The Geological Society | ES3 Earth Science, Systems and Society

ORIGINAL RESEARCH
published: 01 November 2024
doi: 10.3389/esss.2024.10128

Learning and Teaching Geological Field Skills in a Virtual World: Insights From an Undergraduate Virtual Fieldtrip in Kinlochleven, Scotland

Matthew J. Genge*, Valentin Laurent, Philippa J. Mason, Alan R. T. Spencer, Mark D. Sutton and Alex C. Whittaker

Department of Earth Science and Engineering, Imperial College London, London, United Kingdom

Virtual fieldtrips enable the teaching of field geology remotely or in classroom-settings by leveraging video-game technologies. We describe the development of a virtual fieldtrip to Kinlochleven in Scotland to teach undergraduate students geological mapping skills in a structurally complex, polyphase deformed metamorphic terrain. An area of ~4 km^2 of the Highlands was digitally replicated within the game engine Unity and featured 82 outcrops digitized from field data by photogrammetry. Key concepts in the development were: (1) usability on low-specification computers, (2) participant communication within-app, (3) multiscale visualisation of localities, (4) contextualisation of localities within terrain, and (5) a high degree of immersion to replicate the outdoor fieldwork experience. Technology constraints, however, required compromise between the number of localities used and their resolution. Evaluation and assessment data suggests the virtual fieldtrip was effective in delivering the key learning objectives of the course. Student behavioural indicators, furthermore, suggest that the immersive strategy successfully produced a high degree of engagement with the activity. A major limitation of the virtual fieldtrip was in the development of skills requiring spatial visualisation, in particular, the spatial association of features across multiple scales. The virtual fieldtrip had benefits for inclusivity, making fieldwork more accessible than its outdoor equivalent. However, a digital divide was observed to exist between groups depending on experience with gaming and virtual worlds. In addition, neurodiverse group of students required adaptations to assist with spatial awareness in virtual environments. The data obtained suggests that virtual fieldtrips cannot fully replace their outdoor equivalents, however, they are valuable in supplementing and supporting outdoor fieldtrips, in particular by increasing inclusivity and enabling field time to be used optimally.

Keywords: geology, fieldwork, virtual fieldtrip, mapping, pedagogy

Edited by:
Steven Rogers,
Keele University, United Kingdom

Reviewed by:
Natalie Bursztyn,
University of Montana, United States
Jessica Pugsley,
University of Aberdeen,
United Kingdom

***Correspondence**
Matthew J. Genge,
✉ m.genge@imperial.ac.uk

Received: 18 May 2024
Accepted: 18 October 2024
Published: 01 November 2024

Citation:
Genge MJ, Laurent V, Mason PJ, Spencer ART, Sutton MD and Whittaker AC (2024) Learning and Teaching Geological Field Skills in a Virtual World: Insights From an Undergraduate Virtual Fieldtrip in Kinlochleven, Scotland.
Earth Sci. Syst. Soc. 4:10128.
doi: 10.3389/esss.2024.10128

INTRODUCTION

Fieldwork is considered a pedagogic cornerstone of Geoscience (Shulman, 2005). In the field, students learn to understand, synthesise, visualise and apply the knowledge they learn in class. It is only in the field that students can make direct observations of rocks and tectonic structures *in situ*, observations that drive a deeper understanding of Earth processes in their true spatial context. From the onset of the COVID-19 pandemic (early 2020) and until vaccines were developed and delivered to the majority of the population (ca. 2021-2022 depending on country), outdoors fieldwork was difficult or even impossible for most geoscientists over the world and the development of virtual fieldtrips (VFTs) for education became a necessity (e.g., Bond and Cawood, 2021; De Paz-Álvarez et al., 2021; Guillaume et al., 2023; Métois et al., 2021; Peace et al., 2021; Pugsley et al., 2022; Whitmeyer and Dordevic, 2021).

Virtual fieldtrips aim to reproduce the outdoor fieldwork learning experience through digital means (Cliffe, 2017; Klippel et al., 2019). Different technologies can be deployed to achieve this objective, including recorded videos of outdoor fieldwork (Garcia et al., 2023), high-resolution imagery including aerial or satellite images, or three-dimensional virtual environments or 3D models (Buckley et al., 2022; Jones et al., 2009; Marshall and Higley, 2021) deployed in desktop or Virtual Reality (VR) applications (Klippel et al., 2019). Often VFTs present localities as isolated 3D models out of context with landscape (Klippel et al., 2019; Tibaldi et al., 2020), however, virtual environments have the greatest potential for replication of physical fieldwork, although it remains impossible to reproduce all aspects of the experience of being physically in the field (Guillaume et al., 2023). Consequently, to design geosciences curricula of the future, it is necessary to study further the impact of teaching fieldwork virtually instead of outdoors on a student's experience. Are students able to achieve the same learning outcomes? Is the acquired level of understanding similar? Are students able to develop similar field skills? To what extent can VFTs replace outdoor fieldwork? (Cliffe, 2017; Guillaume et al., 2023; Klippel et al., 2019).

In this study, we describe and discuss a fully virtual geological fieldtrip to Kinlochleven (Scotland). This VFT utilises the immersive and interactive 3D model paradigm, and was developed in response to the COVID-19 crisis as a temporary replacement for a long running physical trip to the same location. A virtual environment of 4 km^2 was created to replicate the same mapping area studied during outdoor fieldwork. The VFT was delivered using an in-house remote teaching software package for geology (Earth Science and Engineering Remote Classroom - ESERC). ESERC leverages multiplayer video-game technology and concepts to not simply host interactive models of field landforms and outcrops, but also to provide communication and interaction facilities that mimic the real field environment as closely as possible. The student experience is discussed, including considerations of the broader impacts of teaching fieldwork virtually instead of outdoors. The degree of student understanding of the local complex structural geology acquired in the virtual and outdoor field environments are compared. We conclude that our approach to virtual fieldwork provides the most sophisticated and satisfactory informative alternative yet available to conventional fieldwork, but nonetheless cannot provide a full replacement for it. However, the use of VFTs as a complement to outdoor fieldwork has the potential to provide broader student experience and to increase equality, diversity and inclusivity in Geosciences.

GEOLOGY AND INTENDED LEARNING OBJECTIVES

Geology

Kinlochleven is located in the Grampian Highlands at the end of Loch Leven, 8 km east of Glencoe and 14 km south of Fort William (**Figure 1**). The area provides an excellent location to meet the principal goal of the field course since the geology is dominated by Dalradian metasediments, of greenschist facies, which have been folded by multiple deformation events during the Grampian phase of the Caledonian orogeny. Around Kinlochleven, the Appin and Ballahulish Group of the Dalradian are exposed. In the mapping area surrounding Mamore Lodge, the Appin Group consists of a series of siliciclastic tidal-shelf and near-shore deposits of the Eilde Schist, Eilde Quartzite, Binnein Schist and Binnein Quartzite Formations (Stephenson et al., 2013). The structure is dominated by isoclinal F1 folds, which vary from recumbent folds several kilometres in amplitude, to minor folds visible in a single outcrop. Smaller scale, tight F2 folds are superimposed on the earlier structures and are broadly coaxial. A third generation of open to tight folds is well-developed in the area and forms structures up to several kilometres in amplitude as well as abundant minor folds on sizes down to a few centimetres in the phyllite-dominated portions of the sequence (Ikeda, 1996). A final F4 phase of folding is present largely as small-scale kink bands.

In addition to folds, multiple generations of cleavage are well developed within phyllites, with a pervasive S1 slaty cleavage and S2 and S3 crenulation cleavages. The overall style of deformation is illustrated in **Figure 2**. The area provides an excellent example of polyphase deformation in a sequence with a straightforward stratigraphy suitable to address the overall goal of the field course, and benefits from accessibility and proximity to accommodation and other facilities.

