see Maceachren and Kraak 1997; Andrienko et al. 2007; Virrantaus et al. 2009). Most recently, Çöltekin et al. (2017) applied a top-down and bottom-up approach to identify the challenges plaguing the discipline and identified interdisciplinarity, human factors, and use/user design challenges that have persisted through time. While these are challenges faced by the discipline in general, they are highly relevant to XR technology and the applied research that has been conducted using XR interfaces. This includes research on the use of tangible AR interfaces for face-to-face collaboration (Billinghurst et al. 2002), the impact that AR, proprioception, and sensorimotor function have on spatial knowledge transfer (Shelton and Hedley 2004), the relationship between spatial presence and mental model formation (Coxon et al. 2016), the perceived spatial relationship between users and spatial AR environments (Schmidt et al. 2016), and the effect that mobile AR has on students' geographic learning (Turan et al. 2018) to name just a few.

While XR technologies come with their own hardware- and software-related research challenges and priorities (Çöltekin et al. 2020b)—which must be addressed by the greater XR community and which will arise with each technological advancement—the geospatial community has continually explored the use of XR technology to address specific geospatial problems. Recent applications include the use of VR to visualize and assess geohazards (Havenith et al. 2019), to evaluate the importance of landmarks in mental map formation (Bruns and Chamberlain 2019), to assess the effectiveness of VR in topographic survey training (Levin et al. 2020), and as a tool for geographic education (Lisichenko 2015; Minocha et al. 2018; Jong et al. 2020). Concurrently, AR has also been used in an educational context (Wang et al. 2017; Turan et al. 2018; Al Shuaili et al. 2020; George et al. 2020; Adedokun-Shittu et al. 2020); however, the ability of AR/MR interfaces to connect data and real-world spaces has resulted in several situated, mobile applications. These include: landscape orientation (Carbonell Carrera and Bermejo Asensio 2016), flood risk analyses (Rydvanskiy and Hedley 2020, 2021) and precipitation simulation (Lonergan and Hedley 2014), building damage and safety assessment (Imottesjo and Kain 2018; Liu et al. 2020), emergency egress analyses (Lochhead and Hedley 2018), teaching cultural heritage (Panou et al. 2018; Han et al. 2019; Romano and Hedley 2021), and GIS-enabled smart city applications (Yagol et al. 2018). Despite the proliferation of geospatial XR research, there is a lack of theoretical work focused on *how* and *why* geospatial XR content is designed a certain way.

2.4 Design Heuristics

The multifaceted nature of geovisualization has generated numerous approaches, methods, capabilities, and insights into geovisualization design, as geovisualization itself draws from the scientific visualization, cartography, image analysis, information visualization, exploratory data analysis, and GIS communities (MacEachren and Kraak 2001). While the goal of any geovisualization is to empower the user(s) with the ability to generate new knowledge through exploration, analysis, synthesis, and communication, the formation of knowledge is mediated by the combined characteristics of the user(s), the interface(s), the data, and the use of the geovisualization as it was designed (Fig. 1). Therefore, the design process is critically important and must account for these variable differences, identifying the objectives (e.g., perceptual, cognitive, and interactive) of the geovisualization and adopting established design heuristics—guidelines for the evaluation and design of systems—from cartography and geovisualization, HCI, and XR development that support the defined objectives and maximize the opportunity for knowledge formation through geovisualization use.

Geovisual analysis has always involved technology, the evolution of which has resulted in shifting capabilities and communities of practice. Geovisualization itself emerged as cartography transitioned into the digital era and static maps—designed to communicate specific bits of information—were replaced by dynamic, interactive maps designed to support exploration, analysis, and decision making (MacEachren and Kraak 1997). Despite this significant shift in the presentation and consumption of geospatial data, basic cartographic principles remain an integral part of geovisualization design. This includes the use of basic map elements (e.g., legend, source information, scale, direction, and coordinate system) to help the user understand the nature of the data presented to them, and Bertin's graphic variables (shape, size, value, texture, color, orientation, and position) (Bertin 2011) which inform decisions on graphical representation of geospatial data and which have been adopted as the basic tenets of graphical representation across disciplines (e.g., information visualization) (Çöltekin et al. 2020a). The digital era also ushered in the need for additional dynamic variables (e.g., duration, order, rate of change, and motion), essential to the visualization of spatio-temporal data (Dibiase et al. 1992; Hedley et al. 1999; Carpendale 2003), as well as those specific to 3D displays and VEs (e.g., perspective height, camera position and orientation) (Slocum 2009; Rautenbach et al. 2015). While geovisualizations are more than maps, incorporating emerging technologies and data visualization approaches to address geospatial challenges,

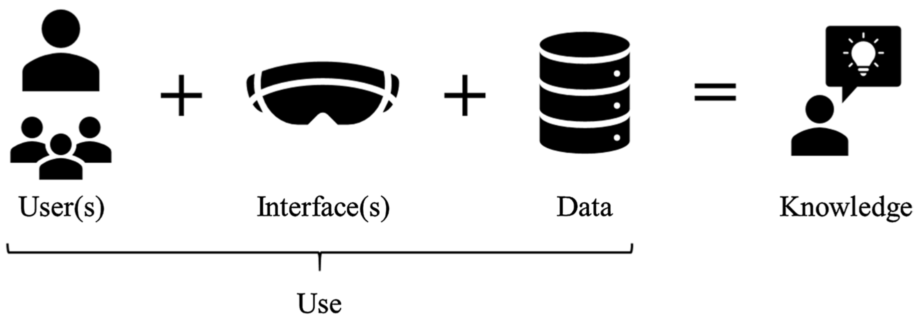

Fig. 1 The objective of any geovisualization is to generate new knowledge through geovisualization use. However, new knowledge is not simply a product of use, but hinges on the combined characteristics of the user(s), the interface(s), and the data. The challenge is to design geovisualizations which optimally combine the affordances and limitations of the user(s), interface(s), and data in a manner that leads to new knowledge

the cartographic principles on which maps are designed are essential to effective geovisualization using modern technology.

An effective geovisualization is one that harnesses the power of human perceptual systems while allowing for seamless interaction between people (users) and computers as users pursue new knowledge through geovisualization use. HCI research strives to improve these interactions so that they are user-friendly and adapt to the needs of the user (Kerren et al. 2007). As the user plays a pivotal role in this relationship, a user-centred design (UCD) approach should be adopted to place an early emphasis on the needs of the user, to iteratively address changes to their needs throughout the design process, and to develop useful interfaces (Nielsen 1993; Roth et al. 2015). Defining the target user is therefore critical to the design and development of a functional prototype from which usability can be evaluated prior to full-scale implementation. Prototypes should be designed following established design heuristics, such as the nine basic usability principles presented by Nielsen and Molich (1990). These usability heuristics, which can be utilized by designers and evaluators when a user study is not feasible (Endsley et al. 2017), state that UIs should use simple and natural dialog, speak the user's language, minimize the user's memory load, be consistent, provide feedback, provide clearly marked exits, provide shortcuts, provide good error messages, and prevent errors. While these design heuristics are the most well known, they are often considered to be too general; therefore, it is common to find adaptations that meet the demands of specific applications and domains (Vi et al. 2019).

