Towards Designing Immersive Geovisualisations: Literature Review and Recommendations for Future Research

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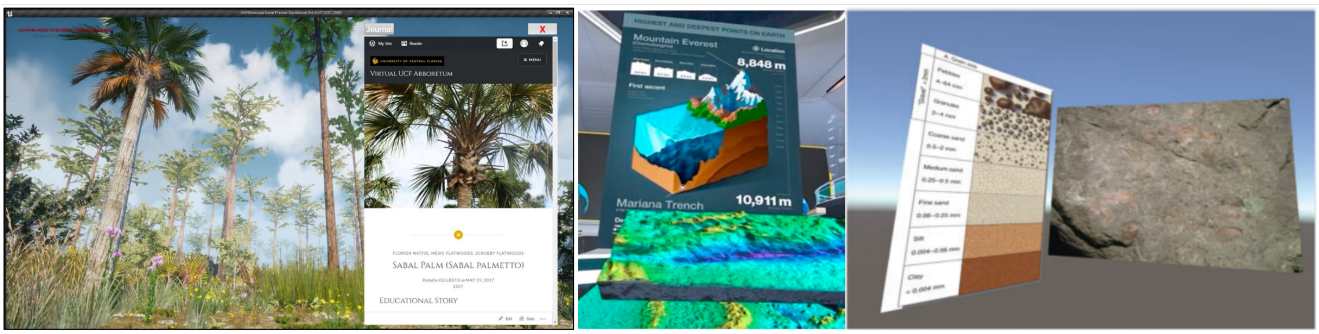

Figure 1: Information Displays: Textual - (Left) Harrington et al. [33] show a pop-up information display resulting from selecting a plant from their Virtual Arboretum (licensed under CC BY 4.0; used with permission); (Middle) Wang et al. [76] show a detailed information board on the Mariana Trench, the focus of their visualisation (cropped; used with permission); (Right) Klippel et al. [44] show an excerpt from a textbook detailing information on grain size for assistance during a guided Virtual Field Trip (used with permission).

ABSTRACT

Geological fieldwork forms an integral part of science discovery, exploration, and learning in many geoscientific domains. Yet, there are barriers that can hinder its practice. To address this, prior research has investigated immersive geovisualisations, however, there is no consensus on the types of interaction tools and techniques that should be used. We have conducted a literature review of 31 papers and present the visualisation environments, interaction tools and techniques, and evaluation methods from this last decade. We found a lack of established taxonomy for visualisation environments; an absence of thorough reports on interaction tools and techniques; and a lack of use of relevant human-computer interaction (HCI) theories and user-centered approaches. This review contributes towards the development of a design framework as we propose a basic taxonomy; demonstrate the need for holistic records of user interactions; and highlight the need for HCI evaluation methods. Addressing these gaps will facilitate future innovation in the emerging field of immersive geovisualisations.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Mixed / augmented reality**; **Scientific visualization**; **Interaction techniques**; *HCI design and evaluation methods*; *Visualization design and evaluation methods*; • **General and reference** → **Surveys and overviews**.

KEYWORDS

geovisualisation, virtual environments, virtual field trips

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1 INTRODUCTION

A new set of realities are emerging in the world of data visualisation - virtual reality (VR), augmented reality (AR), and mixed reality (MR) bring the possibility of novel experiences and interactions with data [24]. The first, and most obvious, advantage of immersive visualisation is that it can display multi-dimensional data in three-dimensional space; thereby creating a more digestible visualisation. A second advantage is the ability to visualise data in a virtual environment that contextualises it and connects it to the real world. Thirdly, immersive systems use natural interactions that afford an embodied experience of data exploration and add to the *sense of being there* [72]. A fourth advantage is the capacity for a multi-sensory experience such as audio, visual, or haptic cues that contribute to the plausibility of the illusion [71] and thereby engage the user [41]. Finally, immersive systems can create collaborative experiences by bringing together distributed or co-located teams in a synchronous or asynchronous manner. These experiences can closely approximate reality by providing a more socially-engaging experience than traditional video-conferencing [59].

With the rise in development of immersive technologies, and therefore the commercial availability of hardware and software, the use of immersive visualisations is becoming more accessible for research and education. The field of immersive analytics [24] has emerged specifically to explore interaction techniques that support research. Applications of immersive visualisations have been explored in many fields such as the life & health sciences [18, 66] and the design of built environments [13]. Geoscience, however, has not yet been thoroughly explored although we argue that it is an ideal use-case for immersive visualisation. Many types of geoscientific data are either spatial or temporal in nature [70]. Geoscientific data can be visualised within a virtual, photorealistic version of a geosite (e.g., [61]) that users can then visit and re-visit as they please. Greater degrees of immersion can be achieved by adding sensory inputs that are congruent with real fieldwork environments such as the sounds of rain or birds. Finally, collaboration is an important aspect of sense-making and learning in geological fieldwork [42, 56]. These are some of the factors that make immersive visualisations a plausible counterpart to real-life field experience.

The promotion of VR as a solution to geovisualisation techniques has already been investigated [70, 78] and in fact, research dates back at least to 1998 [48]. Though despite the passage of time, research with a focus on interaction patterns and design frameworks for use with immersive geovisualisation remains nonexistent. Therefore, there is a limited understanding of which tools support learning and sense-making and which might hinder them (e.g., cybersickness, occlusion). It is unknown whether the development of a framework has not yet been attempted, or whether there is not enough research to support one. For this reason, we have conducted a scoping literature review to help gain an understanding of the current state of research of immersive systems for geoscience, and subsequently to identify any gaps in research. In particular, we aimed to examine the interaction tools that have been designed for use with geoscientific data and visualisations in research and education; and to discern what research has been conducted with these interaction tools. To this end, we have formulated the following research questions:

- What interaction tools and techniques have been developed for immersive systems in geoscience?
- What is the current state of interaction-tool evaluation methods for immersive systems in geoscience?

For our literature search, we used our university library, Scopus, and ACM databases and found 25 peer-reviewed journal articles and six conference papers for a total of 31 papers. These first two databases were chosen due to the availability of cross-disciplinary research, allowing us to conduct searches in both geoscience and computer science journals. ACM was chosen due to its publications focused on innovations in computing.

We found that in the last decade, multiple studies explored whether *immersive* Virtual Field Trips (iVFTs) could be used to support learning outcomes in field geology instruction (e.g., [43, 44]). These featured some novel ideas on how students can interact with virtual geosites such as instructional guidance, and virtual measurement tools. We found that other prior studies focused on the development and implementation of 3D visualisation models and software (e.g., [3, 4, 76]), the user-acceptance of immersive technologies (e.g., [29, 64]), learning effects (e.g., [14, 40]), or user task-performance compared across immersive visualisation environments (e.g., [23, 79]). Very little research was conducted with a focus on the tools that were designed to interact with the data. These studies did not often provide relevant human-computer interaction (HCI) theories to support their choices. Some of the prior research that focused on the user-experience and usability of data visualisations (e.g., [21, 26]) was conducted by experts in geoscience and did not report the use of HCI approaches such as interviews and contextual inquiries with other target users. Overall, the prior research worked towards identifying whether immersive geovisualisations 1) are feasible, 2) are desirable, or 3) improved existing workflows. These findings help to lay the groundwork, however current research seems to lack clear definitions of how to design immersive visualisations for geoscientists. In order to establish frameworks that can guide future developers, holistic reports of interaction tools and techniques, as well as HCI research methods, are needed.

Overall, this paper contributes to the HCI field by providing a state-of-the-art overview of immersive geovisualisations and the interaction tools used to explore them. By drawing attention to the gaps in HCI approaches, we hope to encourage the research of immersive systems for the geosciences, as well as contribute to our own future research in this field. We conclude that a greater understanding how geoscientists learn, explore data, and interact with one another will help designers and developers build an effective framework for interaction.

2 BACKGROUND

2.1 Geoscience Research and Education as Use-Cases

Fieldwork is an integral part of learning in geoscience and typically a starting point for data collection for research [51]. The field is where physical samples are collected, but also where context is provided by the surrounding terrain [56]. From afar, remote-sensing technologies acquire data that inform researchers where to conduct fieldwork [60]. After fieldwork, this data can also be used in Geographic Information Systems (GIS) for the visualisation and mapping of geospatial environments [19, 73]. When geoscientists leave the fieldwork site, they might find that it is too difficult to return due to the following barriers [10, 20, 31, 57, 68]:

- **High Cost**: Expensive and large equipment, large teams, extended stays, and long-distance travel.
- **Geographical Inaccessibility**: Travel to a geosite can be too dangerous, or logistically impossible (e.g., Jezero Crater on Mars).
- **Inherently Destructive**: Fieldwork is a destructive method of data collection which leaves a site forever altered.

- **High Physical Demand**: Hiking with heavy equipment over rough terrain for long distances, digging and carving through dirt and rock, then storing or replacing any dug out terrain.
- **Political Dangers**: Fieldwork sites may be located in politically tense locations, increasing the risk of danger.
- **Cultural Sensitivities**: Fieldwork may require additional permissions and/or extra caution from the geoscientists when excavating a site.
- **Time Constraints**: All of the above constraints can contribute to resulting time constraints and a stressful environment.
- **Low Funding**: Funding towards fieldwork is only decreasing in the face of the problems described above.