Intended Learning Objectives

The Intended Learning Outcomes (ILOs) of any course are the framework upon which its design and development are based. Intended Learning Outcomes are frequently dependent on the demands of the overall degree structure, with complex inter-relationships between courses to build competence over time. In Geosciences degrees, field courses play a crucial role in cementing skills, allowing students to integrate theoretical knowledge from multiple courses and to apply experience with simple examples studied in the classroom to complex natural rocks and structures. One challenge in designing and delivering VFTs is to reproduce the complexity of outdoors fieldwork, to fully meet the intended ILOs.

The overall goal of the Kinlochleven field course at Imperial College is to augment and reinforce previously developed field skills such as observation, description, recording and

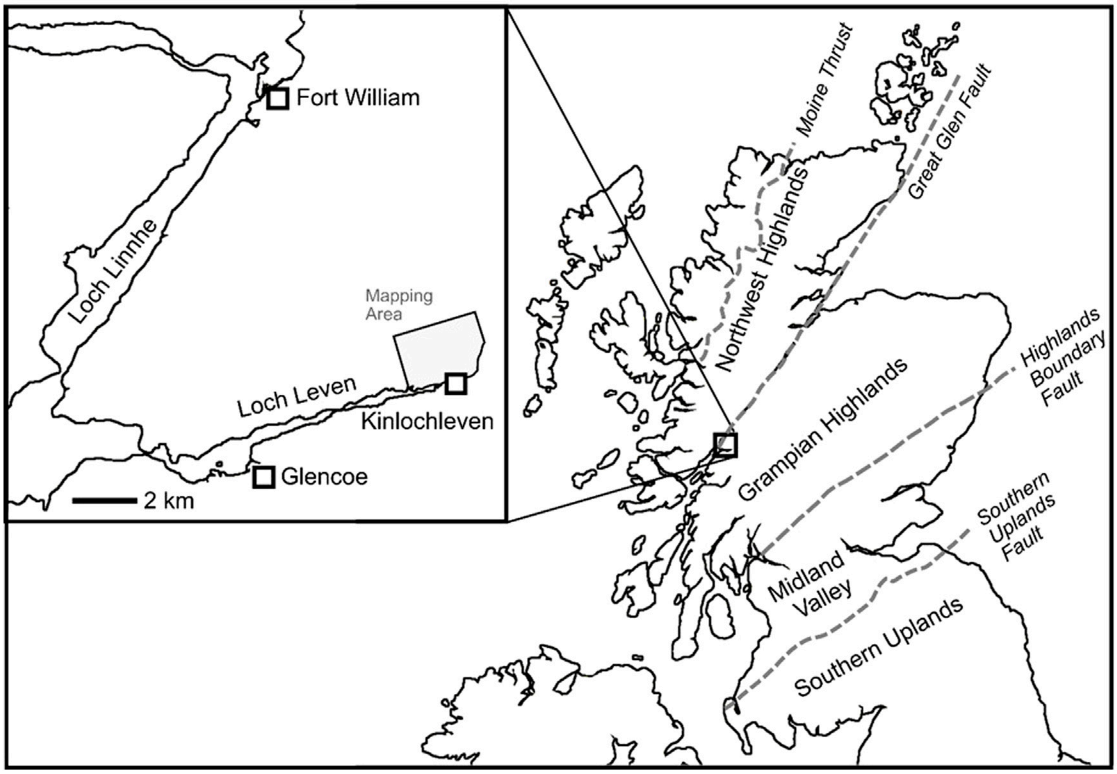

FIGURE 1 | A map showing the location of the Kinlochleven mapping area in Scotland.

interpretation of the local geology at different scales. The field course is run immediately prior to the independent mapping project, and focusses on mapping techniques as a primer for this keystone project.

A secondary goal of the Kinlochleven field course is to foster good mental health and resilience to promote wellbeing during independent project work. Geological mapping projects can be daunting for undergraduate students, and anxiety about their ability to conduct independent fieldwork is common. Building confidence (as well as competence) is an important part of the training, and is achieved through a guided mapping exercise that promotes progressive independence as it proceeds. The structural complexity of the area plays a key role, as it shows students that through systematic application of techniques and thorough observation and recording they are capable of interpreting challenging geology. A crucial element of this training is to develop mental resilience through an understanding that uncertainty is a fundamental part of the mapping processes and should not cause anxiety.

Specific learning objectives of the Kinlochleven field course fall into two categories: (1) mapping techniques, and (2) interpretation of structural geology. Learning objectives in mapping techniques are designed to provide specific methods and good practice. The objectives are: (1) to develop good observational skills for lithology and structure at the locality level, and skills in relating these between localities; (2) to learn excellent recording skills, both on field maps and in notebooks, recording information in a systematic, technical and sufficiently detailed manner; (3) to improve the quality and value of field sketches, with enhanced technical rigor and appropriate annotation; (4) to develop skills in interpreting field observations to reconstruct geological boundaries; (5) to promote efficient mapping through good traverse selection and work time-management; (6) to foster good positional awareness and mapping reading abilities; and (7) to reinforce good practice in field safety. All these objectives are facilitated by the topography and complexity of the outdoor field course, but present challenges for the development of a virtual field course since they are inherently associated with the student's changing perspective within the environment.

Structural geology learning objectives are to cement theoretical concepts learnt in lectures and practicals, through interpretation of complex structures in the field. Specific objectives are: (1) to learn the taxonomy of folds and cleavages to enable technically robust and systematic recording; (2) to develop skills in the measurement of fold axial surfaces, cleavage orientations, and fold plunges and other lineations in the field; (3) to learn how to identify different generations of fold and their associated cleavages, including assessment of fold interference patterns and the relative timing of deformation events; (4) to understand fold and cleavage symmetry and apply this data spatially to evaluate the nature of large scale fold structures; (5) to understand of

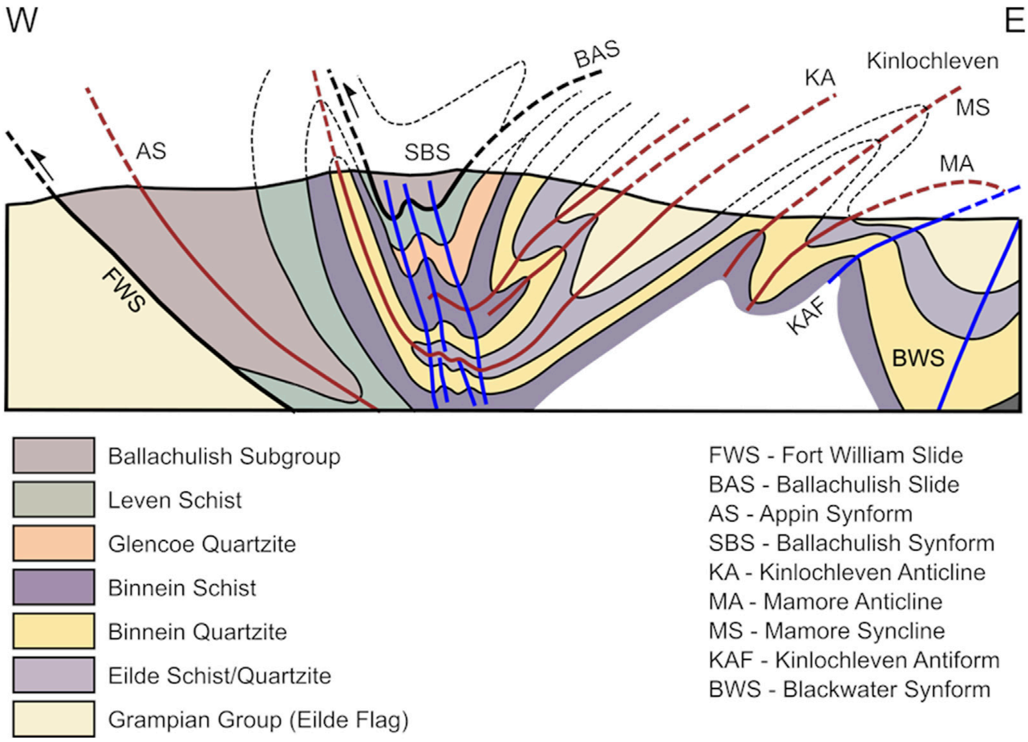

FIGURE 2 | Cross-section along Loch Leven (near Glencoe, several kilometres west of the mapping area), after Roberts and Treagus (1977). Fold axial traces are shown for F1 (red) and later (blue) folds. Bold black lines are slides.

the effect of ductile deformation on the thickness of beds and units; (6) to identify and assess way-up structures, including an appreciation of uncertainty; (7) to learn to use stereonets to analyse the orientations and spatial relationships between multiple generations of folds and associated cleavages; and (8) to interpret complex field data and create robust structural cross-sections.