XR technology has recently entered an era of democratization, whereby increased corporate funding, research, and technological advancement have driven down costs and increased access and availability. This has stimulated an increase in academic, professional, and personal applications, thereby exposing a growing number of novice users to XR interfaces. While Nielsen and Molich's (1990) usability principles do, to some degree, provide a foundation for XR design and development, these heuristics were established while personal computers underwent their own period of democratization, and do not account for the unique design considerations of XR technology. Several heuristics list have been devised to focus on specific applications of AR, VR, and HMD-based technologies (e.g., Dünser et al. 2007; Endsley et al. 2017; Vi et al. 2019; Tuli and Mantri 2020), addressing considerations such as physical ability, physical effort, user environment, alignment of real and virtual worlds, building upon real-world knowledge, and hardware capabilities. While these lists address the basic tenets of Molich and Nielsen (1990)—system should be easy to learn and remember, effective, and pleasant to use—and focus on the user, they also must account for the fact that the system is no longer restricted to the confines of the 2D display, but can encircle the user in both physical and virtual space. As each piece of XR technology and software come with their own idiosyncrasies, a combination of the basic HCI design principles with those specific to the technology, application and domain becomes essential to effective XR-based geovisualization design and development. In the following section, we discuss our workflow in the design and development of IVEVA, incorporating design heuristics from multiple sources to create a VR-based interface for VA.

3 Design and Development of IVEVA

The IVEVA prototype was designed and developed as an immersive VE that extends the space of everyday GIScience practice to include virtual space, creating a VA experience with alternative perspectives, methods of interaction, and tools for scientific inquiry. IVEVA was developed for the Oculus Quest (www.oculus.com) using Unity (version 2019.2.13f1), a game engine which has gained popularity across academia and industry as a 3D visualization tool. The Oculus Quest is a standalone VR system, comprising an HMD and two controllers, offering positional tracking with six degrees-of-freedom through internal sensors and cameras. In the following subsections, we analyze the design and development of IVEVA.

3.1 Designing the UX

As a prototype for an immersive VA tool, IVEVA showcases the power of standalone VR to extend the space of GIScience practice, offering what could be for many users a novel approach to geospatial data visualization and analysis. UX (user experience) design is therefore critical and emphasis should be placed on creating a positive HCI experience that satisfies more than just the instrumental needs of the user, acknowledging the human–computer relationship as a subjective, situated, complex, and dynamic encounter that is a product of the user's internal state, the system, and the context in which it is used (Hassenzahl and Tractinsky 2006). During the development of IVEVA, the UX design process focused not only on the absence of errors, but on creating a pleasurable experience for a specific group of users to explore specific geospatial data in a VE intentionally designed to extend their analytical space and capabilities. The UX design process, while it could not incorporate real-world users, was methodically and iteratively conducted according to the author's own experiences and perspectives, drawing on insight provided by users and user groups from past and present visualization research. While usability and user needs were central to the UX process, it was equally important to create an experience that would be enjoyable and efficient, thereby allowing the user(s) to focus on creating new knowledge.

Traditional UX design principles concentrate on technology and applications utilizing 2D displays and do not properly address the idiosyncrasies of 3D spatial environments and interactions (Vi et al. 2019). These very issues resonate deeply with the challenges faced by mainstream GIS, to reconcile methods and cultures of practice of planar cartography and spatial analysis, with well-established 3D data acquisition, and now emerging 3D interface platforms. While some design heuristics may be universal in principle—such as using cues to attract the user's attention—in practice, when 2D displays are replaced by 3D VEs, they are not.

In the design and development of IVEVA, UX design principles from multiple sources (including Dünser et al. 2008; Endsley et al. 2017; Vi et al. 2019; Tuli and Mantri 2020) were incorporated in the design of a usable and enjoyable UX. This includes the ability to customize the space to match user's needs and preferences (i.e., reposition objects, activate and deactivate objects, change surface textures, and adjust light levels), to attract the user's attention through visual and spatialized audio cues, to make menus available when and where they are needed, to interact with objects at a distance, and to explore the data through trial and error without fear of making irreversible mistakes. Ensuring user comfort and enjoyment also entailed efforts to reduce or prevent motion sickness by avoiding disparity between what users feel and what they expect to feel (Vi et al. 2019). This included reducing point and polygon counts and baking scene lighting to avoid latency issues, and not introducing user movement not initiated by the user.

3.2 Designing a Virtual Space for Multifunctional Geovisual Analysis

The virtual space within IVEVA comprises two adjoining rooms—a larger primary room and a smaller secondary room—in which different yet related spatial data sets can be presented to the user (Fig. 2). The primary room contains a rectangular data table, on which smaller-scale 3D spatial data are presented, and the secondary room is an empty space with a recessed floor, within which larger scale 3D spatial data related to those in the primary space can be rendered. The virtual space was designed and developed within Unity using ProBuilder, a 3D modeling and design package that was imported into the Unity project.

The virtual space is a simple, empty canvas in which 3D data, tools, and supporting information are presented to the user. The space was designed to be customizable, allowing the user to adjust the color of the walls and floor, change the light level, close the blinds, alter the height of the data table, and reposition supporting documentation (Fig. 3). These features were designed to promote user comfort through customization, to minimize distraction and not overwhelm the user with unnecessary visual clutter, to be familiar and harness real-world knowledge (e.g., the light panel is in a familiar position near the door), and to be efficient by allowing the user to access supporting documentation when and where it is needed (Endsley et al. 2017; Vi et al. 2019). While the customizability of the virtual space is currently limited to the developed feature set, it was designed to highlight how the user can'tune' the virtual space to match their everyday workspace, establishing congruence between the virtual and real space of GIScience practice, and could be tailored to the specifications of the user as required. The virtual space also features an isolation dome (Fig. 4) that can be activated to encapsulate the data, thereby removing all peripheral visuals to allow the user to focus on the data.

3.3 Designing the UI

Upon entering the virtual space, users are presented with a tooltips menu that outlines the functionality of each of the