These barriers have led to demands for more effective fieldwork. New information communication technologies (ICT) have been developed to facilitate field data collection and logging [77]; and faster and more effective software for data acquisition and 3D modeling [5, 46, 74]. These barriers are also present in geoscience education and limit the amount of field experience that students are exposed to [68]. Fieldwork is an experience that geoscience instructors value highly [16, 25] as it provides embodied and situated context to students [56]. It is also a unique chance for practical skills to be used and developed. During the Covid-19 pandemic, many instructors were forced to cancel field experiences and instead turned to virtual experiences [7, 12, 32]. Campus-based fieldwork [62] and Virtual Field Trips/Tours/Guides (VFT/Gs) are educational tools that allow users to investigate real-world geosites using a collection of data including Digital Outcrop Models (DOMs; high-resolution visualisations of geological outcrops), videos, photographs, and GIS data [10, 16, 68]. However, the former lacks authenticity where the latter lacks immersion. Some researchers agree that they have limitations [16, 22, 49].

If funding is approved and field trips are organised, researchers and students still face two more unique challenges. They must recollect and contextualise their fieldwork findings by relying on their memory, photographs, GPS data (such as Google Earth), and others who were present [56]. The second challenge is to make sense of spatial and temporal data through the constraint of 2D desktop visualisations. In geoscience education, these two challenges can be inhibitors to comprehension and learning [69]. In research applications, 3D visualisation environments for desktop environments are still in development and under investigation for their effectiveness [28]. On the other hand, immersive systems are a potential medium for solving these two challenges simultaneously. Prior research has been conducted towards the development of immersive geovisualisations and reviews of this research exist [70]. However, up until now, these reviews have focused broadly on comparing and discussing the developed immersive geovisualisations. This scoping literature review instead focuses on the developed interaction tools and techniques, and how those tools were evaluated.

2.2 Interaction Tools and Techniques

Buschel et al. [8] have outlined an initial set of interaction tasks from state-of-the-art literature on immersive analytics. These tasks include selecting objects, filtering objects, sorting data, navigating physically through the environment, re-configuring attributes and variables, and labelling and annotating. Selection tasks are those that target objects for further interaction such as displays of information, filtering, and sorting. This is fulfilled in immersive systems by natural gestures (e.g., pointing), ray-casting (visualised by a laser-pointer), eye-gaze, vocal input, and more. Filter tasks are used to filter out objects depending on the type of visualised data. Filtering could be used to hide or highlight data points. Sorting tasks allow users to organise data according to some attribute. Navigation of a virtual space refers to how one physically moves around the data visualisation. There are multiple types of locomotion, especially for VR, including walking, flying, teleportation, and world-pulling. Reconfiguration refers to the reassignment of attributes and variables to allow users to change the visualisation directly. Labelling and annotating are tasks that allow users to keep track of their thoughts for later presentation, sharing, reporting, or discussion.

These interactions allow users to interface with the data visualisation and complete their objectives [70]. In addition, the geoscientific domain, and the visualisation environment, will provide the context around the interaction tasks used in prior research (see Fig. 2). For example, the choice of visualisation environment may influence whether it is suited for VR, AR or Cave Automated Virtual Environments (CAVE), which in turn influences the software, hardware, and physical tools that are available [8, 52]. The interaction tools may be further influenced by the availability of existing software (e.g., libraries of gestures available for the HoloLens). Therefore, to present the state-of-the-art interaction tools and techniques, we need this contextual information.

2.3 Visualisation Environments for Geosciences

In Marriott et al. [52], the authors present a design framework for immersive analytics in which they define five questions: Where-What-Who-Why-How. For the purpose of this scoping literature review, we provide the findings for the *where* question for each of the reviewed papers. The *where* question tackles the presentation method, the available interactions, the degree of world knowledge, and the physical environment; the presentation method depends on the presentation device (e.g., head-mounted display, smartphones, tangible interfaces); the interaction component depends on the interaction modalities of the system; world knowledge reflects how much of the physical world is used by the system; finally, the environment is the physical space in which the system is designed to run. The totality of these elements, as defined by the authors, equals the visualisation environment of the presentation method.

3 METHODS

First, a preliminary search was conducted using the university library database and Scopus to identify recognisable terms. From these, four search phrases were developed (see Appendix A) and used in the same two databases with the addition of the ACM digital library using the appropriate syntax changes. An initial search phrase focused solely on earth and planetary sciences. However, there are other geoscientific fields that make use of remote-sensing data for fieldwork. Therefore, the search was later expanded to

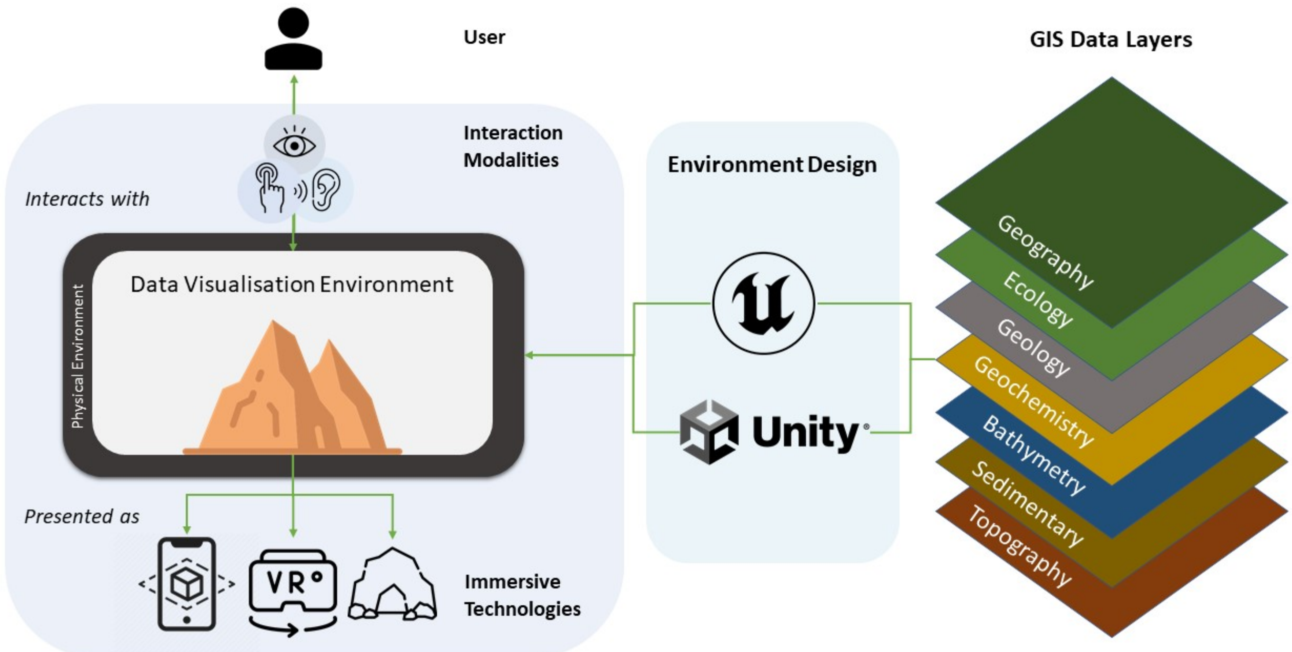

Figure 2: Interactions with Immersive Analytics in the geosciences, based on Wang et al. [76] (used with permission) and Marriott et al. [52]; This image has been designed using resources from Flaticon.com (Pixel perfect; Freepik; Goodware)

include archaeology, ecology, environmental sciences, natural hazards, and geography. Additionally, research that focused on geographical visualisations of human populations and urban environments were excluded. The same applied for research relating to mining. The interaction tasks associated with these visualisations were deemed to be too different from our target geoscientific research.

To begin with, papers were only included if the authors had conducted some research with participants and where immersive hardware (e.g., Head Mounted Displays) was used. However, this criterion was later made more flexible due to the low quantity of yielded results. The review now includes proof-of-concepts where the only evaluation was conducted by the authors. In addition, research with immersive systems was found as early as the 1990s. These earliest papers appeared to tackle broad technical challenges to overcome and recommendations for software and hardware development. Today, however, commercially-available software and hardware have shifted the types of challenges that are encountered. For this reason, papers written prior to 2010 were excluded which corresponds to the year that the first prototype of the Oculus Rift was developed. The final inclusion criteria are as follows:

- **conference paper or journal article (peer-reviewed & English language)**
- **visualisation or environment developed for immersive systems**
- **contains an evaluation of the visualisation**
- **designed for one of the specified geoscientific domains**
- **published after 2010**

Four search terms were used and can be seen in Appendix A. The criteria were checked by reading the keywords, abstracts, and backgrounds of the papers. The first search term returned 85 results, the second returned 88, the third 17, and the fourth 32. From these results, 80 unique abstracts were found, initially, to fit the criteria. From those papers, 22 (71%) papers were ultimately fitting for the final selection after reading through the methods. An additional nine papers (29%) were found via snowball sampling (seven out of nine) from the 22 selected papers and other review papers (two out of nine) that were found. This produced a final total of 31 papers from which the following data was extracted by the primary author:

- publication type (journal article or conference paper)
- visualisation environment (i.e., how the researchers chose to display their visualisations in 3D space)
- immersive hardware (e.g., HTC Vive)
- immersive software (e.g., Unity3D)
- geoscientific domain (e.g., natural hazards)
- domain expert input (prior to research)

And where applicable:

- methodology (e.g., comparative study)
- experimental design (e.g., between-subjects, within-subjects)
- number of participants

- scope of the study (e.g., duration, in-the-wild)
- interaction tools and techniques (e.g., type of locomotion)

The findings are detailed in the next section of this paper.