In the outdoors Kinlochleven fieldtrip (**Figure 3A**) these objectives are facilitated by the excellent exposures of deformed metasediments, since these display large numbers of examples of folds at multiple scales. Here, in particular, the simple and contrasting lithologies, assist in the identification of fold structures and interference patterns, whilst cleavages are well developed and easily identified in most localities, with exposures illustrating bedding to cleavage symmetries well (**Figures 3B, C**). Furthermore, way-up structures, in the form of trough cross-bedding (**Figure 3D**), and syneresis cracks, are present at most localities, allowing stratigraphic orientation to be used to help interpret the large scale fold structures. Although exposure is sufficient in the mapping area to allow interpretation of the fold interference pattern comprising the large-scale structure, it is not complete and thus is both challenging and a useful example of how to interpret incomplete data.

Many of the features of the outdoor environment are, however, difficult to implement within a VFT, in particular those objectives requiring spatial awareness of correlations across the landscape, or observations at very different scales. Furthermore, effective teaching of such complex multi-scale structural features requires a high degree of educator-student interaction on a group and one-to-one basis, requiring virtual teaching tools to enable effective communication.

THE KINLOCHLEVEN VIRTUAL FIELDTRIP

In response to the COVID-19 pandemic, the 2020 Kinlochleven fieldtrip was replaced by a fully virtual course to the same field area with the same overall goals, and intended to fulfill the same learning objectives. To deliver as optimal a learning experience as possible, a virtual field environment was produced that replicated the outdoor field environment closely. This was delivered as an interactive three-dimensional digital package, leveraging video game technology and paradigms. The decision to deliver the course as a virtual environment package (VEP), rather than as a course based on remote sensing data or field data, such as photographs/videos and structural measurements, followed from the successful delivery of the department's third year Sardinia fieldtrip as a series of localities recreated as virtual environments within the game engine Unity. In contrast to this forerunner course, however, the Kinlochleven fieldtrip was designed to operate within the in-house multiuser platform ESERC. This approach provided a key advance in the delivery of learning objectives since its multiuser capabilities allowed direct realtime interaction between students and educators.

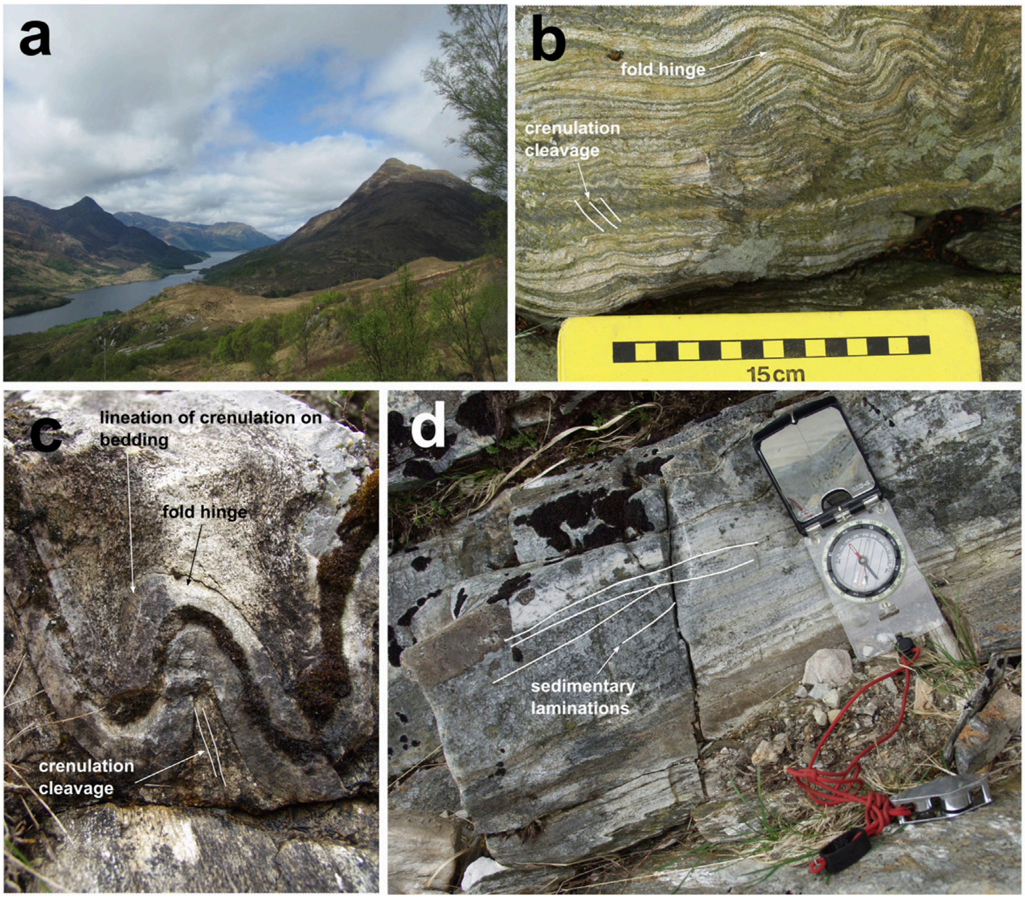

FIGURE 3 | Field photographs from Kinlochleven. **(A)** A view of the landscape viewing west from Mamore along Loch Leven, **(B)** open minor folds and crenulation cleavage in the Binnein Quartzite Formation, **(C)** a tight minor fold with z-symmetry in the Eilde Schist Formation. The fold is plunging towards the viewer. **(D)** Trough cross lamination within the Binnein Quartzite Formation revealing an upright way-up.

The two elements of the Kinlochleven VFT, the virtual environment package (VEP) and the ESERC platform are described below, including the key design and development criteria used to fulfil teaching objectives.

ESERC Software

The ESERC software was developed in-house by Mark Sutton in order to support a wide-range of remote virtual activities including thin-section and hand-specimen inspection, single locality field activities, bespoke lab-based activities, and entire fieldtrips. The software is a desktop application (i.e., not virtual reality) and acts as a portal to activities allowing students to download activity packages, and controls access and permission levels for students, staff and teaching assistants. A desktop application was chosen to ensure inclusivity since students used their own laptops and desktop computers to run ESERC, most of which had too low performance to enable VR headsets. It also provides networking support through server and client applications, allowing student-educator interaction in real time including communication by text, voice and video. These facilities allowed up to 100 students and educators to be present within a single instance of a virtual environment, with multiple instances potentially running at a single time.

The technical details of ESERC design and implementation are beyond the scope of the current paper, however, the client software was created in Unity with networking support created using the Dark Rift library. Individual activity packages are opened within ESERC using as asset bundles using a bespoke package manager designed to allow scripts to be included along with bundles allowing custom behaviours and events to be added to each activity.

The Virtual Environment Package

Whilst ESERC provided communication and group-management tools, and access to packages, Virtual Environment Packages (VEPs) provide the specific content used to meet course objectives. The VEPs for the fieldtrip were constructed using technology developed for the creation of video game worlds and recreated ~4 km^2 of the mapping area utilized in the real world Kinlochleven fieldtrip. An ESERC VEP is implemented as a Unity prefab (a hierarchically organized collection of Unity game objects), which can contain custom code implementing unique behaviours. ESERC VEPs are implemented using a custom export/import system, akin to Unity bundles.