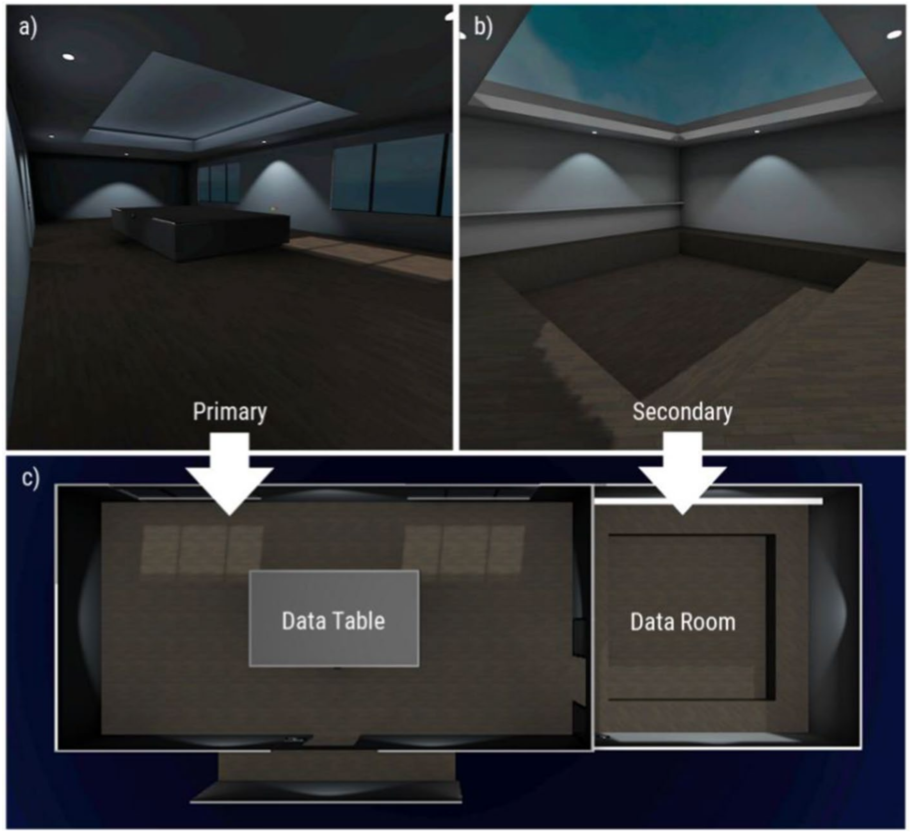

Fig. 2 The virtual space was designed for two distinct spaces of analysis: **a** a primary space—built around a central data table—for smaller-scale data sets, and **b** a secondary space, or data room, designed for larger-scale data sets, simulations, and hands on analyses. **c** Users can easily move between the primary and secondary spaces

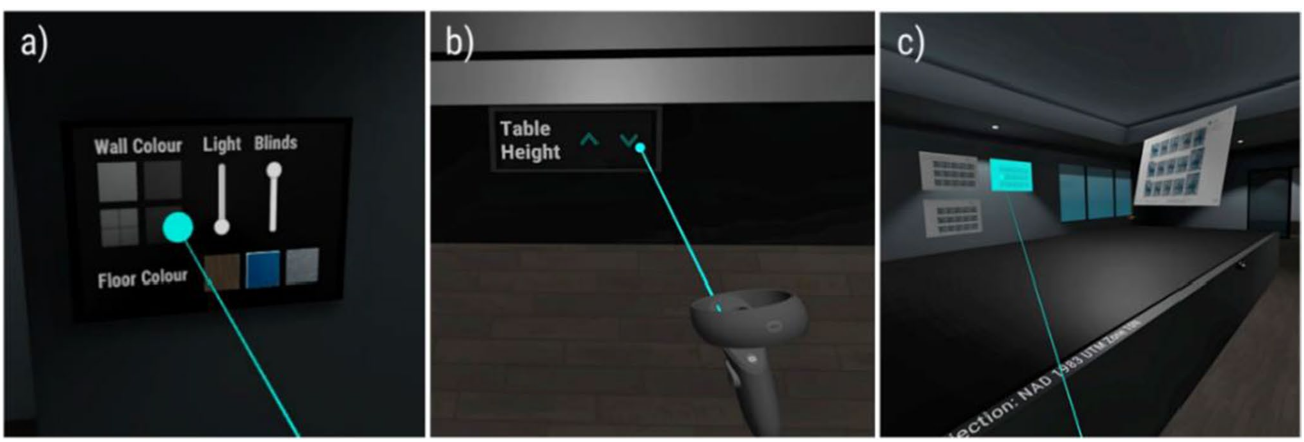

Fig. 3 IVEVA was designed to allow users to customize the virtual space. The wall/floor color and light levels (**a**), data table height (**b**), and position of supporting information (**c**) can all be adjusted to suite the user

controller's buttons (Fig. 5). This menu is attached to the controllers and can be activated/deactivated, allowing the user to quickly recall or hide the menu as required. This relieves the user of the cognitive overhead necessary to remember the action performed by each button, but provides the support necessary for them to learn how to perform those actions. In addition to the tooltips menu, users can activate/deactivate a data menu and a tools menu, both of which are attached to the left-hand (LH) controller.

The data menu is the primary UI in IVEVA (Fig. 6). This menu appears slightly above the LH controller and allows the user to select which case study is active and which data are displayed. The UI automatically updates as the user selects each case study, thereby ensuring that the UI always

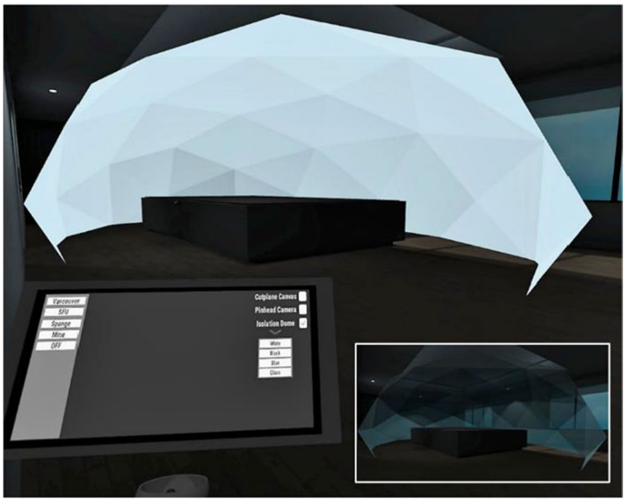

Fig. 4 The isolation dome is designed to eliminate peripheral virtual content from the user's view, allowing them to focus their attention on the data. The color and transparency of the dome can be changed to allow the user to control the contrast between the 3D data and the dome itself (inset)

matches the active case study and that it is not cluttered with additional irrelevant options. Furthermore, the UI also automatically updates as the user moves between the primary and secondary data space, providing only that functionality which is relevant to their current position in the VE. The data products of the tools in the 'tools menu' are also presented to the user on the data menu. The tools menu is the secondary UI in IVEVA (Fig. 7). It is a three-sided UI that is attached to and surrounds the LH controller, allowing the user to select from and operate a suite of tools relevant to each case study. As with the data menu, the tools menu automatically updates as the user activates each case study.

A collection of spatial tools, beyond the tools within each case study (Fig. 8), are also available. These tools provide height and scale references and additional visual perspectives, and allow the user to perform simple queries. For example, a cut plane tool can be activated on the data table to create a cross-sectional view of the active data set—this cross section is displayed on the wall adjacent to the cut plane; a pinhead camera can be placed anywhere within the VE, providing an additional perspective from the camera's position—the perspective view is then displayed on external displays which can be positioned anywhere within the VE and a measurement tool can be activated to make distance measurements within each data set.

Interaction with the UI and other 3D content within the VE is provided through the Virtual Reality Toolkit (VRTK) (www.vrtk.io) and the Oculus Integration package for Unity. Users move throughout the scene by either physically walking or by teleporting using the solutions provided by these packages. Additional functionality, such as the ability to grab objects from a distance or spawn and place 3D objects within the scene, was programmed into IVEVA and draws upon the VRTK solutions. Our objective was to create a suite of tools and functionality that gives the user a sense of control that exceeds natural human ability yet feels natural and integral to immersive VA.