4 FINDINGS

4.1 Visualisation Environments for Geosciences

As the authors develop their data visualisation, they make a choice on what the virtual environment should look like. In order to define this decision, we chose to look for the visualisation environments defined or described in each of the papers. We identified three different broad terms for types of visualisation environments as defined by the authors of the reviewed literature. These terms were Virtual Environments, Scenes, and Virtual Terrains. *Virtual Environment* was a term used in 11 out of the 31 papers [21, 23, 26, 30, 34–38, 40, 64]; more specific versions included Collaborative Virtual Environments (CVEs) [21], Virtual Geographic Environments (VGEs) [26], Virtual Reality Environments [37, 40], Virtual Reality Geomodeling Environment [38], Interactive Virtual Reality Environments [35], and Geovisualisation Immersive Virtual Environment (GeoIVE) [36]. *Scenes* was the term used in four papers [3, 4, 14, 26]; more specific versions included 3D panoramic scenes [14], Surface Topography Scene [3], Bed Topography/Bathymetry Scene [3], and VR Flood Scene [26]. *Virtual Terrain* was the term used in four papers [29, 33, 67, 76]; other versions included 3D Terrains [29], and Virtual Reality Terrain Representation [67].

Aside from these three main terms, five of the papers with VFTs referred to their environments as immersive Virtual Field Trips (iVFTs) [43, 44, 55, 63], or Virtual Tours [53]. Of the remaining visualisation environments, these included Spatial Information Overlays [39], Virtual Worlds [50], Terrain Models [55], immersive 3D Geovisualisations [64], and Immersive Visualisation Environments [80]. Two papers did not use an overarching term for their visualisation environment [65, 79].

Overall, we found a variety of terms with varying degrees of specificity for which there were three main overarching terms: virtual environments, scenes, and virtual terrains. There are no distinguishing definitions between each of these terms in the reviewed literature.

4.2 Interaction Tools and Techniques

In the following sections, we describe the interaction tools and techniques used in the reviewed literature. They can all be found in Appendix B, Table 1.

They are grouped under the categories of *virtual field trips & tours*, *geo-spatial models*, *maps & globes*, and *augmented reality*. These categories were chosen after reading through the reviewed literature and assessing trends in the visualisation styles. Each category displays geological data but to different extents, for different purposes. *VFTs*, described earlier in this paper, typically take users through a guided experience of a geovisualisation for the purposes of education or tourism [16]. *Geo-spatial models* are used in this context to refer to any surface, terrain, or subsurface which contain elevation data, point-clouds, or other [1, 70]. Both of these visualisation styles can include Digital Elevation Models (DEMs; including Digital Surface Models, DSMs and Digital Terrain Models, DTMs) or Digital Outcrop Models (DOMs). However, in *VFTs*, the purpose of the visualisation is to teach specific learning outcomes, whereas *non-VFTs* are more open-ended and exploratory. This distinction therefore helps to delineate the separate types of interaction tools and techniques that each visualisation style might afford. The visualisations that did not fit into either of these categories were maps and globes. These are tools often used by geoscientists to gain an understanding of a geosite and its geological context, or even to plan fieldwork [17, 70]. They feature a flat or topographical (but none as high-resolution as DEMs) view of the Earth or other planet surfaces. Augmented reality visualisations are categorised separately; though we found similarities between AR and VR visualisations, the styles were expressly different and manifested most often as an overlay. These differences made it difficult to present AR and VR together without diluting what divides them. Therefore, we found it befitting to separate these categories to allow for more effective comparison between these two immersive technologies.

4.2.1 *Virtual Field Trips & Tours.*

These seven papers are displayed in a table with findings in Appendix B, Table 4.

In seven out of the 31 papers, authors created a Virtual Field Trip/Tour/Guide (VFT/G) for their geovisualisations [14, 33, 40, 43, 44, 55, 63]. These serve an instructional purpose for typically non-expert users. In the reviewed literature, there were three different types of VFT/G. The first and most common type (five out of seven) featured 360-degree photos that were stitched together to form a virtual environment [14, 40, 43, 44, 55]. One of these environments was made for Google Cardboard [40], one for so-called "Desktop VR" [14], one for both [55], and two were made for the HTC Vive [43, 44]. As a result, it is assumed that users can look around using their head in the Google Cardboard and HTC Vive cases, whereas select-and-drag is used in Desktop VR. Interaction is limited in Google Cardboard and Desktop VR, and as a result, these visualisations provided no user-locomotion nor any data-interaction capabilities. The environments that required the HTC Vive (both made by the same authors) indicated a desire to provide students with additional autonomy. To do this, they gave them the ability to teleport through the environment to pre-determined locations and additional interactions with a DOM in an isolated view. This included the ability to pan, rotate, and zoom in on/out of the DOM, distance-measurement tools, and a dashboard to record collected data. In the other visualisations, interactions included element-creation options [14] and geo-tagging [40].

The second type of VFT featured a computer-generated environment with open-exploration [33]. This environment worked with the HTC Vive and therefore also allowed freedom in locomotion by physically walking on a treadmill. The authors indicated that it was designed to support independent exploration. Both the first type and second type of VFT guided their users through displays of information. These included pop-ups such as information boards that appeared when highlighting certain objects [33, 55], quizzes [14, 40, 55], video tutorials [55], textbooks [43, 44], and instructions [55]. Some included additional audio information as guided instructions from a teaching assistant [43, 44], or environmental audio cues [33].

The third type of VFT featured an immersive 360-degree video with no interaction capabilities [63]. This was a fully on-rails experience for users. The authors were searching for the effects of immersion on learning and persuasion. This experience was brought to users with Samsung Gear VR, a smartphone-powered HMD.

4.2.2 Geo-Spatial Models. These 14 papers are displayed in a table with findings in Appendix B, Table 5.

In 14 out of the 31 papers, authors chose visualisations such as Digital Elevation Models (DEMs), Digital Terrain Models (DTMs), Digital Surface Models (DSMs), Orthomosaics, and/or Subsurface Models [3, 26, 30, 34–38, 50, 64, 65, 67, 76, 80]. Each of these methods of data presentation are useful to geologists for providing detailed height and depth information which can be measured with virtual interpretation tools. These models can visualise the bathymetry (the floor of a body of water) or topography (the actual land surface's forms and features) of the geological environments of interest, and are usually very high resolution [1, 70]. Four out of these 14 papers explained that they chose spatial, immersive visualisations in order to layer multiple types of complex datasets [35, 50, 67, 76]. The use of 3D space implies that the models themselves become more digestible and easy to comprehend. Three of the 14 used CAVE [34, 64, 65], whereas the rest used a kind of PC-Powered HMD (HTC Vive [26, 50, 67, 80], Oculus Rift [3, 30, 36–38], or unspecified [35, 76]).

In nine out of these 14 papers, the visualisations were presented *in-situ* with a generated environment around the model [3, 26, 30, 34, 36, 37, 50, 64, 65]. To navigate these environments, the developers employed a variety of styles of locomotion, but was in large part user-centric. Users could move themselves virtually by walking [3, 30], flying [3, 26, 30, 36, 50], jumping [50], or as a drone [3, 30]. Alternatively, some allowed users to teleport [26], either freely within the space [37], or to predetermined locations [50]. Locomotion in the CAVE environments also differed greatly; in one, users could tilt their controllers and move some joysticks [34]; in the second, users moved around as a rover [65]; and in the third, users were stationary relative to the display, which in turn could be manipulated [64]. To create these VR environments, one half used Unreal Engine [36, 37, 50] and the other used Unity3D [3, 26, 30]. One paper used OpenSceneGraph to create their CAVE [34], whereas the other two did not specify which tools or kits were used.

The remaining five papers chose to visualise their geomodels in their own 3D space [35, 38, 67, 76, 80]. Either this space was empty to focus on the data [35, 38, 80], or had a workplace-style environment [67, 76]. To create these environments, four of them used Unity3D, and one used VRED (Autodesk) [35]. In the visualisations with a lack of generated environment, locomotion is not as necessary; in one, users could walk (slow) or use joysticks (fast) [38]; in another users were stationary and instead the model is manipulated [80]; in the third, the authors did not describe a style of locomotion [35]. In one workplace-style environments, users could move a limited amount by physically walking [67], and it the other, users entered a free-flight mode [76]. Limited mobility can create a need to manipulate the visualisation by panning, rotating, and zooming [38, 76, 80]. Additional manipulation tools included deforming terrain (according to specific parameters) [38], displacing the model along a vertical axis [80], geo-tagging [67], and toggling the quantity of visible data [80]. One visualisation used sliders to translate a cross-section through the model, to adjust vertical exaggeration, and to adjust the quantity of visible data [67].

The physical controllers used in each of these *geo-spatial model* environments were quite similar, although how their use differed (e.g., mapping of buttons) was not described. Interaction tasks were also rarely reported, left only visible in figures and supplementary materials such as demo videos. However, one recurring interaction task was data-querying. Users could query the models to measure distances between points [3, 34, 50, 67, 80], heights of objects [50], area [80], volume [3, 80], slope angles [50], and/or latitude & longitude [76]. In some cases, users could record their findings by taking screenshots [3, 50], or by storing data in some manner [80]. In seven of the visualisations, users could switch between different view-points (and sometimes different locomotion) [3, 26, 30], variations of the visualisation [26, 34, 37, 67, 76, 80], or interaction modes [34, 76, 80]. On occasion, additional information was available to users during the immersive experience. This was provided through informational text on objects in the environment [34, 36, 37, 76] (e.g., information boards or pop-ups), audio cues [36] (e.g., guided narration), or through location-based information (e.g, GPS coordinates or cardinal direction with a compass) [34, 36, 50].

Only three papers seemed to have integrated collaboration functionalities through screen-sharing [38, 64] or remote collaboration [67, 76].