As in video games, the design and development of the VEPs required compromise decisions to be made between teaching content and application performance. The key technical concepts of video game worlds were, therefore, important in delivering content since inclusive delivery of the course depends on the performance of the application, which requires a sufficiently high framerate for an immersive and interactive experience. Design of VEPs also was guided by the structural geology of the mapping area, as they must include key outcrops required to characterise the structures and to allow identification of the stratigraphic units present within the area. Furthermore, the reproduction of the key outcrops was also subject to data collection limitations.

In addition to technical and geological constraints, the Kinlochleven field course also aimed to recreate as much of the field experience for undergraduates as possible, since environmental factors such as vegetation and topography are important elements in geological mapping, and logistical factors such as traverse selection and work progression are key to the success of mapping exercises. In addition, the inclusion of realistic and in particular animated features (such as traffic on roads, sheep, and midges) increases immersion in, and hence engagement with, the virtual environment. These three elements of VEP design: 1) the video game technology, 2) key geological constraints, and 3) environment recreation and immersion are described in the following sections together with a brief description of the practical methods used.

Technical Aspects of Video Game Worlds

Many video games utilize virtual environments as digital recreations of fictious (or real) spaces that allow the user to explore an area with a degree of immersion. Three-dimensional worlds within modern games use digital models of physical objects to recreate the environment. Models also can be used to define the user interactivity with the environment through the physics engine of the game application, allowing some elements to be solid objects and others to trigger coded events. The rendering engine of a video game application composites the image shown on the computer screen at every timestep (frame) by calculating and constructing the view observed by a virtual camera located in the game world. Models are, therefore, the fundamental elements of 3D synthetic worlds and their technical aspects are important to understand since they have overhead requirements that determine application performance and thus activity inclusivity.

Digital models consist of a mesh of faces (either triangles or quads) defined by corner vertices over which a texture is projected (e.g., Copine, 2011; **Figure 4**). Each vertex in the model has a unique index, a position (a three-dimensional position vector) and a UV coordinate (a two-dimensional vector, where U and V denote the reference axes). UV coordinates identify the position within the texture image that is to be displayed at that location on the mesh. Vertices can also include a normal vector, which defines the orientation of the surface at that location on the model. Faces are represented as lists of the index numbers of either three vertices (triangles) or four vertices (quads).

The structure of models influences their overhead. Typically all meshes and textures used in a scene are loaded into random access memory (RAM) when the scene is initialized, and when used they are moved to the separate (smaller but faster) RAM associated with the GPU. Owing to the finite nature of both forms of RAM, excessive memory demands can significantly slow applications or in a worst-case scenario cause an application to stop responding. The cumulative size of models and textures is thus a crucial consideration when designing a virtual world and in particular in the maximum complexity that can be included. In general meshes are cheaper than textures since those comprising a few tens of thousands of faces usually provide a sufficiently accurate representation of a solid object when used in combination with detailed textures. The memory dedicated to textures is a more significant problem since they determine the ultimate pixel resolution on the model. In a 10 × 10 m outcrop, for example, a 1024 × 1024 pixel texture image provides a resolution of only 1 cm per pixel, meaning smaller scale detail cannot be observed, and has a memory cost of ~3 Mb. In contrast a texture image of 8192 × 8192 pixels provides a resolution nearer 1 mm, but the memory cost increases to 192 Mb. Although 32–64 Gb of system RAM and 4–8 Gb of GPU RAM might be present on a high-end gaming computer or workstation, we targeted a more realistic minimal specification of 4 Gb system RAM, of which up to 2 Gb may be required by the operating system, and ~0.5 Gb is required to operate the ESERC platform. GPU RAM may also be very limited on low-specification computers. A limit of ~1 Gb of RAM for the VEPs was implemented in the design stage in order to ensure the VFT could be used by all students registered on the module. Designing VEPs, therefore requires careful evaluation of the minimum required texture resolution for each outcrop.

Decreasing RAM overhead is crucial in ensuring the VEP can operate satisfactorily for all students. Algorithmic compression of textures provides one means of decreasing texture memory overhead, as modern GPUs are capable of operating directly on compressed texture images, decompressing them on use with little performance cost. The Unity game engine utilized in Kinlochleven VEPs supports several such compression options; highly compressed textures can reduce memory cost by an order of magnitude or more, but at the expense of degradation of image quality. A per-texture choice was made on the degree of compression applied, and the number of 8192 × 8192 textures kept to a minimum, with 4096 × 4096 textures preferred whenever possible for large outcrops.

An additional method of reducing memory cost was the reuse of models and textures. During development those outcrops considered essential in defining the tectonic

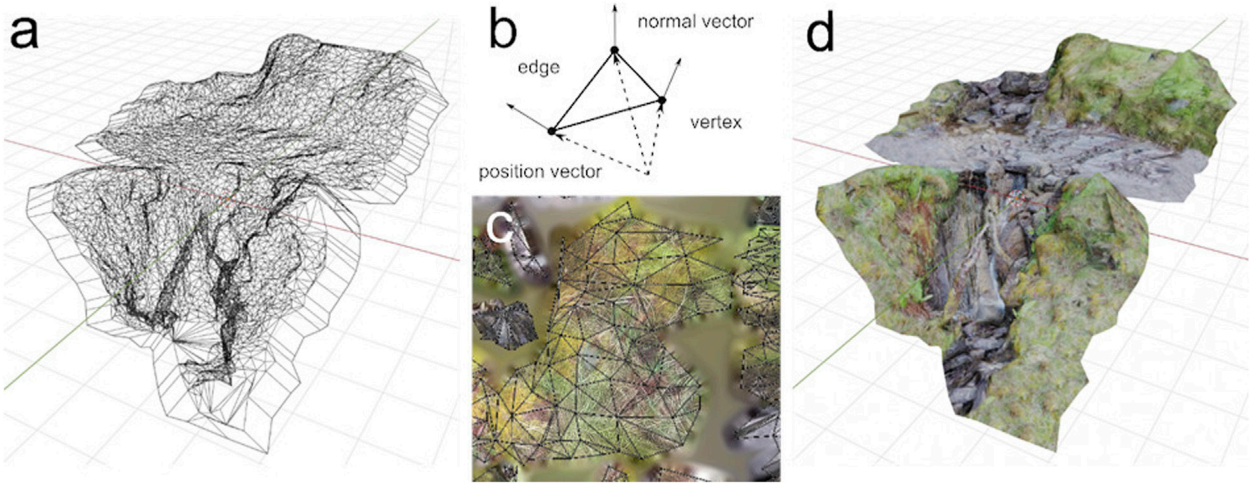

FIGURE 4 | Concepts in 3D models showing a locality in Kinlochleven. Models consist of meshes **(A)** that are constructed from triangular faces **(B)**. Each vertex in the face has normal vectors and stores the UV coordinates **(C)** of the texture that will be projected over it **(D)**.

structure were identified as critical and were generated from field-collected photogrammetry data. In game development parlance these are known as *hero assets* – entities to which greater resources are devoted since they are crucial to core game mechanics. In a video game an example of a hero asset would be a unique monster that must be defeated at the end of a game level. In the Kinlochleven VEP many more non-unique outcrops were identified, often those which were small and poorly exposed. These are termed here scatter assets and were used largely to provide opportunities for bedding and way-up measurements and to constrain the location of mappable boundaries. Scatter assets are duplicated in the scene with only their location, scale and orientation stored with a reference to the same model and texture stored (once) in memory. Some scatter asset outcrops were created by cutting of hero assets in a 3D modelling applications, thus their meshes and textures were based on field collected data providing a realistic appearance at a low memory overhead.

In addition to outcrops, boulders were also added to the VEP. In Unity large numbers of objects can be added to the terrain as decorative elements and are generated by GPU instancing, which allows data on a single mesh and texture to be ultilised to generate many different objects. Boulders of particular lithologies were added to the VEP to provide geological information with variations in abundance of lithologies occurring in the vicinity of boundaries and within stream sections.