3.4 3D Data-Driven Case Studies

In this section, we describe the five case studies used within IVEVA. Rather than simply reporting on a single, idiosyncratic applied example, as is common in the literature, our aim was to demonstrate a variety of spatial phenomena represented by a range of data types as exemplars of typical and emerging GIScience, which constantly integrates data of

Fig. 5 A tooltips menu is presented to the user upon entering the virtual space. This menu can be activated/deactivated as required, providing a quick reference without constant visual distraction

Fig. 6 The data menu is the primary UI through which the user activates a scene and toggles spatial data sets on/off. Real-time data related to the spatial tools are also presented here

many forms. The following five case studies utilize a combination of traditional GIS workflows, 3D modeling, and game engine development to produce a collection of 3D assets and 3D visualizations. Digital elevation models (DEMs) were either downloaded from open access databases or were generated from LiDAR point clouds using ArcMap (10.7.1)—the resultant DEMs were converted to 3D assets using Maya 2019. The 3D point clouds in IVEVA were either produced from a collection of photographs using PhotoScan Professional (1.4.0) or were downloaded from open access databases. In either case, point cloud density was reduced within CloudCompare (2.10.1) and ASCII files were converted to OFF files with MeshLab (2016.12), which were then used to create 3D assets within Unity using Point Cloud Viewer—a free Unity asset from the Unity Asset Store. Other 3D assets were generated using a combination of Maya 2019, Blender (2.81a), and SketchUp. Further information about each case study is provided in the following subsections.

3.4.1 Case Study 1: Glass Sponge Morphometry

This case study presents an immersive visualization of 3D glass sponge morphology as an alternative to current practices using 2D photographs (mosaics) and videos, to be utilized by marine ecologists as a VA and communication tool. In this visualization the location of glass sponge bioherms within Howe Sound, BC are presented on the data table against the 3D topography and bathymetry for the region (Fig. 9)—obtained from the open data repositories of British Columbia, Canada, and the National Oceanic and Atmospheric Administration (NOAA)—and a 3D point cloud representing a glass sponge from that region is presented in the data room (Fig. 10).

Users can interact with the 3D map on the data table, selecting which data is presented to them and accessing more information about each glass sponge bioherm by highlighting it on the map. Additionally, the location of an underwater SfM survey is provided on the map; that survey corresponds to the 3D point cloud in the data room. By activating the SFM data, users are then able to interact with, manipulate, visually inspect, and query the 3D point cloud. A suite of tools was developed to allow the user to make measurements, visualize cross sections, observe source data, and even simulate data collection through a working model of the data capture rig. Our objective with this visualization was to create a VE in which marine ecologists can perform analyses of glass sponge data which has been collected over time, exploring, interacting with, and querying 3D data in 3D space.

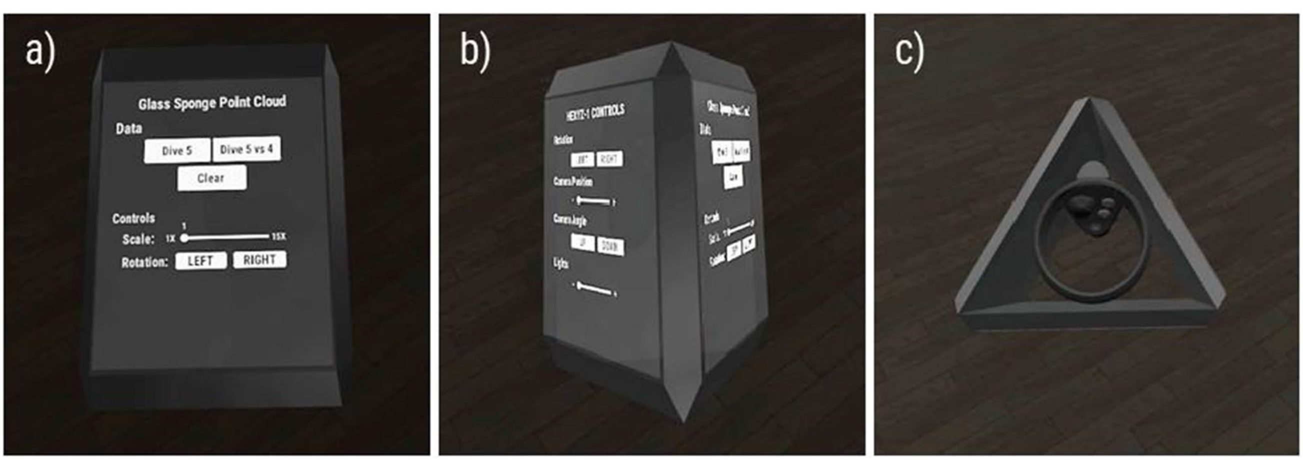

Fig. 7 The tools menu is a three-sided UI allowing the user to customize and control the tools within each case study. The menu is fixed to the left-hand controller and can be toggled on/off as required. **a** Front view, **b** perspective view, **c** top view

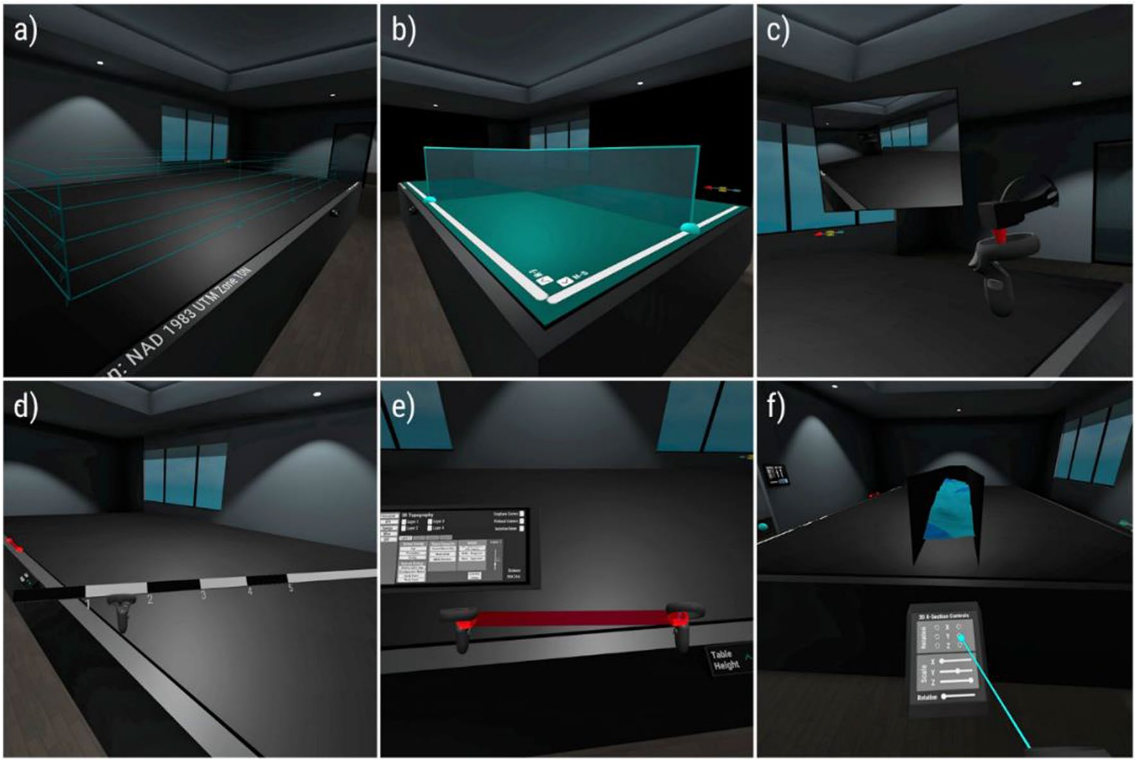

Fig. 8 A suite of spatial tools are available for spatial reference and inquiry. This includes **a** height reference grids, **b** cut planes, **c** pinhead cameras, **d** scale bars, **e** precise measurements, and **f** cross sections