4.2.3 Maps & Globes. These three papers are displayed in a table with findings in Appendix B, Table 6.

In three papers of the 31 [21, 23, 79], the authors chose to visualise immersive versions of maps and globes. These are commonly used for geographical applications, but are still often used in geoscience for orientation, site-selection, or to get an impression of scale [1, 17, 70]. All three visualisations used the HTC Vive, and two of them used Unity3D to build their environment [21, 79], while the third used Vizard engine (software intended for researchers). Despite these similarities, the methods for locomotion varied. In the first, users must physically walk to navigate the environment [21]; in the second, users can grab-and-pull the world [79]; and in the third, users are stationary [23]. The first visualisation allowed for remote collaboration [21] and users could see each other's gaze direction by a virtual head mounted display shown on the avatars. The second visualisation allowed users to pan, rotate, and zoom [79]. For the third, no additional interaction tools or techniques were described or demonstrated.

4.2.4 Augmented Reality. These nine papers are displayed in a table with findings in Appendix B, Table 7.

Out of the 31 papers, nine visualisations were made for AR [4, 29, 33, 34, 39, 47, 53, 54, 75]. Of these nine, four were made for educational purposes to be used with a mobile device (i.e., phone or tablet) [33, 39, 53, 54]. All of them mapped data visualisations onto the real-world, like an overlay. Three presented data *in-situ*, where one overlaid a point-cloud onto a rock face [39], another overlaid a subsurface model onto a landscape [54], and a third overlaid geological layers, topographic models, and DTMs over a geosite [53]. The fourth visualisation instead projected a virtual woodland onto the floor of a museum, allowing visitors to interact with the rich virtual display [33]. Each of these visualisations had limited interactivity. In one, a slider could be used to adjust the quantity of visible data (sparse vs dense point cloud) [39], and in another users could switch between two viewing modes [33]. In two of the visualisations, users were provided with an information display to support learning, where one provided it with a text overlay [53] and the other with interactive audio [33]. One of the visualisations had no described interaction tools or techniques [54].

Of the remaining five AR visualisations, three of them also displayed data *in-situ* as an overlay onto the real world. Two of them did so using mobile devices [29, 47], whereas one used a multi-camera setup [75]. One of these provided a multitude of interaction options for expert users including to switch between viewing modes, create points of interest (geo-tagging), visualise a virtual terrain over actual terrain, and use measurement tools for calculating plane dip and strike [29]. They allowed users to adjust visual elements of the display such as opacity, and location was displayed in the form of coordinates. Users could save this information with a screenshot. In another visualisation, users could geo-tag a map with locations of boreholes, which then could be overlaid onto the real world [47]. Additional information displays are accessed when selecting one of these tags. All the information could then be stored in list or map format. One visualisation only allowed users to switch between different viewer modes [75]. Of the last two visualisations, one used the HoloLens to display a DEM of the Antarctic shelf [4]. These authors discussed that their choice to attempt immersive visualisation was for the purpose of layering multiple types of data, without making interpretation too complex. As a result, users could adjust the visibility of these displays, and the vertical exaggeration of the DEM. The final visualisation used a tangible interface to display the sea floor and artefacts scattered from a shipwreck [34]. Users could select artefacts to see an information display, use a ruler tool to measure distances between artefacts, and store artefacts.

Overall, we found that in the reviewed literature, geo-spatial models are the most common use of VR, AR, and CAVE. The most common educational application was the Virtual Field Trip over open-ended exploration. Throughout, we see a wide variety in the quantity of interaction tools offered to users. Not all of the researchers provided detailed accounts of the tools that were built into their systems, so it is unclear if some of these visualisations had more to offer or if they were truly bare-bones. A wide array of locomotion styles were used when the visualisations had some environment, and in the rest, users were mostly stationary and could manipulate the environment around them instead. Most of the AR applications were used to overlay data onto the physical world and the majority of them were to be used *in-situ*.

4.3 Visualisation Evaluation Methods

The same categories are used in this section as in the previous to allow for comparison.

Of the 31 papers retrieved in the literature search, 17 of them (55%) contained formal studies (i.e., comparative studies, case studies, or user studies) with participants (*min* = 5, *max* = 590, *Mdn* = 37) [14, 21, 23, 26, 29, 33, 34, 40, 43, 44, 55, 63, 64, 67, 75, 79]. Eight of the studies were conducted using PC-powered VR (*min* = 12, *max* = 228, *Mdn* = 44), two were done with smartphone-powered VR (*min* = 93, *max* = 102), six were done with AR (*min* = 5, *max* = 56, *Mdn* = 10), two with CAVE (*min* = 15, *max* = 42) and two with desktop VR demonstrators (*min* = 11, *max* = 590).

A total of 17 of the 31 papers (55%) included or consisted entirely of a proof-of-concept [3, 4, 30, 33–39, 47, 50, 53, 54, 65, 75, 76]. In these papers, the authors developed a geovisualisation in an immersive system with no formal user-testing conducted or described. Some informal user-tests may have been conducted by the authors. Two of these papers are the cause of the overlap and therefore contain both a proof-of-concept evaluation with one visualisation, and a formal user study with another [33, 34]. Nine of the papers (29%) contained descriptions of VR visualisations [3, 30, 35–39, 50, 76]. Six of the papers contained descriptions of AR visualisations (19%) [4, 33, 47, 53, 54, 75], and two contained CAVE visualisations out of the total three CAVE papers (6%) [34, 65].

4.3.1 Virtual Field Trips & Tours. These seven papers are displayed in a table with findings in Appendix B, Table 8.

Six of the seven VFTs were investigated through comparative studies on science learning (*min* = 37,*max* = 590, *Mdn* = 51) [14, 40, 43, 44, 55, 63]. One of these was conducted in a lab setting with a within-subjects design [40]. The rest were conducted *in-the-wild*, where two had a between-subjects design [43, 44] and one had a within-subjects design [55]. The remaining two had a mixture of within- and between-subjects design, using a pre- and post-test method [14, 63]. Participants spent a median of 67 minutes interacting with the visualisations (*min* = 20min, *max* = 120min). In one study, interactions were carried out over three separate intervals throughout a lecture setting [40]. In a different study, the participants spent approx. 3hr15min in a workshop that took place over a day, that revolved around their 20-min experience with the virtual environment [63]. In another study, the participants were tested for their retention ability 10 weeks after their instructional experience with the visualisation [55].

4.3.2 Geo-Spatial Models. These 14 papers are displayed in a table with findings in Appendix B, Table 9.

Of the 14 visualisations that used geo-spatial models, only four carried out formal studies. One of these was an *in-the-wild* user study of unspecified duration (*n* = 42) [64]. The remaining three papers conducted their studies in a controlled, lab setting. One conducted a user study of 60-120 minutes [67], one conducted a comparative study [26], and one conducted both [34] (*min* = 11, *max* = 60). Both comparative studies had a within-subjects design, in one of which users interacted with the visualisation for three minutes [26] and the other is unspecified [34]. The other was a user study [67]. Only one of these visualisations received input from domain experts prior to formal evaluation [34].

The remaining nine papers evaluated their visualisations using a proof-of-concept [3, 30, 35–38, 50, 65, 76].

4.3.3 Maps & Globes. These three visualisations are displayed in a table with findings in Appendix B, Table 10.

All three maps & globes visualisations were evaluated in a lab setting, where two were comparative studies and one was a user study (*min* = 30, *max* = 228) [21, 23, 79]. Of the two comparative studies, one had a between-subjects design where participants interacted with the visualisation for 15-20 minutes [23]. The other had a within-subjects design that lasted for an unspecified duration [79]. The user study also had an unspecified duration [21].

4.3.4 Augmented Reality. These seven visualisations are displayed in a table with findings in Appendix B, Table 11.

Three of the seven visualisations were evaluated with a formal, in-the-wild study (min = 5, max = 56, Mdn = 15) [29, 33, 75]. One of these was a case study in which participants (domain experts) spent 60 minutes with the visualisations during fieldwork [29]. Another visualisation was evaluated through a pilot user study for an unspecified duration [33]. The third was evaluated through a comparative study with an within-subjects design, for an unspecified duration [75]. Of the remaining four papers, all were evaluated using a proof-of-concept [4, 39, 47, 54].

Overall, we found an equal number of proof-of-concept evaluations of geovisualisations as those evaluated by formal study. The formal investigations were by a slight majority conducted mostly in-the-wild where they were integrated in students' and researchers' workflows.

5 DISCUSSION

This scoping literature review of interaction tools and techniques in immersive systems for geoscience is based on a sample of 31 papers found in a basic literature search of three databases: our university library, ACM, and Scopus. The review has provided novel insights into the current state of the use of immersive systems for geological sciences and education.

5.1 Interaction Tools and Techniques

We found some recurring types of interactions that did not occur in immersive data visualisations as listed by Buschel et al. [8]. These interactions seem specific to geovisualisations and the goals associated with geologists as users. We identified these new interactions based on the reviewed literature and some prior reviews of geovisualisations [70]. These interaction techniques include *data queries* and *data collection.*

Data-query interactions deal with the exploration of the immersive visualisations. A prominent example would be measurement tools for calculating distances, area, volume, and altitude (see Fig. 3). The intended use is to emulate real-life fieldwork investigations that lead to the calculation of geological folds, stratigraphic models, and more. Another example of data-querying is when users target an object by hovering or selecting, or when leaning in with a phone or tablet in AR [33], and additional information pops up in a display. This interaction was typically provided to users when additional guidance was needed (see Fig. 1). They could manifest when set to active, or at a predetermined time. This was also used to aid expert users during data exploration and analysis (e.g., [34]). The information is displayed in forms ranging from external notes taken by users, to textbooks, or simply as virtual information boards. Text was not the only medium used in the reviewed visualisations; audio was used in the form of guided narration, and video as instructional tutorials. Information displays with location-based data such as GPS, coordinates, and cardinal directions (e.g., as a compass) were also quite common in papers that treated scene navigation as an interactive aspect of the immersive experience. *Data collection* interactions, on the other hand, deal with the ability to acquire, store, edit, and manage data that is gained during exploration and analysis. This could be a direct result of a data query, and take the form of personal notes, a dashboard with one's data-query history, or even screenshots of the visualisation (see Fig. 5).