Whilst mesh-models of outcrops provided the core data for Kinlochleven VEPs, landscape and decorative elements were also important for context and immersion. Landscape was implemented using Unity's Terrain system; terrains (e.g., Polack, 2003) are defined by a grid of height measurements (a *heightmap*) and are rendered by the Unity engine via internal conversion to an optimally efficient mesh surface that is automatically simplified with distance from the camera to improve performance (Lindstrom et al., 1996). Heightmaps can be created from an imported greyscale heightmap image, and/or manually edited within the Unity design environment. For the Kinlochleven VEPs, available digital elevation models were used to generate terrain with a horizontal resolution of ~2 m using four 1024 × 1024 heightmaps. The choice of terrain resolution is important since it determines how closely the height can be matched to certain features. Note that Terrain/heightmap rendering of landscape does not support overhangs; where these are required, mesh-models must be used.

Terrains in Unity can be textured with repeated tiled texture images, providing enhanced detail and realism (e.g., Polack, 2003). Textures can be used to denote areas with different vegetation (**Figure 5**). Each texture used in terrain painting must be carefully prepared to be "seamless," i.e., to be tileable without the boundaries between each identical image being apparent. Textures should also be relatively homogeneous since a pronounced feature, such as a darker area, will be repeated to produce a regular pattern across the terrain, which looks unrealistic. Unity terrains support multiple texture images for any given terrain, although larger numbers of textures impacts performance (see below). Texture images are blended according to gridded control data ("splatmaps"), which defines the strength of each image in the blend at any point. Splatmap blending is editable through manual and semi-automated painting tools, allowing the addition of noise, and can provide a high degree of visual realism for terrains.

Unity terrains provide tools for the semi-automated scattering of predefined mesh-models onto the terrain surface; this approach is typically used for the placement of large areas of vegetation. While control over model placement is limited, with variations in models (e.g., scale and rotation) being randomly generated by the engine, this approach provides a simple method of placing very large numbers (10 s of thousands) of objects such as trees, bushes and boulders onto a terrain. Mesh-models placed in this way use a single mesh and texture, and thus have limited memory cost.

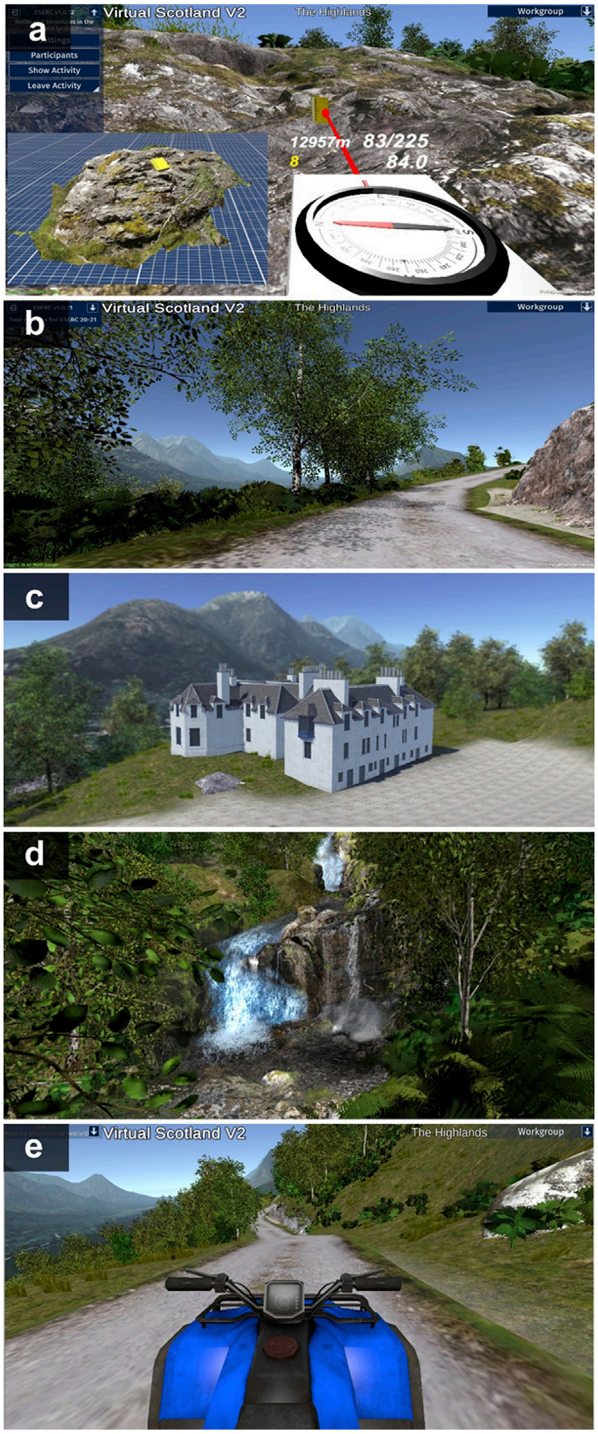

FIGURE 5 | Screenshots of the Kinlochleven virtual environment package. **(A)** An outcrop model with virtual compass taking a measurement on a notebook. The notebook is aligned to a structural feature. The inset shows a detailed model of part of the outcrop. **(B)** A view along the loch showing a road constructed from a texture mesh. On the left is an outcrop of porphyry. On the horizon is the distance landscape created from a simple textured mesh. Notice the realtime shadows cast by the trees. **(C)** Mamore lodge. The model was created from photo references. **(D)** A waterfall on one of the rivers. **(E)** A user-controlled quad bike.

Another important factor in the performance of video games is rendering speed. Rendering is the process by which a virtual camera captures an image of the scene and then transfers it to the screen buffer. Rendering occurs at each timestep and is performed by a sequence of steps known collectively as the rendering pipeline (e.g., Akenine-Möller et al., 2018). The pipeline involves evaluating screen geometry, calculating light from virtual light sources in the scene to determine the gain of colours, transforming the world coordinates of models and terrain into camera/screen coordinates, and rasterizing the image into individual screen pixels for display. Rendering has been designed to be as efficient as possible and modern GPUs are designed specifically to accelerate the rendering pipeline, which is implemented using "shader" programs that run in a massively parallel manner on the GPU rather than the CPU. The speed of rendering (the frames-per-second or fps) is crucial in the performance of a 3D application. At low fps, 3D applications become less immersive and difficult to control, or even can cause physical discomfort to the user.

Several techniques are used to improve the speed of rendering and most are applied by the game engine with no intervention required by the application developer. Frustrum culling is one such optimisation; this restricts many of the calculations to geometry that lies within the field of view of the virtual camera and between the near and far clipping plane. Any model closer to the camera than the near plane and further than the far clipping plane will not be rendered. Only user-interface elements (e.g., menus) and a specialized distant entity known as the skybox will be rendered without being affected by the clip planes of the camera. Rendering will also frequently perform backface culling, in which faces of mesh-models that are oriented away from the camera are ignored, dramatically decreasing the amount of data that needs to be processed.

Multum in Parvo (Mip)-mapping is also used by the Unity rendering pipeline to increase rendering speed. Mipmaps are a set of versions of a texture at decreasing resolution. Mip-mapping uses lower resolution textures at greater distance from the camera, increasing rendering efficiency at the cost of a small increase in memory cost. It also decreases artifacts generated by aliasing and Moire patterns that occur when a patterned image is reduced in resolution (e.g., with distance). Mipmaps are auto-generated when images are imported into the engine.