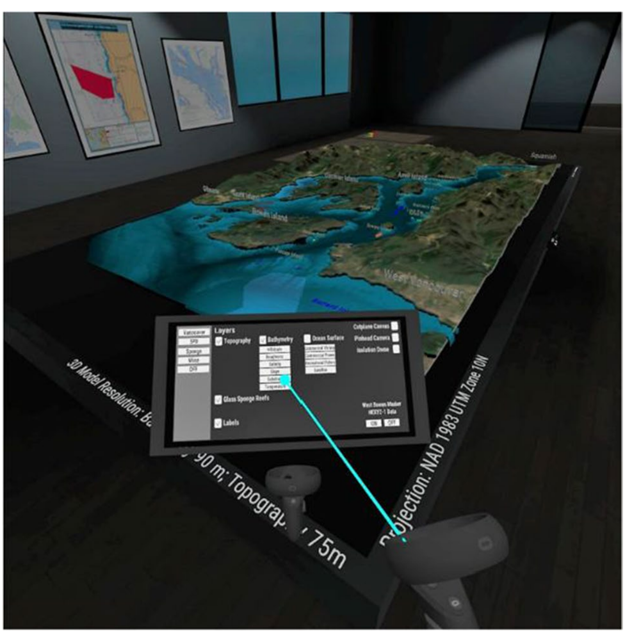

Fig. 9 An overview of the glass sponge bioherms within Howe Sound, BC is presented to the user on the data table in the primary data space

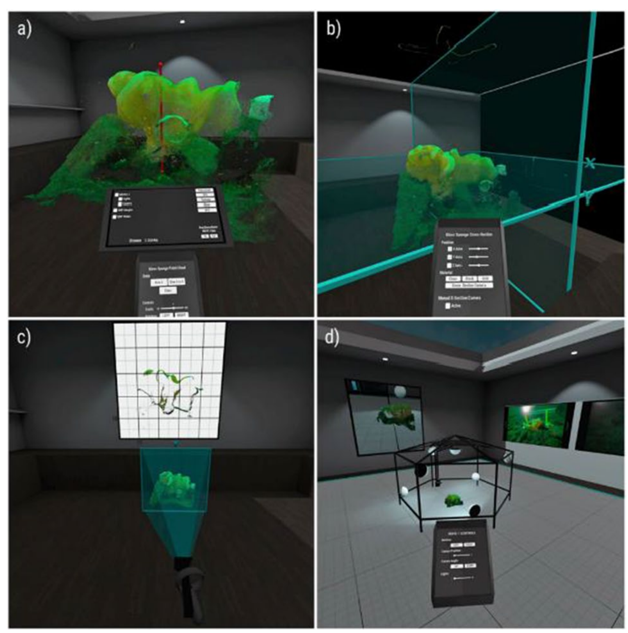

Fig. 10 A 3D glass sponge point cloud is presented to the user in the secondary data room. Users can scale and rotate the model, measure it (**a**), create cross sections (**b** and **c**), and simulate the data collection process (**d**)

3.4.2 Case Study 2: Human Movement in Built Environments

This case study presents VR as an authoring and visualization tool for human dynamics simulations—in this case, emergency egress and socially distanced movement in a built space. It was designed as a tool allowing emergency management and safety officers to simulate and explore human movement in built environments. This visualization contains a 3D point cloud representing Burnaby Mountain and Simon Fraser University (SFU) (Fig. 11) and a 3D model of the Academic Quadrangle in which human movement simulations can be created and observed (Fig. 12).

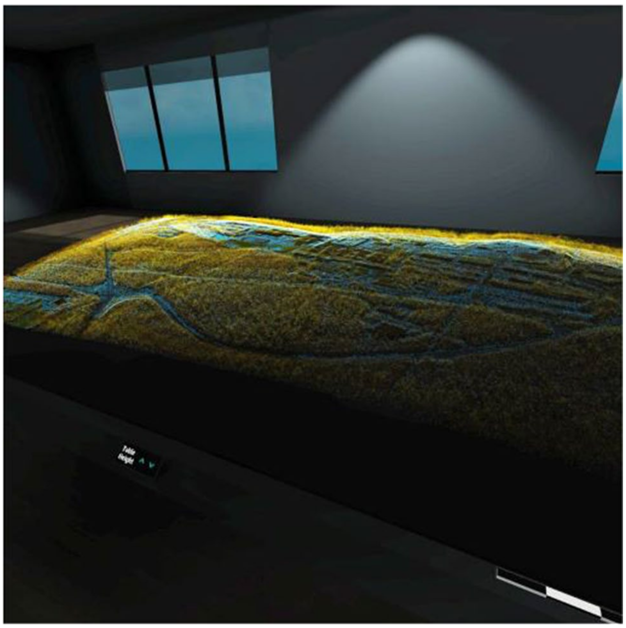

Fig. 11 A 3D point cloud for Burnaby Mountain and the SFU campus in the primary data space

The primary data space was designed to provide an overview of the campus and the restrictions that are placed on human movement by both the design of the campus and its location atop Burnaby Mountain. Users can create and observe simulations of human movement within SFU's Academic Quadrangle (AQ). The AQ can be populated with agents (people) of varying speeds that use Unity's NavMesh to navigate from the location at which they are placed to the target location defined by the user. The user can activate trail renderers to observe agent pathways, social distancing buffers to observe the impact that social distancing has on human movement in the AQ, gates to quantify the speed at which those agents move throughout the AQ, and obstacles to explore the impact that potential impedances would have on human movement. Our objective with this visualization was to create an immersive VA tool that can be used to both create and visualize human movement simulations in built environments.

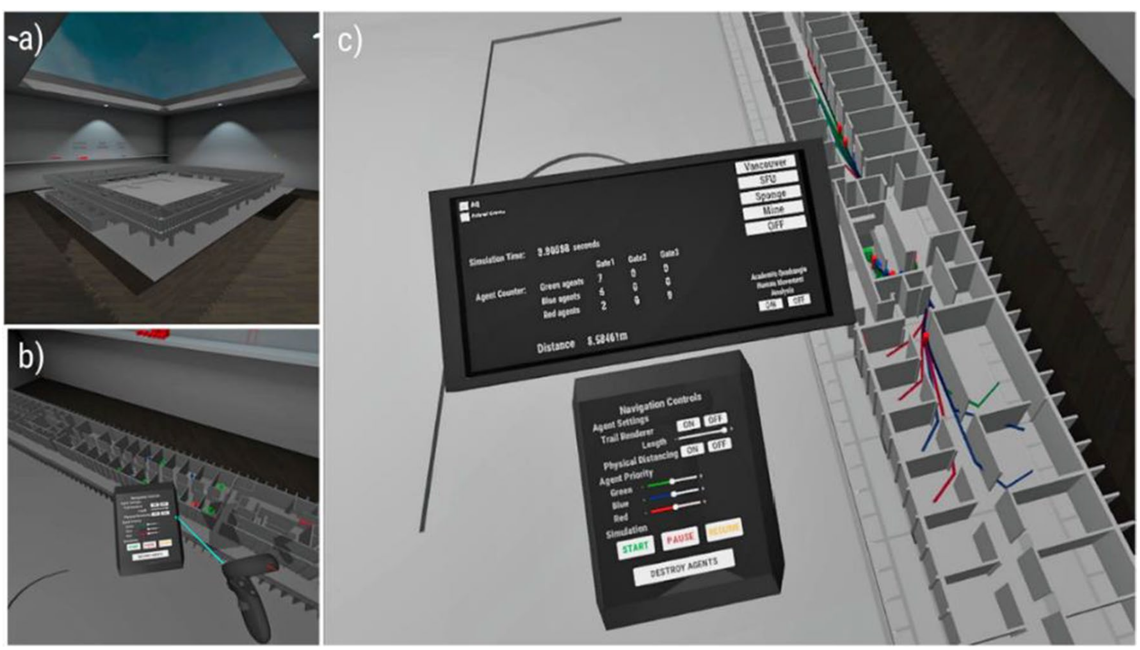

Fig. 12 **a** A 3D model of the Academic Quadrangle is presented in the data room. **b** Users can create simulations of human movement during an evacuation or the impact that social distancing has on the flow of people, and **c** analyze those simulations in real-time