In addition, we found that it was common in the literature to allow users to switch the current viewpoint, visualisation style, or locomotion style (see Fig. 4). Users could thereby adopt a multi-perspective understanding of the data visualisation.

Aside from these forms of interaction, we found that the majority of the visualisations did not have annotation tools, scene navigation, or integrated collaboration. Each of these are common aspects of real-life geological fieldwork and therefore their absence may be likely to contribute to a lack of acceptance of immersive systems as a medium for geovisualisation. Annotation tools allow users to take notes, offload cognition onto the environment, and exist in many virtual work-space applications [15, 58]. However, only Antoniou et al. [3] showed an annotation tool as a part of their UI (see Fig. 6 under "Field Survey Tools"). Unfortunately, the authors provided no description of this UI element and so it is unclear what this icon truly represented. The lack of annotation tools present in the reviewed literature may be largely due to technical constraints [45]. While writing in virtual spaces remains unrefined, it may be wise to avoid the frustration it might induce in user-testing. Although, in Klippel et al.'s [44] VFT research, their users (students) did complain about the omission. Scene navigation is the interaction of exploring using various styles of locomotion through a virtual environment. For researchers, the ability to navigate through a scene may be important to establish the points of interest at a geosite (e.g., targeting a location for a core sample). For students, it is a form of free exploration that follows after guided learning. In some of the visualisations, the locomotion was very limited where only head-movement played a roll in orienting oneself. On the other hand, some offered several ways to navigate the visualisation environment, but it is unclear if the intention was to allow for variable exploration, to provide options for those susceptible to cybersickness, or were made available just because the developers had the data for it. Generally, the most common method of locomotion (in VR) was teleportation, in which users could often only target a predetermined location to travel to (see Fig. 7). Teleportation is also a common form of locomotion in general which is likely due to the lack of physical space required and the low cybersickness factor [11, 27]. If a majority of these authors explained their choice of style of locomotion, this review would have a better indication of which techniques have been testes and found to be most effective for learning. Instead, the choices seem arbitrary.

Social interaction is an important aspect of situated cognition and contributes to improved learning and comprehension [6]. Therefore, the lack of collaborative functionalities built in the visualisations is worth noting. In some of the visualisations, the main user could interact with the data in AR or VR, and share their display with other desktop users. The social-interaction capabilities are limited between users in these scenarios as a form of screen-sharing rather than immersive collaboration. In other VR visualisations, users could collaborate remotely and synchronously. Although, these

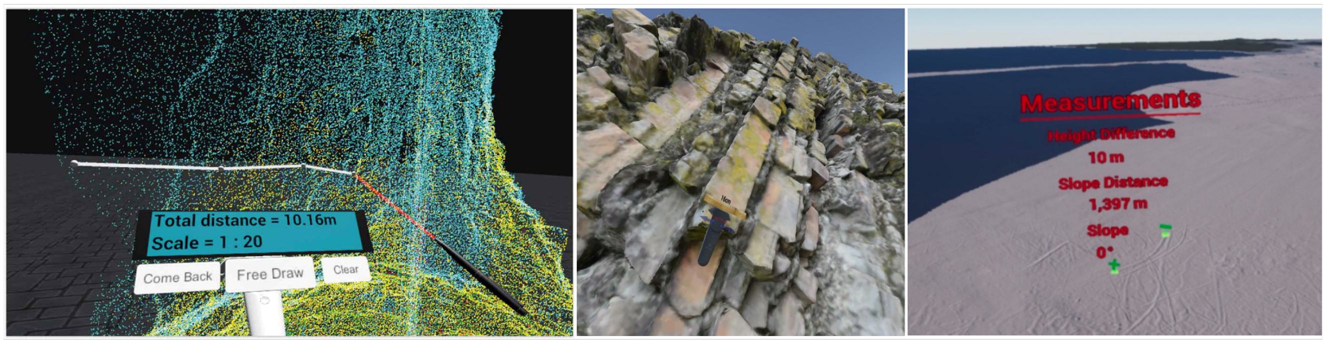

Figure 3: Measurement Tools - (Left) Zhao et al. [80] show a free-drawing tool which allows the calculation of the distance between two points in three-dimensional space (licensed under CC BY 4.0; used with permission); (Middle) Klippel et al. [44] show a ruler tool that is placed against the digital outcrop model to measure the layers (used with permission); (Right) Lütjens et al. [50] show a tool that measures the height difference between two points, the slope distances, and the slope angle (licensed under CC BY 4.0; used with permission).

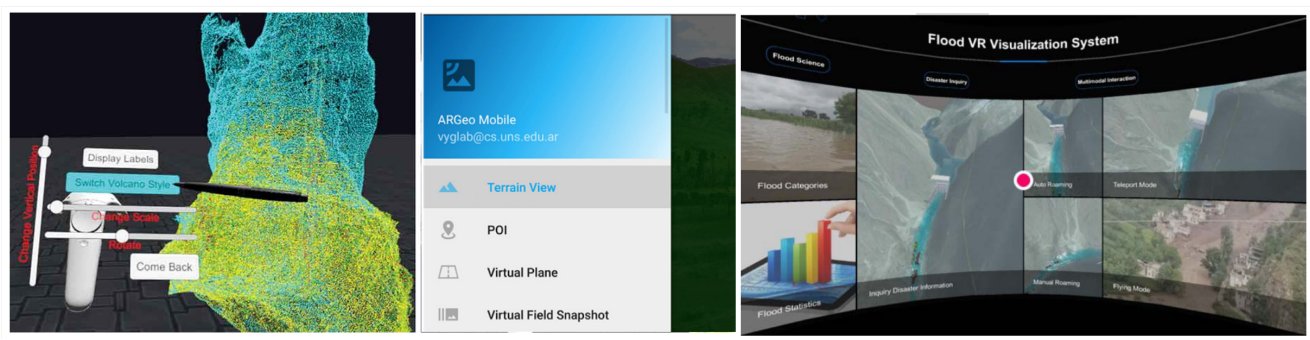

Figure 4: View Switching - (Left) Zhao et al. [80] show a menu option to "Switch Volcano Style" (licensed under CC BY 4.0; used with permission); (Middle) Gazcón et al. [29] show a series of menu options to switch between the Terrain View, Point-of-Interest (POI) View, Virtual Plane View, and Virtual Field Snapshot View (used with permission); (Right) Fu et al. [26] show a menu with options such as Auto Roaming Mode, Manual Roaming Mode, Teleport Mode, Flying Mode and more.

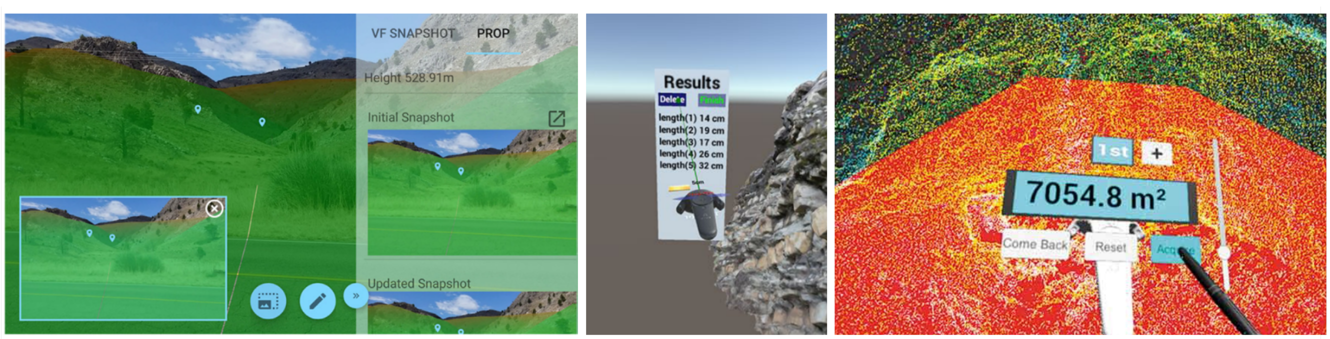

Figure 5: Data Collection - (Left) Gazcón et al. [29] show an example of collecting snapshots of the visualisation for later site-comparison (awaiting permission); (Middle) Klippel et al. [44] show an example of a data dashboard with the collected measurements from the layers of an outcrop (used with permission); (Right) Zhao et al. [80] show an area-measurement tool with a UI menu option to "acquire" this data point for later storage (licensed under CC BY 4.0; used with permission).

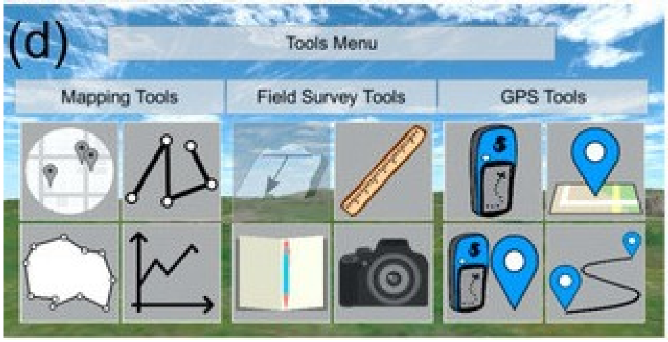

Figure 6: Antoniou et al. [3] show their UI Menu, displaying options under Mapping Tools, Field Survey Tools, and GPS Tools (licensed under CC BY 3.0; used with permission).

applications did not provide additional interactions or functionalities to facilitate social engagement between users. Two exceptions were Doležal, Chmelik and Liarokapis [21] and Šašinka et al. [67] as they provided users with tasks to be completed in pairs. In Doležal, Chmelik and Liarokapis [21], one user was an experimenter acting as an instructor and in Šašinka et al. [67] users were equals in trying to solve a task. Both chose to display other users as low-fidelity avatars with visualised HMDs to show gaze-direction.