Some rendering efficiencies are controlled by design choices, in particular in the models used in a scene. Level of Detail (LOD) is a commonly used technique where multiple versions of a mesh are supplied to the engine, each increasingly simplified, and these simpler versions are used as stand-ins for the mesh when it is distant from the camera. As simpler versions contain fewer faces, they are quicker to render. LOD systems in Unity support developer-defined distance thresholds for model switching, and transition techniques that reduce visual artifacts associated with model-switching (known as "popping"). Creating LOD models can be time-consuming since it requires generating many versions of the same mesh and combining them in the game engine into a single asset. Often automatic approaches to mesh simplification ("decimation" algorithms) produce imperfect results and require manual alterations. Generation of LODs is, however, typically worthwhile for assets that are duplicated around a scene, such as trees or boulders. Often the two lowest levels of detail of LOD assets are billboards and culling. A billboard is a simple one-sided plane, which usually faces the camera, and is used when the object is sufficiently small in the field of view. Grass painted on terrain can use billboards with little artefact (although grass will rotate to face the camera as the player moves). Culling is typically used at the largest distance and prevents the asset from being rendered. The object thus disappears from the screen. Appropriate use of LODs can allow a scene to include tens of thousands of objects, such as trees, even on lower specification computers.

The choice of texture type is also important in rendering. Textures that are partially transparent have a high cost during rendering since they must be rendered in order of their distance from the camera (their z-depth), and are hence used sparingly. Other implementational details are also important. Rendering computation involves the composition by the CPU of a number of *draw calls*, individual packages of instructional data sent to the GPU. Draw calls are relatively expensive, and the number of draw calls in each frame can strongly influence rendering speed. Factors influencing the number of draw calls are complex and dependent on details of engine implementation, knowledge of which can hence greatly impact performance. For example, in Unity every 4 textures used on terrain requires another draw call, and thus increasing texture count on a terrain from 4 to 5 results in a much greater reduction in performance than increasing it from 3 to 4.

In addition to rendering performance, computationally expensive code can cause performance issues in video games. Raycasting, for example, is a particularly intensive process that searches for the first object to be encountered along a ray (vector). Raycasting is used for numerous purposes, for example, to detect the height of the terrain/objects at a particular location, or the presence of an obstruction in front of the player. Collision detection is also expensive and is determined by the intersection of collision meshes. Complex objects such as outcrops of rock, on which a player is likely to want to interact with, will require complex collision meshes, whilst objects such as trees can be simplifed to an appropriately chosen mesh, such as a cylinder representing the tree trunk. Careful choice of the collision meshes used and the type of collision detection (e.g., discrete or continuous) can greatly improve the performance of code processed between timesteps.

Physics in games can also affect performance. In most video games physics calculations are performed by the engine, often using physics dedicated GPU which performs a simplified simulation of a subset of objects in the scene (e.g., Millington, 2010). Typically, most objects in game scenes are set to be static, rather than dynamic, to lower the cost of the physics simulation. In Unity, physics is only applied to those objects with a rigid body component. Objects that are not moving are set to sleep until a force is applied to them, culling them from calculations and decreasing computational costs further. The number of rigid bodies active at one time can thus be an important consideration for performance.

Geological Considerations

Accurate representation of exposures is crucial for the creation of a virtual environment suitable for geological mapping and interpretation of tectonic structures. For the Kinlochleven fieldtrip 3D models were created from key exposures using drone imagery collected specifically for the course in August 2020. The choice of exposures was critical and dependent on the learning objectives of the field course. Owing to the polyphase deformation and the greenschist facies metamorphism, identification of the generation of folds requires detailed models of minor folds, to identify their symmetry, and data on the orientation of crenulation and pervasive cleavage. Localities with clear minor folds and cleavages were selected, particularly where they help define the locations of fold axial traces or geological boundaries across the terrain. In addition, some boundaries in the area must be inferred from the quartzite to phyllite ratio within exposures since they are gradational, thus localities with good exposure of lithology were also selected. Several intrusions of porphyry and lamprophyre are also present in the mapping area, and thus localities with good exposure were collected to provide context for lithological examination. Finally, although most data was collected to enable reconstruction of 3D models, a large number of oriented photographs were taken at outcrops to provide the highest resolution data. This was particularly important in recording way-up structures. High resolution images also provide information on lithology and mineralogy, particularly relevant for the igneous rocks in the area and the interpretation of their emplacement mechanisms.

Images of 82 outcrops were collected over a 1-week field visit to the mapping area, totaling 65 Gb of data. The quality of models produced by photogrammetry depends on many factors, such as lighting angle, shadow intensity and the presence of obscuring vegetation or water. Overcast lighting is preferable for data collection since model resolution is impaired by deep shadows on outcrops and colour can be over-saturated in bright sunlit conditions. Models generated in overcast conditions can also be rendered in the game engine in lit mode, allowing the engine to render shadows from the virtual lights present in the scene. Limited field time, however, meant it was impossible to wait for optimal conditions, and much data had to be collected in direct sunlit conditions. A useful compromise to enable realistic reproduction of outcrops collected in bright conditions with dark shadows is to set their rendering preferences to unlit and adjust the virtual directional lighting (sunlight) in the scene to match the majority of such model outcrops.

Data collection by drone requires the choice of resolution according to drone camera resolution and height. In part the choice of resolution is dependent on the scale of detailed features. In Kinlochleven, for example, the Binnein and Eilde Quartzite formations often have thicker beds and larger scale folds than in the Binnein and Eilde Schist formations and thus lower resolution, higher altitude data collection was possible. Resolution may also depend on the size of exposures and processing constraints as described below.

The practicalities of data collection also depend on the nature of exposure. Many drones can follow user-defined flight patterns, such as grids, to ensure suitable photograph overlap for photogrammetry. Flight patterns, however, are most appropriate for exposures with little topography and cannot collect data from beneath overhangs. For exposures on steep slopes, with highly irregular surfaces, or with nearby obscuring vegetation, manual flight and over-coverage of imagery provides more reliable results. Issues were encountered in the forested areas on the lower slopes of the mapping area, especially where small birch trees were present, and in deep ravines close to waterfalls where maneuvering a drone between overhanging trees can be difficult. Drone imagery at multiple angles is also useful to ensure coverage on outcrops with highly irregular surfaces.

For the Kinlochleven data a lightweight (249 g) DJI Mavic Mini was used to collect data. This drone has a flight time of ~20 min per battery, which allowed for approximately 1.5 h of flight time per day with three batteries and a power bank. Operation of a drone in UK airspace requires the operator to have a drone pilots license and the drone flight regulations must be followed. Scotland is a restricted airspace at certain times owing to military training flights and NOTAMS (Notifications for Airmen) must be checked prior to flying.

In addition to drone imagery, data was also collected by hand-held camera to capture small areas of exposures with significant features, in particular to illustrate minor fold and cleavage symmetries and orientations (**Figure 5A**). Numerous photographs were taken at incremental angles around the area of interest and at several different heights. Variable numbers of photographs are required to ensure successful reconstruction by photogrammetry with a minimum of 3 needed. A selfie-stick or tripod proved useful to obtain additional elevation. In several cases hand-held images were used to reconstruct images in locations where a drone could not be flown, for example, within 50 m of a road or building where it is illegal in the UK to fly.

Processing of drone images to generate 3D models was performed by photogrammetry (e.g., Mikhail et al., 2001) using the applications Zephyr and Meshroom. The latter application is free to use and generates excellent textures, however, it suffers from artefacts related to vegetation, which can be rendered as indented topography. Processing of drone data required a dedicated high specification computer and over ~500 h of processing time. Generated models also usually require manual editing to remove artefacts, particularly around the edges of models. Blender, a free 3D modelling application, was used to edit meshes by deleting unwanted faces and sculpting areas with geometry artefacts. In some cases missing data was present within outcrops, in particular in those collected by drone in areas where maneuvering was limited. Sculpting and texture painting was used to recreate missing parts of some models using field photographs. Manual editing was a significant time component in preparing the VEP.