3.4.3 Case Study 3: Urban Development

This urban environment case study was designed and developed to allow city officials and community stakeholders to both explore and visualize urban development in Vancouver, BC and the shadows that that development would cast on the surrounding community. This visualization employs 3D point clouds, to characterize existing buildings and vegetation, and a 3D model of the topography textured with an aerial image (Fig. 13)—all acquired from the City of Vancouver Open Data Portal.

This visualization was designed to utilize the primary data space only, rendering the 3D assets on the data table. Users can select which 3D point clouds are visible, whether the DEM is visible, and can add 3D cubes (buildings) of different heights to perform shadow analyses. The shadow analysis allows the users to activate a virtual sun, set the sun height according to season, and cycle the sun from sunrise to sunset (Fig. 14). Shadows are updated in real time so that users can see how each of these changes impacts the size and position of the resultant shadow on the community.

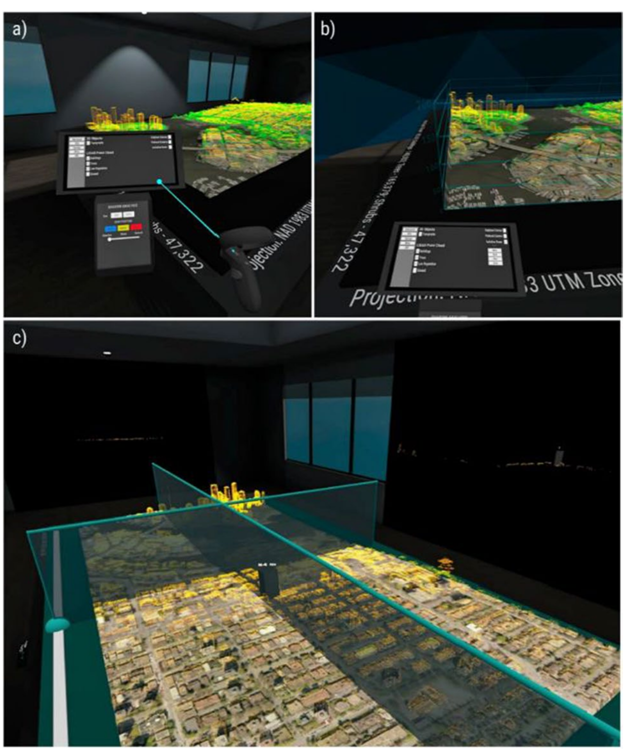

Fig. 13 This visualization allows stakeholders to visualize urban development and the shadows that would be cast on the surrounding community. **a** Users can select which data are visible, **b** they can activate reference grids to visualize relative building height, and **c** can perform cut plane analyses to visualize future skylines

3.4.4 Case Study 4: Resource Management

The resource management visualization was designed to highlight the potential for immersive VEs as a VA and communication tool to be used in the analysis of GIS-based spatial data layers. This visualization combines multiple data layers—obtained from the British Columbia Open Data Catalogue—and allows users to adjust the position and transparency of those layers to explore the relationships between the presented data (Fig. 15).

This visualization was designed only for the primary data space, presenting data on the data table. Users can combine data layers—for surface and bedrock geology, natural resources (e.g., forests, watersheds, and rivers), and wildlife—to explore and visualize the relationships between the data and the surrounding landscape. The user can control the height and transparency of each layer, make measurements, and examine cross sections in any size and direction. Our objective with this visualization was to showcase an immersive VE that may help to reveal new information by providing new experiences and perspectives.

3.4.5 Case Study 5: Flood Risk Governance

This case study discusses the design and development of an immersive VE for city officials and community stakeholders to explore climate futures and flood risk. This visualization combines topography, LiDAR point clouds, and climate change storm surge data produced by JBA Risk Management—a firm specializing in flood risk modeling—to enable visual analyses of the potential impacts that flooding events could have on the environment and infrastructure (Fig. 16).

Fig. 14 A virtual sun, controlled by the user, casts real-time shadows on the surrounding topography. Users can analyze the impact that urban development would have on available sunlight

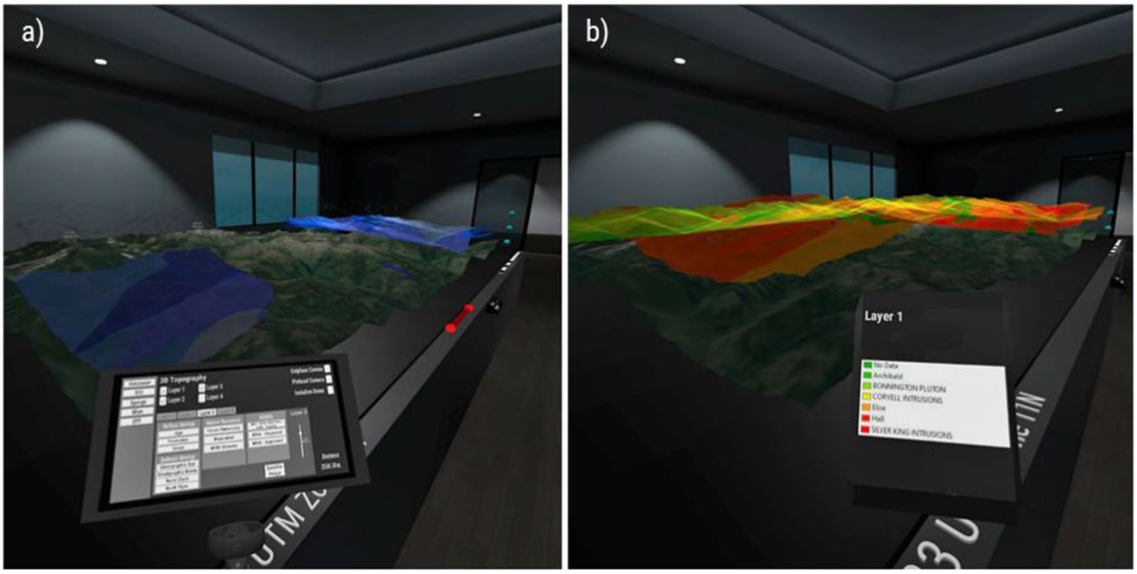

Fig. 15 This visualization combines multiple spatial data layers in a GIS-like interface. **a** Multiple data layers can be activated at one time using the data menu, and **b** users can analyse that data and its relationship with the surrounding environment

This visualization was designed for both the primary and secondary rooms, allowing users to visualize and explore climate scenarios against 3D models on the data table, and compare multiple climate scenarios against each other in the data room (Fig. 17). In both cases, users can examine individual flood risk scenarios or they can observe animated GIFs that cycle through those scenarios. The objective with this visualization was to allow the user to observe the real impact that climate futures would have on the environment and infrastructure by combining modeling data with 3D topography and LiDAR point clouds and integrating interactivity that allows the user to experience the data.