Overall, we identified common threads between the reviewed literature to make use of data-querying and data-collection interactions. However, there are three main aspects of geological fieldwork that remain under-represented: annotation, exploration, and collaboration. These may not be included in existing literature due to technical limitations or scope. Future research should investigate how to implement these interactions into immersive geovisualisations.

5.2 Methods of Visualisation Evaluation

One of the original goals of conducting this review was to find which interaction tools and techniques had been evaluated. This would then establish some foundation for what had already been explored and what needed further research. However, we found that the main focus of the majority of the reviewed studies was on the technical design and implementation of data geovisualisations in immersive systems. Overall, there was a lack of HCI approaches towards the development of new tools and techniques. HCI theories that argue for the use of immersive systems for scientific discovery and education were rarely cited (only in six out of the 31). This means that many of the design choices made by the authors were not grounded in relevant HCI or educational theories such as place plausibility [71], embodied cognition [2], situated cognition [6], and social presence [59]. It is therefore unclear for purposes of review why some authors made the decisions they did regarding UI design, the mapping of buttons on controllers, locomotion, etc. It is subsequently unclear which design choices have contributed towards knowledge consolidation in educational applications, and those that contributed towards facilitating scientific discovery. This hinders the transfer of knowledge towards future innovations through this review.

A portion of 17 papers contained a proof-of-concept evaluation of their immersive visualisation and another 16 papers had participants to test them with (with a two-paper overlap). As a result, a bit over 50% of the immersive geovisualisations was tested only by the authors themselves. Of those 17 papers, many of the authors are experts in fields of geoscience (e.g., geochemists, cartographers, biologists, etc.). Therefore, it is likely that the authors are intimately aware of their use-case and the interpretations they have of their own visualisation are valued insights. However, other users are bound to encounter issues or disagree with design choices [9]. This is why the inclusion of users early on in the process can be beneficial, but out of the 31 papers, only four reported to have done such user testing. These findings demonstrate the need for more user involvement through the design, development, and testing phases of future research in immersive systems for geoscience.

Of the 17 papers that did evaluate their visualisations with participants, we have found some gaps in the methods. Only one paper contained a study that lasted longer than one day, and only two more had participants interact with the visualisation over the course of a day. All three of these papers were focused on education and integrating immersive systems into the workflow of a student workshop or fieldwork. As a result, there appears to be a lack of research investigating the long-term usability of immersive geovisualisations in research and in education after the initial novelty wears out. Furthermore, we found inconsistencies with the participant numbers across papers with different technologies. The papers that conducted research with VR were able to recruit a large number of participants. This applied even to research with high-end PC-powered HMDs such as the Oculus Rift and HTC Vive. On the other hand, AR applications lacked participant numbers, with a median of 10 participants across five separate studies compared to 44 for VR; even participant numbers with CAVE visualisations ranged from 15 to 42. Given that smartphones are a widespread technology, it is surprising to find that AR had such low participation in the reviewed literature. However, this could be due to the ease of use of software for VR applications relative to the SDKs made available for AR (see Table 7). AR is also known for its technical limitations and might be deemed too unreliable for use outdoors which we found to be AR's most common use-case. Future use of AR in research for immersive geovisualisations will likely be determined by the increase in accessibility to software, and technical innovation. Overall, future research may engage higher number of participants with the applications for longer periods of time or multiple times to understand the longer term value of the interaction tools and visualisations.

5.3 Visualisation Environments for Geosciences

Across the visualisations, we found many similarities between the choices different authors made for visualising geological data. However, when presenting our findings, we found it challenging to demonstrate them. With the taxonomy provided by the authors, terms like Lidar, Digital Elevation and Outcrop Models (DEM/DOMs), bathymetry topography - all household terms for many geoscientists - were not sufficient to help us compare the varying presentation methods. 3D visualisations are inherently

Figure 7: Locomotion: Teleportation - (Left) Klippel et al. [44] (used with permission); (Right) Zhao et al. [80]; in both examples, users target the red spot or the green spot as the destination of teleportation (licensed under CC BY 4.0; used with permission).

Figure 8: (Left) Boghosian et al.'s [4] DEM (used with permission); (Right) Antoniou et al.'s [3] DEM (used with permission)

different from 2D visualisations due to their use of spatial environment. Boghosian et al. [4] and Antoniou et al. [3] both use Digital Elevation Models (DEMs) in their visualisations. Therefore, we know that the topography of the terrain is visualised in some manner, excluding surface objects like natural and artificial structures. Although, the visualisations in these two environments look very different. Antoniou et al. [3] present an environment in which users can interact through physical exploration and measurement tools whereas Boghosian et al. [4] present an antarctic ice-shelf, purely visualised for analysis (see Fig. 8).

Another example is Harrington et al. [33] who used Geographic Information System (GIS) data of an ecosystem, but instead of visualising it as a grid of data, they developed an elaborate, flourishing, natural environment. To describe the environment, the authors used a variety of terms: "immersive game level environment", "virtual field guide", "data visualisation virtual field trip" and "virtual forest" to name a few. While it is clear that all of these terms do apply to the example visualisation, the varying hierarchy of specificity in these terms makes it unclear how one should refer to it. We argue that by establishing a taxonomy by which we can refer to different styles of visualisations, we gain ease of communication. Therefore, such a taxonomy should help to inform on the use-cases of each visualisation style. This can also help to establish improved multi-disciplinary communication between geoscientists and HCI researchers. To this end, we contribute a preliminary, basic taxonomy based on the reviewed literature and Sherman et al.'s [70] review of geological data types. The terms we propose are geo-virtual exploratory landscapes, exploratory subsurfaces, geo-spatial models, overlays, and immersive environments.

- **Geo-virtual exploratory landscapes (GvEL)** refer to the visualisation of 3D-reconstructed geological models derived from photogrammetry in a contextualised environment. Some such models include Digital Elevation Models (DEMs; including Digital Terrain Models, DTMs and Digital Surface Models, DSMs) and Digital Outcrop Models (DOMs). This environment can include planetary surface morphology, as well as natural or artificial structures. Virtual landscapes therefore provide a sense of scale and highly detailed elevation data of a geosite. This is ideal for exploratory tasks.
- **Geo-virtual exploratory subsurfaces (GvES)** refer to the visualisation of 3D-reconstructed geological *subsurface* models. These visualisations can either be derived from photogrammetry (e.g., caves) and from non-photogrammetric sources (e.g., Ground-Penetrating Radar, GPR and Structure-from-Motion, SfM). These visualisations can also include natural or artificial structures, and provide a sense of scale and highly detailed elevation data of a subsurface. This is ideal for exploratory tasks.

- **Geo-virtual terrain/surface models (GvT/SM)** refer to the visualisation of 3D-reconstructed models in a standalone, contextual-less environment. These visualisations are purely focused on data which is ideal for unobstructed analysis. For smaller models such as hand samples and thin-sections, the term *geo-virtual artefacts* could be used instead. However there are no examples of this in the reviewed literature.
- **Geo-virtual overlays (GvO)** refer to the layering of visualisations on top of an environment. This could be used to highlight points of interest, or display height-maps. This visualisation would be useful for preparing for fieldwork (i.e., deciding on a site).
- **Geo-virtual immersive environments (GvIE)** are contextualised environments that can hold a variety of different types of geovisualisations, but additional sensory information may be provided through auditory, visual, or haptic cues such as weather, and local fauna and flora.
  Examples of each of these visualisation environments from the reviewed literature are shown in Fig. 9. The terms were chosen for the ease of comprehension of multiple scientific disciplines.

This scoping literature review has yielded a variety of research in the field of geoscientific visualisation for both education and research. Existing literature has yet to establish how to design for geoscientists based on their needs, and which interaction tools and techniques may fulfill those needs. Research has yet to explore desirable interactions such as annotating and collaborating remotely. In addition, the design of scene navigation and its impact on the experience of virtual fieldwork is not explored. We have provided a first step towards a taxonomy for styles of geovisualisation environments, however, more research is needed to find terms that provide common ground between HCI and geoscience. This review has primarily established that a systematic review of interaction tools and techniques in geovisualisation would not likely be possible, due to the lack of holistic reports in the reviewed literature. We would encourage HCI researchers to take an interest in this field as HCI contributions are needed towards the development of a design framework. Contributions could include user-centered approaches, long-term studies of the effects of immersive visualisations on research or education, or research that focuses user interaction. Furthermore, we hope to use this scoping literature review to contribute towards our own studies and a design framework that will begin to establish design patterns for immersive geovisualisation.

6 LIMITATIONS

This study has limitations. First, the study selection only included papers written in English. It is likely that informative work has been published in other languages that were not included in this review. Second, due to the limited search terms and the limited number of large databases used, it is likely that this scoping literature review has missed some relevant publications.

There are also limitations in our findings due to the information we could retrieve from the papers. In the sampled literature, often only a part of the user interface was reported by authors (see Table 5. for "Not Specified"). This made it unclear whether information was missing, or intentionally omitted. Occasionally, missing information could be partially recovered by looking at figures or demo videos provided by the authors. However, these additional media were not sufficient to explain the purpose or design of the interaction tools. This emphasises the need for the holistic recording of interaction tools and techniques for purposes of replicability and future research in immersive geovisualisations.