Environment and Immersion

Immersion is a key principle in video games since it enhances engagement with the activity. It is through immersive elements within the game world that users develop a mental involvement with the events and intellectual challenges that make up the activity (Michailidis et al., 2018). Immersion was adopted as a fundamental concept in the development of the Kinlochleven VEP to address the overall goal of the course since studies have shown that active participation enhances learning outcomes (Fletcher et al., 2007). In this paper immersion is defined as “a psychological concept that describes the experience of being present in the game’s virtual world” and differs from its common usage in VFTs, where it is often held that only virtual reality (via headsets) is truly immersive since it surrounds the user with the virtual world (Klippel et al., 2019). Here it is argued that whilst iVR experiences certainly provide enhanced immersion, desktop applications can also be immersive, indeed that desktop computer games can cause users to lose a sense of the passing of time and to become unaware of the real world are a testament to their potential for immersion (Michailidis et al., 2018).

Although an interpretation of the structure could have been made from digital models of outcrops inspected using a model viewer, with the spatial relationships illustrated using maps or Google Earth, this exercise would have provided a learning experience fundamentally different to real world fieldwork, involving different work progression, and artificial synthesis of data. In contrast, making the experience immersive, and thus as similar to real fieldwork as possible, engenders direct practice of skills relevant to the real world. Immersion also overcomes a major disadvantage of virtual activities, namely the fatigue that can result from repetitive tasks. In an immersive environment the presence of special features not only provides a more realistic experience, but also continually re-engages students with the activity by presenting new and unique elements.

In the Kinlochleven VEP the wider landscape of the highlands was recreated to reinforce the realism of the scene (**Figure 5B**). The mapping area topography was generated as a textured terrain 4 km^2 in area, as described in *Geological Considerations*, however, the mountains outside this area, including the Munro Na Gruagaichean and the characteristic Sgorr na Ciche (Pap of Glencoe), were created as a lower resolution mesh textured with aerial imagery. The camera far-clipping plane was set to a distance of 10 km to allow these features to be observed and a distance-dependent atmospheric haze (known as a fog in video games) was used to emphasize the scale of the landscape. The objective of this landscape was in part to make students feel they really had visited the Highlands, improving satisfaction, however, more subtly it ensures that different parts of the mapping area presented different views to reduce activity fatigue.

Some immersive elements were introduced owing to their application to specific learning objectives. Map interpretation and orientation is an important skill in geological mapping and thus having realistic topography is essential. Mountain peaks, rivers, roads and buildings all provide opportunities to find a location accurately using traditional techniques on a map. Including these elements realistically in the VEP allowed educators to teach positional awareness and to observe geology across landscape. A teaching decision was made not to display coordinates to make students evaluate their location using traditional techniques. Models of buildings, bridges and signs were particularly important since they relate to map reading, however, they also generate unique features that renew interest in the activity. These were created manually using Blender from photo references (**Figure 5C**).

Bodies of water are difficult to represent in video games owing to their complex reflections and refractions. In the Kinlochleven VEP a custom water shader was applied to a simple mesh representing the surface of the water. The shader calculates a rendering effect on the graphics pipeline for the water object. The shader works by imposing spatially variable normal, derived from textures, which influence lighting to generate wave-like patterns across the surface. The texture was offset with time to represent wave motion, whilst two textures, moving at different speeds, were combined to generate a wave interference pattern. For rivers the movement speed was set by the slope of the water plane. To enable transparency and refraction the scene image behind the plane was captured and deformed by values obtained from the fluctuating normal. These images were then blended with a water colour according to the depth of the surface below the water plane. Reflections were enabled using an entity known as a reflection probe which consists of six orthogonal cameras which capture images of the scene from a view-point below the player. These images were combined with the diffuse colour generated from the previous steps to produce a simulated reflection. To enhance the immersion, sound emitters playing a stream sound effect were added to the scene with a volume dependent on the distance to the player. Physical effects on the player were also added when in water, such as a downstream velocity in rivers, and buoyancy. These effects were included in the coded behaviors of the player as described below. Special features, such as waterfalls were created by applying moving foam textures and sound effects where the slope of the water plane was highest (**Figure 5D**). The combination of visual, audio and dynamic effects was necessary to ensure rivers met the expectations of the user since counter-intuitive elements in virtual environments can be immersion-breaking.

A crucial immersive element of the VEP is vegetation since it restricts the view distance of the player. In outdoor fieldwork vegetation obscures exposure and forms natural barriers influencing the choice of optimal traverses in mapping structure. Vegetation forces students to be observant of their surroundings and prevents direct observation of spatial correlations dictating the use of structural measurements to determine changes in orientation and identify major fold axial surfaces. Models of vegetation were constructed using meshes to represent trunks and branches, and transparent planes displaying leaf textures to recreate foliage. Grass was created as simple billboards. In the VEP ~30,000 instances of birch and beech trees with LODs were painted on terrain, together with ~60,000 ferns and ~500,000 grass objects (**Figure 5**).

Realistic behaviours are also important in generating immersion. In a simple 3D model viewer users have full control of the camera and can view models from any direction and at any scale. Although free camera movement is the optimal means of inspecting structural features it is not possible in the real world. Learning how to inspect exposures is an important objective of the course, for example, folds are most readily observed when viewing along plunge. Realistic behaviour of the user, is therefore a key element in virtual teaching of mapping skills.

To facilitate immersive user behaviour a physics-based player controller was used. These entities consist of a collision mesh, in this case a capsule, set as a rigid body with rotation only permitted on a vertical axis. Gravity and friction are applied to the player game object by the physics engine whilst user input from the keyboard or mouse is applied by incrementing or decrementing linear and angular velocity. The virtual camera is set as a child of the player object, meaning its position and rotation are changed as the user moves. To enable the view direction to change independent of player facing-direction, the camera orientation can be changed through user input, simulating head movement. A wide range of behaviours are possible with physics-based controllers, the player can walk, run, jump, slide and float. In addition to user-controlled camera rotation, an involuntary head bob, involving oscillating the vertical position of the camera within the player object, was implemented to reinforce the sensation of walking and running. A sound emitter attached to the player was used to play footstep sound effects, dependent on forward or backward velocity to engender realism. The sound effect that played was also changed depending the surface below the user, with foliage, wood, gravel and water splash sounds used. Walking and running speed were set to higher than normal real world speeds as is typical in video games.

A key issue in creating immersion is environment resolution. Outcrops typically have meshes with resolutions of 10 cm to 2 mm, depending on their size, whilst the terrain mesh has a resolution of 2 m. Realistic placement of outcrop models, therefore, poses an issue since the terrain cannot be simply sculpted and thus gaps occur between the model and ground. Three solutions were utilized in the VEP to reduce these artefacts: 1) sculpting of the outer parts of outcrop models to fit, 2) using duplicated meshes having the same texture as the ground to fill spaces, or 3) obscuring gaps with vegetation. The former is the most time-intensive and is not possible with some outcrop models.

Detailed environment features, such as roads and paths, are also affected by resolution issues. Although terrain painting can be used to produce these features it has too low resolution to generate abrupt changes in ground texture or generate complex boundaries. Accurate reconstruction of roads and paths is, however, crucial since they are important in finding position during mapping. To overcome these issues roads and paths were modelled as meshes fitted to the terrain and were created procedurally (**Figure 5B**).

Interaction with outcrop models was achieved using ESERC hotspot tools that allow interactable volumes to be placed in the virtual world. Hotspots allowed higher resolution models or images to be viewed, for example, illustrating individual folds or lithologies. Measurements were facilitated using tools coded into the VEP. A compass clinometer was included as a dynamic model fixed to the camera so it always appears in the field of view when activated (**Figure 5A**). The compass has a north arrow but also displays the looking direction as a bearing and the dip of the compass. A laser-pointer was added to the compass to allow the user to activate a measurement of the dip and dip-direction under the laser point, whilst lineations could be measured from the looking bearing and dip of the compass by sighting along the compass. To enable measurements to be made by sighting, a notebook that could be aligned with a planar feature was added. The compass clinometer could then be used to take a measurement of the dip and dip-direction of the notebook. These measurement methods were chosen to closely resemble the operation of a real compass clinometer to ensure that the skills learnt were as transferable to the real world as possible. Orientation based on user input was not used since orientation of dip direction is difficult in desktop applications (e.g., Bursztyn et al., 2022).