3.5 Design Considerations

The iterative design process began with careful consideration of the spatial phenomena that would be presented in IVEVA, the user(s) of IVEVA, and how and what they may use IVEVA for. By first developing this contextual foundation, we were able to gather and process the spatial data and 3D assets necessary for the development of a VE suitable for VA. IVEVA was designed around the users and the data, with use and user at the forefront of the design process. IVEVA and the tools within it were constructed to not only allow the user to see data from a new perspective, but to allow them to interact with and explore the available data in their quest for knowledge.

Testing served an important role throughout the design process, as multiple configurations of each data variable,

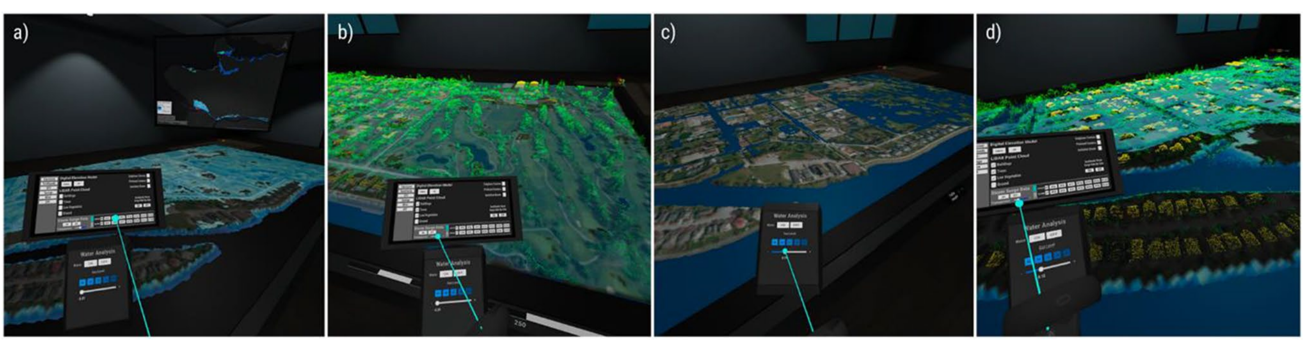

Fig. 16 Flood risk analyses can be performed in the VE by analysing **a** different climate futures, **b** the impact on existing infrastructure, **c** sea level rise scenarios, and **d** the impact on local communities

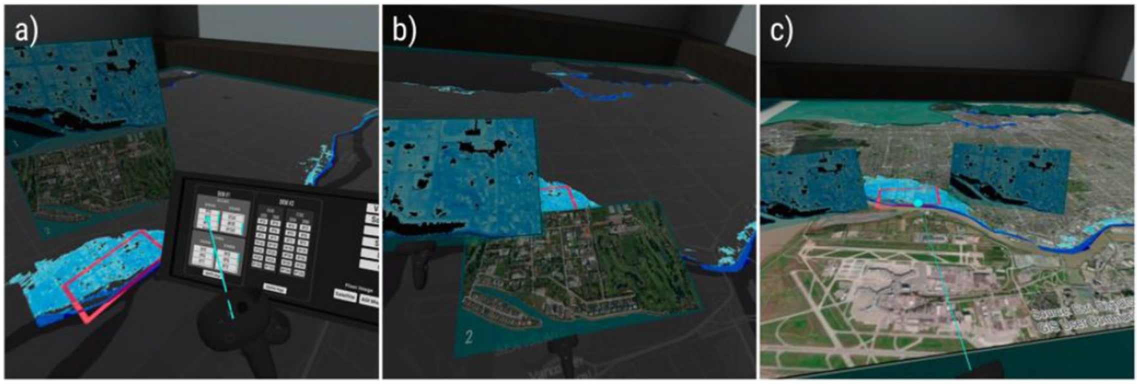

Fig. 17 The data room allows users to compare multiple flood risk scenarios by **a** defining which data appear on which display, **b** adjusting the position of those displays to suite their needs, and **c** comparing the area of interest to other portions of the city

tool, UI, and interaction method were assessed to achieve the design configuration and customization options necessary to promote usability and usefulness. The IVEVA prototype offers a window into the future of visualization and VA, where a diverse group of users can be immersed in, interact with, and explore 3D spatial data in an analytical VE using accessible modern technology that transforms the relationship between users and spatial data.

4 Discussion

IVEVA was developed to highlight the potential for immersive VEs as VA tools and to emphasize the value of a multidisciplinary approach to the design and development process. While geovisualizations are not conventional maps, much can be gained from the principles of cartography; while XR devices are not traditional computers, there are many HCI principles that can be applied to VR; and, while VR does not epitomize XR, VR design can benefit from the lessons learned in the design and development of other XR interfaces. As a VA application, IVEVA draws on the knowledge, experiences, and design heuristics from multiple disciplines to support the development of a VE, spatial data, UI, and UX that promotes knowledge building.

VR-based 3D VEs are popular for their ability to provide realistic experiences that immerse the user in the VE and can promote a sense of presence, or the feeling that they are situated in the VE rather than in the real world (Edler et al. 2019; Keil et al. 2021; Hruby et al. 2019). Often, immersion and presence are exploited to transport users to virtual copies (digital twins) of real-world environments, allowing them to explore 1:1 representations of those environments for a variety of reasons (for example: simulations, route planning, and training). However, these digital twins are not the only useful application for VR, and IVEVA highlights how VR can be utilized to expand the space for data analysis rather than to replicate the space being analyzed. While the nuance may be subtle, exploring 3D data in an immersive space is quite different than exploring 3D data spaces.

IVEVA strives to provide a UX that extends the human capacity to perform analytical reasoning through visual representations of spatial data. VA emerged out of the demand for tools and techniques that assist people with the synthesis of information, the quest for insight, the detection and discovery of patterns and relationships, and the assessment and communication of data for effective action (Thomas and Cook 2005). As the objective of VA is to facilitate human–information discourse using tools that provide innovative interaction techniques and visual representations, the characteristics of the tools and their ability to drive knowledge formation by connecting people and data is critically important. The tool (VR), in and of itself, is just a tool. The usefulness of that tool is determined by its ability to connect people and data in a manner that promotes analytical reasoning and new knowledge.

From a design perspective, IVEVA incorporates cartographic principles for the visualization of spatial data in a 3D living map, liberating the visualization and analytical space of GIScience from the 2D confines of traditional displays, while maintaining the conventions and familiarity of spatial data representation. IVEVA was designed for the user: to provide a compelling data experience that empowers them in their exploration and analysis of spatial data; that is easy to learn, comfortable in use, and does not overwhelm; and to use metaphors and real-world knowledge to provide intuitive functionality. The VE itself is simple, designed as a space for data analysis rather than a space to be analyzed. The VE is customizable, allowing the user to rearrange data elements to suite their physical and cognitive needs, to change the visual characteristics of the space to fit their preferences, and to isolate themselves from the space to focus solely on the data.