7 CONCLUSION

We conducted a scoping literature review, in which we collected a sample of 31 journal papers and conference papers to understand the state-of-the-art interaction tools and techniques for immersive geovisualisations, and methods used to evaluate them. We have presented the visualisation environments, interaction tools and techniques, and evaluation methods from each of these papers. We found that there was no established taxonomy for visualisation environments for immersive geovisualisations; an absence of thorough reports on interaction tools and techniques; and a lack of use of relevant HCI theories and user-centered approaches. These findings demonstrate that existing research is not sufficient to develop a consensus. Our scoping review also demonstrates that a systematic review of interaction tools and techniques used for geoscience would not be possible. This research gap implies a need for thorough HCI research methods based on supported theories. This scoping review can nonetheless help to establish design patterns in immersive geovisualisations and their respective use-cases. We contribute towards the HCI field by highlighting the interaction tools and techniques that have been investigated, and which methods were used to evaluate them. We conclude that future research needs contribute towards a concrete understanding of what geoscientists need for data exploration and comprehension. This could be achieved by including target users throughout the design process, and by developing a framework that makes use of established taxonomy. In future, it would prove more beneficial if detailed reports of interaction tools and techniques were provided in research that addresses the design and development of immersive geovisualisation.

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Australian Government

Australian Research Council

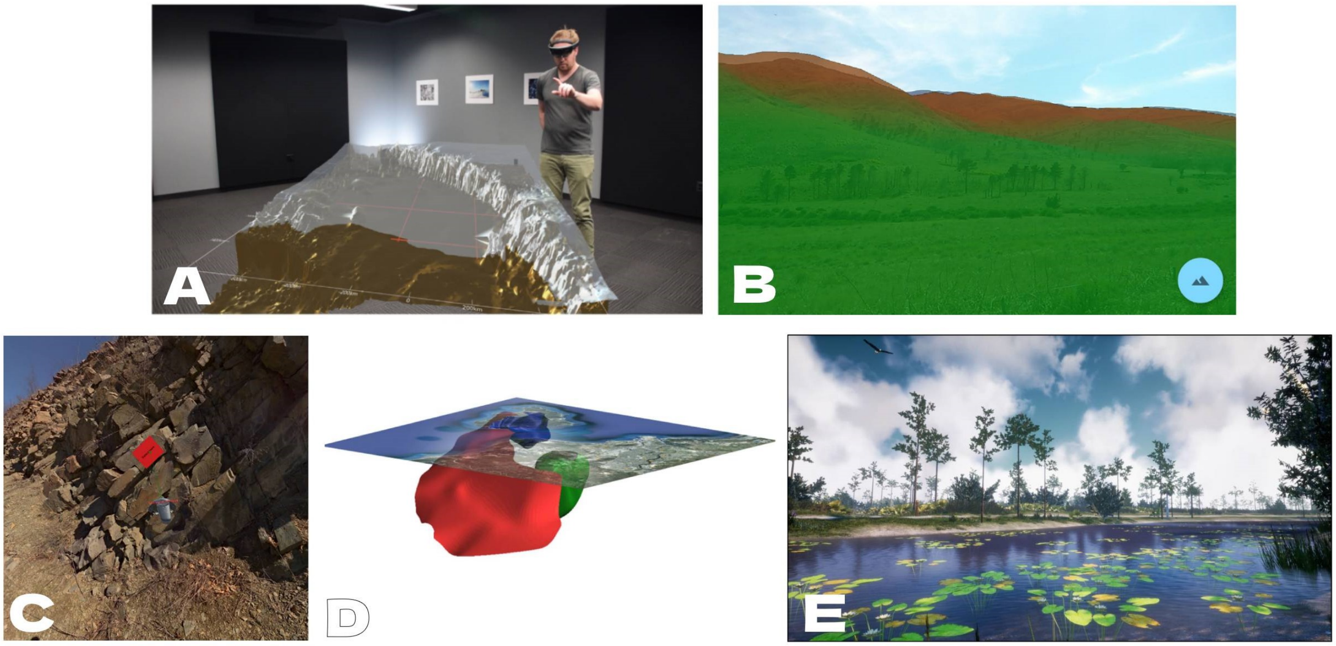

Figure 9: Examples of A) Geo-virtual terrain model cropped from Boghosian et al. [4] (used with permission), B) Geo-virtual overlay cropped from Gazcón et al. [29] (used with permission), C) Geo-virtual landscape cropped from Klippel et al. [44] (used with permission), D) Geo-virtual subsurface cropped from Mathiesen et al. [54] (used with permission), E) Geo-virtual immersive environment cropped from Harrington et al. [33] (licensed under CC BY 4.0; used with permission)

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A SEARCH PHRASES

A.1 Scopus

ALL ((immersive OR augmented OR virtual OR mixed) realit* OR system*) AND (data AND (analysis OR visuali?ation) OR collaboration OR sensemaking OR learning) AND (spatial AND presence OR telepresence OR self-presence OR immersion) AND (geoscience OR ((planetary OR earth) science)) SUBJAREA (comp) SUBJAREA (eart) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp"))

ALL ((immersive OR augmented OR virtual OR mixed) realit*) AND (data AND (analysis OR visuali?ation) OR "interaction tools" OR "immersive analytics") AND (collaboration OR sensemaking OR learning) AND (presence OR telepresence OR self-presence OR immersion) AND (geoscience OR "earth science" OR ecology OR archaeology OR geodesy OR "remote sensing" OR geography) (SUBJAREA (comp) OR SUBJAREA (eart) OR SUBJAREA (envi)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (EXACTKEYWORD , "Human Computer Interaction"))

A.2 ACM

("data visuali?ation*" OR "geospatial data" OR "3D interface" OR "spatial interaction" OR "virtual environment*") AND (collab* OR teamwork OR co-operat* OR co-locat*) AND (ABSTRACT: "immersive system*" OR ABSTRACT: "Virtual Reality" OR ABSTRACT: "Augmented Reality" OR ABSTRACT: "Mixed Reality") AND (geoscien* OR "earth scien*" OR "planetary scien*") (learn* OR educat* OR classroom) AND (collab* OR teamwork OR co-operat* OR co-locat*) AND (ABSTRACT: "immersive system*" OR ABSTRACT: "Virtual Reality" OR ABSTRACT: "Augmented Reality" OR ABSTRACT: "Mixed Reality") AND (geoscien* OR "earth scien*" OR "planetary scien*")

B TABLES

Use of Interaction Tools			
Manipulation of Visualisation		**Locomotion**	
Pan, Rotate and Zoom	[38, 43, 44, 75, 76, 79, 80]	World Pulling	[79]
Terrain Deformation	[38]	On Rails	[63]
Vertical Displacement	[80]	Teleportation (Pred.)	[21, 43, 44, 50, 80]
Geo-Tagging	[29, 40, 47, 67]	Teleportation (Free)	[37]; [26]**
Toggle Visibility of Data	[34, 37, 80]	Stationary	[14, 23, 26, 40, 55, 64, 80]
Object Grab-and-Place	[21]	World Anchor (AR)	[4, 29, 39, 47, 53, 54, 75]
Sliders*	AD [29]	Joystick	[34, 38]
	Q [39, 67]	Walking	[3, 30, 33, 38, 67]
	T [67]	Flying	[3, 26, 30, 36, 50, 76]
	VE [4, 67]	Drone	[3, 30]
	VP [4, 29, 67]	Rover	[65]
		Controller Tilt	[34]
Element Creation	[14]	Jump	[50]
Object Selection		**View Switching**	
Laser Pointer	[23, 26, 33, 34, 38, 43, 44, 50, 64, 67, 76, 79, 80]	Visualisation Style	[26, 29, 34, 37, 43, 44, 67, 75, 76, 80]
Gestures	[4, 29, 34, 40, 55]	Locomotion Style	[3, 26, 30, 50]
Voice Activation	[4]	Interaction Mode	[29, 33, 34, 43, 44, 76, 80]
Mouse & Keyboard	[14, 55]		
Data Queries		**Data Collection**	
Distance-Measurement	[3, 34, 50, 67, 80]	Data Dashboard	[34, 43, 44]
Height-Measurement	[43, 44, 50]	Screenshots	[3, 29, 50]
Area-Measurement	[80]		
Volume-Measurement	[3, 80]	**Collaboration**	
Slope Angle Measurement	[29, 50]	Desktop Screen-share	[38, 64]
Latitude & Longitude	[76]	Joint Display	[64]
Strike & Dip	[29]	Remote VR	[21, 67]
Information Displays		**Some Not Specified**	
Text (e.g., pop-ups)	[26, 29, 33, 34, 36, 37, 43, 44, 47, 50, 53, 55, 67, 76, 80]	Manipulation Tools	[3, 23, 26, 30, 34, 36, 37, 39, 47, 50, 53, 54, 63–65, 67]
Audio	[33, 36, 43, 44, 63]	Data Query and Collection Tools	[4, 14, 21, 23, 30, 35, 38–40, 47, 53, 54, 75, 79, 80]
Location	[29, 30, 34, 36, 50, 67]	Locomotion	[35]
Video Tutorials	[55]		
Quizzes	[14, 40, 55]		

Table 1: Overview of 31 papers according to Interaction Tools: *Sliders: AD, Angular Displacement, Q, Quantity of Visible Data, T, Translation of a Cross-Section, VE, Vertical Exaggeration, VP, Visual Preferences); **It is unclear whether Fu et al. had pred. or free teleportation