The case studies presented in IVEVA were intentionally selected as exemplars of different spatial phenomena and spatial data types with different VA objectives. While VR offers a unique opportunity to immerse users within VEs and spatial data, neither the interface nor the act of immersion guarantees the transfer of knowledge. The interface must be designed to account for the differences in spatial phenomena, how they are characterized, how they can be represented in a VE, and how they are perceived and understood. For IVEVA, this involved careful consideration of the context of each case study and the data type, extent, resolution, texture, colour, transparency, emissivity, occlusion, physics, and the interplay of these variables within and between disparate data sets. Each decision is highly dependent on the relationships between the data, interface, user, and use; therefore, each decision should allow for the contextual variability that defines the *ideal* combination of these variables for effective sense making. The data presented in the IVEVA case studies were intentionally selected to help the user paint a picture, to help them explore and understand the data in the context that it is presented to them. As much as possible, the user should be given agency to make their own decisions concerning what, when, and how those data are presented.

The IVEVA prototype showcases VR as a platform for immersive 3D VA and implements design heuristics from cartography, HCI, and XR development in the design and development process. IVEVA extends both the space in which GIScience can be performed and the ways in which users can visualize, explore, and interact with spatial data. Therefore, the relationship between the user, the interface, and the data is critical to the UX and the knowledge building process. The UX for XR design heuristics published by Vi et al. (2019) provided an excellent foundation for the design and development of IVEVA; these heuristics helped to:

- Maximize efficiency through the organization of the spatial environment—the virtual space is simple and does not contain superfluous content that distracts the user away from the data. The virtual space is divided into two complementary rooms, each serving a different function but both offering a convenient and comfortable data experience.
- Ensure flexible interactions and environments—the virtual space can be customized to match the user's personal preferences: the wall color, floor material, and light levels in the virtual space can be modified and the position of supplementary data and analytical tools can be rearranged for convenience.
- Design for user comfort—the personal space of the user is respected by not overwhelming them with content in their immediate field of view. The user can adjust the height of the data table so that the data environment matches their physical preferences and visualization and interaction do not require physical strain.
- Focus on simplicity: do not overwhelm the user—the virtual space is clean and simple, and the UI is intuitive and automatically updates to match the data and environment. Users do not have to search for the tools or menus, and both can be hidden to avoid cluttering the user's view.
- Design according to the hardware capabilities and limitations—IVEVA was designed specifically for the Oculus Quest and does not overwhelm the hardware with excessive files sizes, complex processing, or unnatural or complicated commands.
- Guide users throughout the experience using cues—the user's attention is directed toward features of interest using spatialized sound and visual cues.
- Provide a compelling XR experience—supplementary visual elements and audio were included to enhance the experience and to make the user feel comfortable in a virtual space designed to extend their everyday analytical space.
- Leverage real-world knowledge—the design of the virtual space and the presentation of spatial data were intended to be familiar. The virtual space represents a generic office space; control panels were placed near doorways as a light switch would be placed in the real world; and map marginalia are provided for reference.
- Offer users feedback and consistency—the user's interactions are accompanied by visual or audible feedback that informs them if an action can, cannot, or has been performed.
- Place the user in control of the experience—the user is in control of the experience and the data, allowing them to explore, experiment, and analyze the data as they want.
- Promote unencumbered trial and error—any action performed by the user on the data can be reversed or reset, allowing the user to explore IVEVA without worry.

.While the IVEVA prototype was designed to promote human-information discourse there are limitations to IVEVA which hinder this exchange. First, the spatial data presented in IVEVA required significant time and effort to convert from its raw form into one appropriate for Unity. This process reduces the user's ability to quickly import, visualize, and analyze spatial data in applications such as IVEVA; however, the emergence of plugins such as the ArcGIS Maps SDK, bridging the gap between their GIS software and Unity, should improve this process. Second, IVEVA was developed for a single user, while analytical reasoning is a process that can involve several different people separated by space and time. This limitation can be overcome through packages such as Photon Unity Networking (PUN), allowing multiple users to collaborate in the same VE.

Further development of IVEVA should adopt a user-centered design approach that directly incorporates the user in the design cycle IVEVA was designed and developed with the perspective of specific stakeholders (marine ecologists, emergency management personnel, city planners, government officials, community members, and GIScientists) in mind, but without the ability to actively incorporate them in the design cycle. As a VA prototype, designed through heuristic evaluation based on the intuition and knowledge of the developers (Nielsen and Molich 1990), IVEVA sets the foundation for further design and development with invested stakeholders. Undoubtedly, this would include multiple individuals from diverse backgrounds; therefore, future versions of IVEVA should be developed as a collaborative VA interface, allowing concurrent occupation of the VE by multiple VR users.

5 Conclusion

This paper introduced IVEVA, an immersive virtual GIScience data visualization space, and a set of 3D data-driven geovisualization case studies. IVEVA is a VR interface, and while it was designed for VR, design heuristics from cartography, HCI, and XR development played an integral role. However, in adopting design heuristics from disparate fields, careful consideration must be given to the implications that different use, user, data, and technology combinations have on those heuristics in an applied context. For example, a given material, spatial resolution, interaction method, visual cue, or feedback mechanism that is appropriate for one application, spatial phenomena, or data type may not be appropriate for another. These design challenges can be diminished through a proactive and iterative user-centered design and heuristic evaluation process that incorporates, tests, and modifies interface features and functionality to ensure useful, usable, and enjoyable XR interfaces for 3D GIScience and VA.

Emerging XR technologies have the potential to transform the relationship between people and data. As we incorporate these technologies into the social, professional, and academic realms it is important that XR interfaces account for the variability in use, user, data, and technology. In this paper we presented a design and development approach that integrates multiple design heuristics to address the multifaceted challenges associated with creating this immersive VA space. The UX and data were crafted specifically for VR. While our design and development decisions may prove useful for other XR interfaces, they were selected to optimize human–computer–data interaction in VR and promote knowledge formation through immersive visual analyses. Therefore, the design of VR interfaces for immersive VA should adopt the basic tenets of cartography and HCI, as those are the fundamental building blocks for spatial data visualization using any piece of technology. However, emerging XR interfaces are different from one another and from conventional 2D interfaces, requiring unique heuristic design considerations broadly following those outlined by Vi et al. (2019).

The presented case studies are exemplars for different spatial phenomena and spatial data types presented in VR. Each case study has an overlying objective, and the characterization of the spatial phenomena and the data is driven by the context of that objective. Therefore, it is difficult to say that one data type is better suited for VR than the other without first considering its purpose in the analytical process. While the basic vector and raster files that typify conventional GIS may be extremely useful in VR under certain contexts, VR can provide much more than shapefiles in an immersive 3D VE. For example, an ongoing critique of conventional GIS has been an impeded ability to display topologically 3D data, whereas VR allows the user to transcend the physical limitations of the real world, to figuratively step into the computer to inhabit the data space, to interact with the data, to experiment with the data, and to experience the data in 3D, which is not possible with conventional 2D interfaces. Therefore, it is not so much the data in and of itself, but the collection of and context in which the data is presented, the spatial tools that are provided to allow users to manipulate and query that data, and the user–data relationship mediated by emerging XR technologies that will drive the future of GIScience and VA. We hope that IVEVA and the presented case studies stimulate further dialogue and collaboration with members of this research community.

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Availability of Data and Material Not applicable.

Code Availability Not applicable.

Declarations

Conflict of Interest There are none to declare.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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