Immersive Systems Hardware Use				
VR	HTC Vive	10	32%	[21, 23, 26, 33, 43, 44, 50, 67, 79, 80]
	Oculus Rift	5	16%	[3, 30, 36–38]
	Samsung Gear VR	1	3%	[63]
	Google Cardboard	2	6%	[40, 55]
	Desktop VR	2	6%	[14, 55]
	Not Specified	3	10%	[14, 35, 76]
		23	**74%**	
AR	Mobile Devices	6	19%	[29, 33, 39, 47, 53, 54]
	Microsoft HoloLens	1	3%	[4]
	Tangible User Interface	1	3%	[34]
	Multi-Camera Setup	1	3%	[75]
		9	**29%**	
CAVE	-	3	**10%**	[34, 64, 65]

Table 2: Immersive Systems Hardware Use in Research

Immersive Systems Software Use				
VR	Unity3D	11	35%	[3, 21, 26, 30, 38, 39, 44, 67, 76, 79, 80]
	Unreal Engine	5	16%	[33, 36, 37, 50, 76]
	SteamVR Toolkit	3	9%	[21, 26, 67]
	Vizard Engine	1	3%	[23]
	Google Tour Creator	1	3%	[40]
	VRED (AutoDesk)	1	3%	[35]
	Developed by Authors	1	3%	[55]
	Not specified	3	10%	[14, 43, 63]
AR	Mobile Device SDK (e.g. Android)	2	6%	[29, 54]
	Unity3D	1	3%	[4]
	Developed by Authors	5	16%	[29, 33, 34, 47, 75]
	Not Specified	1	3%	[53]
CAVE	OpenSceneGraph	1	3%	[34]
	Developed by Authors	1	3%	[65]
	Not Specified	1	3%	[64]

Table 3: Immersive Systems Software Use in Research

	IS	Hardware	Locomotion	Interaction Tools & Techniques	VS	Collab.
[14]	VR	Desktop VR	Stationary	Element Creation; Information Displays (Quizzes)	No	-
[40]	VR	Google Cardboard	Stationary	Geo-Tagging; Information Displays (Quizzes)	No	-
[55]	VR	Google Cardboard; Desktop VR	Stationary; On Rails	Information Displays (Text, Quizzes, & Video)	No	-
[63]	VR	Samsung Gear VR	On Rails	Information Displays (Audio)	No	-
[43]	VR	HTC Vive	Teleport (Pred.)	Pan, Rotate & Zoom; Measuring Tools; Information Displays (Text & Audio)	Yes	-
[44]	VR	HTC Vive	Teleport (Pred.)	Pan, Rotate & Zoom; Measuring Tools; Information Displays (Text & Audio)	Yes	-
[33]	VR	HTC Vive	Walk	Information Display (Text & Audio)	Yes	-

Table 4: Interaction Tools & Techniques: *Virtual Field Trips/Tours/Guides*; VS = View Switching; N/S = Not Specified

	IS	Hardware	Locomotion	Interaction Tools & Techniques	VS	Collab.
[3]	VR	Oculus Rift	Walk; Fly; Drone	Measuring Tools (Distance, Volume & more); Screenshots	Yes	-
[30]	VR	Oculus Rift	Walk; Fly; Drone	Information Display (Location)	No	-
[36]	VR	Oculus Rift	Fly	Information Display (Text, Audio & Location)	No	-
[37]	VR	Oculus Rift	Teleport (Free)	Information Display (Text); Toggle Visible Data	Yes	-
[26]	VR	HTC Vive	Fly; Teleport (?)	Information Display (Text)	Yes	-
[50]	VR	HTC Vive	Fly; Jump; Teleport (Pred.)	Measuring Tools (Distance, Height, Slope); Information Display (Text & Location); Screenshots	Yes	-
[34]	CAVE	-	Joytstick + Tilt	Measuring Tools (Distance); Information Displays (Text & Location); Toggle Visible Data	Yes	-
[64]	CAVE	-	Stationary	N/S	No	Screen-Share
[65]	CAVE	-	Rover	N/S	No	-
[38]	VR	Oculus Rift	Walk; Joysticks	Pan, Zoom & Rotate; Terrain Deformation	No	Screen-Share
[80]	VR	HTC Vive	Teleport (Pred.); Stationary	Pan, Zoom & Rotate; Vertical Displacement; Toggle Visible Data; Measuring Tools (Distance, Area, Volume); Information Display (Text)	Yes	-
[67]	VR	HTC Vive	Walk	Slider (Toggle Visible Data; Cross-Section; Vertical Exaggeration; Contour Lines); Geo-Tagging; Measuring Tools (Distance); Information Display (Text);	Yes	Remote or Co-Located
[35]	VR	N/S	N/S	N/S	No	-
[76]	VR	N/S	Fly	Pan, Rotate & Zoom; Measurement Tools (Latitude & Longitude); Information Display (Text)	Yes	Remote

Table 5: Interaction Tools & Techniques: *Geo-Spatial Models*; VS = View Switching; N/S = Not Specified

	IS	Hardware	Locomotion	Interaction Tools & Techniques	VS	Collab.
[21]	VR	HTC Vive	Walk	Grab-and-Place Objects	Yes	Remote; Synchronous
[23]	VR	HTC Vive	Stationary	N/S	No	-
[79]	VR	HTC Vive	World-pull	Pan, Rotate & Zoom	No	-

Table 6: Interaction Tools & Techniques: *Maps & Globes*; VS = View Switching; N/S = Not Specified

	IS	Hardware	Locomotion	Interaction Tools & Techniques	VS	Collab.
[33]	AR	Smartphone; Tablet	Walk	Information Display (Text & Audio)	Yes	-
[39]	AR	Smartphone	Walk (World Anchor)	N/S	No	-
[53]	AR	Smartphone	Walk (World Anchor)	N/S	No	-
[54]	AR	Smartphone	Walk (World Anchor)	N/S	No	-
[4]	AR	HoloLens	Walk	Toggle Visible Data; Vertical Exaggeration (Slider)	No	Screen-Share
[29]	AR	Smartphone	Walk (World Anchor)	Angular displacement (Slider); Adjust visual Preferences; Geo-Tagging; Information Display (Location)	Yes	-
[47]	AR	Smartphone	Walk (World Anchor)	N/S	No	-
[34]	AR	Tangible Interface	-	Measuring Tools (Distance); Information Displays (Text & Location)	Yes	-
[75]	AR	Multi-Camera Setup	Walk (World Anchor)	N/S	Yes	-

Table 7: Interaction Tools & Techniques: *Augmented Reality Visualisations*; VS = View Switching; N/S = Not Specified

	IS	Hardware	Method	Setting	Design	n	Duration (min)
[40]	VR	Google Cardboard	Comparative Study	Lab	Within-subjects	93	60-75 (Three 15-min intervals)
[14]	VR	Desktop VR	Comparative Study (Pretest/Posttest)	In-the-wild	Mix within / between subjects	51	90-120
[55]	VR	Desktop VR	Comparative Study	In-the-wild	Within-subjects	590	90-120; + 10 week delay
[63]	VR	Samsung Gear VR	Comparative Study (Pretest/Posttest)	In-the-wild	Mix within / between subjects	102	20 (All-day workshop)
[43]	VR	HTC Vive	Comparative Study	In-the-wild	Between-subjects	37	35
[44]	VR	HTC Vive	Comparative Study	In-the-wild	Between-subjects	51	40
[33]	VR	HTC Vive	Proof-of-Concept				

Table 8: Evaluation Methods for Virtual Field trips & Tours; N/S = Not Specified

	IS	Hardware	Method	Setting	Design	n	Duration (min)
[26]	VR	HTC Vive	Comparative Study	Lab	Within-subjects	60	3
[67]	VR	HTC Vive	User Study	Lab	-	12	60-120
[64]	CAVE	-	User Study	In-the-wild	-	42	N/S
[34]	CAVE	-	User Study	Lab	-	11	N/S
			Comparative Study	Lab	Within-subjects	15	N/S
[38]	VR	Oculus Rift	Proof-of-Concept				
[3]	VR	Oculus Rift	Proof-of-Concept				
[30]	VR	Oculus Rift	Proof-of-Concept				
[36]	VR	Oculus Rift	Proof-of-Concept				
[37]	VR	Oculus Rift	Proof-of-Concept				
[50]	VR	HTC Vive	Proof-of-Concept				
[65]	CAVE	-	Proof-of-Concept				
[35]	VR	N/S	Proof-of-Concept				
[76]	VR	N/S	Proof-of-Concept				

Table 9: Evaluation Methods for Geo-Spatial Models; N/S = Not Specified

	IS	Hardware	Method	Setting	Design	n	Duration (min)
[21]	VR	HTC Vive	User Study	Lab	-	30	N/S
[23]	VR	HTC Vive	Comparative Study	Lab	Between-Subjects	228	15-20
[79]	VR	HTC Vive	Comparative Study	Lab	Within-subjects	32	N/S

Table 10: Evaluation Methods for Maps & Globes; N/S = Not Specified

	IS	Hardware	Method	Setting	Design	n	Duration (min)
[29]	AR	Mobile Device	Case Study	In-the-wild	-	5	60
[33]	AR	Mobile Device	Pilot User Study	In-the-wild	-	56	N/S
[75]	AR	Multi-Camera Setup	Comparative Study	In-the-wild	Within-subjects	15	N/S
[4]	AR	HoloLens	Proof-of-Concept				
[34]	AR	Tangible Interface	Proof-of-Concept				
[47]	AR	Mobile Device	Proof-of-Concept				
[53]	AR	Mobile Device	Proof-of-Concept				

Table 11: Evaluation Methods for Augmented Reality Visualisations; N/S = Not Specified