Finally, some dynamic coded elements were added to the VEP to make the environment and activities more engaging to the user. The Kinlochleven to Oban road lies within the VEP and thus cars were added. Cars were created as wheeled vehicles, a specialized type of object in the Unity game engine, which enables a physically realistic simulation of vehicle behaviour using wheel colliders attached to a rigid body. The spawn times, positions and velocities of vehicles were synchronized between users using the ESERC to ensure that all users saw cars at the same time. The inclusion of cars within the VEP enabled aspects of field safety to be included in the activity. Interactions between cars and users were coded using collision detection. On collision with a car, at above a threshold impulse, a random acceleration is added to the player object, and constraints on rotation were removed. Sound effects and decals were used for dramatic purposes.

Vehicles were also provided for students to use as transport within the VEP. Although the mapping area is only 4 km^2 in area, walking from one side to another is tedious in a virtual environment, even with immersive elements. Quad bikes were provided and were constructed as physics-based wheeled vehicles that could be controlled by the user (**Figure 5E**). Mounting and dismounting bikes was achieved by updating the player object position according to the position of the quad bike, with a spring calculation used to determine player position for a realistic response to acceleration. Sound effects were also applied to increase realism.

To further engage students with the environment other interactive elements were used in the VEP. Sheep were added to some areas and have coded behaviours. These are animated models created in Blender. Sheep have idle behaviours in which they walk and graze at random in an area within a certain distance of their spawn point. When the player enters a trigger surrounding the sheep it runs away from user and bleats. Sheep, therefore, can be herded using either the quad bike or on foot providing a mini-game that renews engagement. Clouds of midges were also added to the VEP as simple models consisting of rotating transparent planes covered with dots. Midges move slowly towards the player when they enter its trigger and nudge the player intermittently whilst emitting annoying sound effects. Midge clouds were placed at locations where they do not interfere with outcrop inspection (contrary to the real world).

Finally, a few music triggers were used in the VEP to engender an emotive connection between students and the environment. Traditional folk music was used to highlight the magical sensation associated with the Highlands, and were placed at locations where the landscape view is suddenly revealed.

Construction Methods

Unity, like most game engines has in-built tools to allow the construction of environments. The Unity editor allows model and texture assets to be imported and stored in folders. These assets can then be dragged and dropped into the scene and positioned and oriented either using numerical values or through manipulation of handle gizmos. Orientation is crucial for proper structural interpretation and models were oriented using measurements taken during the real fieldwork, and from maps created by Dr Paul Garrard over the 30 years the fieldtrip has been operated by Imperial College. High resolution models, which are loaded from interaction hotspots, were oriented using images of a compass clinometer placed on the outcrop during data collection.

Terrain was generated by importing a digital elevation model as a greyscale heightmap followed by minor sculpting using tools available in Unity. Sculpting was performed since, even with a 2 m resolution DEM, roads and paths were not suitably recreated. Ravines and river beds also needed some sculpting by reference to photographs to adequately match the topography maps. Terrain textures were manually painted using the brushes available in Unity. Trees and grass were also added by painting on the terrain.

Course Delivery

The completed virtual environment was a 950 Mb asset bundle and was downloaded by students within ESERC. The course was run for 45 students over 7 full days following the same schedule as the real-world fieldtrip. The duration of daily VFT sessions was 9 am till 5 pm with an hour break for lunch. The first 4 days of the course the students were given daily introductions and followed set traverses in small groups of 4-5 students, with educators moving between groups to provide guidance. The traverses were chosen to provide a step-by-step introduction to the over-all structure and lithologies, starting with definitions of the mappable units and then defining different generations of fold and their characteristics. In the last few days of the course students worked independently and chose their own traverses in order to complete the map and characterize the structures. During the course summaries and explanations were given to groups at critical exposures ensuring that students understood important concepts. A built-in virtual slide screen, which can be summoned by the educators, was used in these sessions. Students recorded data within notebooks and on printed topography maps. Notes included field sketches. These techniques were chosen, rather than electronic maps and screen-captures, to ensure the skills learnt were transferable.

The Student Experience

Students experienced the activity as a desktop application showing the 3D view of the world in their avatars looking direction. Students participated online from home during pandemic lockdowns using their own laptops or desktop computers. Students were able to move freely in the world using either movement keys (WADS) or mouse (middle mouse button). The mouse could also be used to look in different directions by changing the orientation of the camera. Students interact with the environment using measurement tools (*Environment and Immersion*) and through hotspots allowing access to either high resolution field images or higher resolution models loaded into a separate scene. Measurements available depend on the locality. Detailed models were used for critical localities (hero localities) on which a large number of measurements (>10) on folds and cleavages were possible. Typically these localities had 4–10 hotspots with either higher resolution models or images. Scatter localities had more limited measurements, typically restricted to bedding orientation with a single image hotspot showing way-up structures.

Interaction was achieved via voice or text communications built-into the ESERC framework. Communications operate differently depending on group settings. In megaphone mode all communications were global with all students able to hear and speak to educators and other students. In group mode students can only communicate with other students in their group, but can message staff whether they are currently in the same instance as that group of students. This allows students to request educator assistance. Educators can enter one to one communication with an individual student, can switch to different group instances or can activate megaphone mode to communicate with all students. Educators can also teleport to the virtual location of students or teleport students to their location.

Virtual *Vs.* Outdoor Field Geology

Behavioural Indicators

Although qualitative, observations of student behaviour during the course suggested excellent engagement and immersion in the activity. As students were present as avatars and their looking towards directions could be seen, it was noticeable that students would look towards the educator's avatar when they spoke, even though this is not necessary in the virtual world. Similarly end of day summaries were given in a global voice channel, and all users in the environment, wherever they were, could hear the summary. Despite this, students automatically gathered around the educator during summaries as they would in outdoors fieldwork. Students arranged themselves in the virtual world where they had a clear line of sight to the educator's avatar, mirroring real world behaviour.

Some student behaviour revealed the extent of the engagement with the activity. Students were discovered to be filming screen captures of each other jumping off waterfalls into the underlying plunge pool. These films they posted on social media. Students also were found engaged in races on their quad bikes, or had competitions to see who could jump the furthest off a cliff. After discovering cars could collide with their avatars, students actively started looking both ways before they crossed the road and warned each other of approaching traffic. Finally, students were discovered to be using the virtual environment for social purposes outside of work hours, suggesting they were very comfortable spending time in the virtual world. All these behaviours suggest excellent spatial presence (Klippel et al., 2019).

Whilst the level of engagement with the world and activity was excellent an initial familiarization with the mechanics of the virtual world was necessary. Although most students were familiar with movement controls, which followed a similar format to first-person-shooter video games, some students struggled for the first few hours with controls and navigation. Some students complained on the first morning of being stuck behind trees and being unable to jump over small obstacles and required teleporting to educator locations. Teleport requests ceased after the first day suggesting acclimatization to controls. Similarly students struggled to identify folds in the first day owing to issues with spatial visualisation of 3D objects in desktop applications. Unlike in VR applications spatial visualization requires camera movement to adequately observe perspective. After the first day, however, structural measurements made by students suggested they had acclimatized to the medium.

Finally, student behaviour also suggested an elevated degree of social anxiety in the virtual activity. Students usually used text rather than voice to communicate whilst in global discussions, unlike in outdoors fieldwork where only verbal contributions are possible. In small group virtual settings, in contrast, students preferred to communicate by speaking to educators. Overall anxiety, however, appeared to be lessened in the VFT, with no student displaying obvious behavioural signs of stress, however, it is possible that these were simply masked by the virtual interface.

DISCUSSION

Learning Outcomes

The educational benefits of video games have been considered extensively by past studies and have demonstrated enhanced learning outcomes compared with traditional learning techniques (Barab et al., 2007; Steinkuehler and Duncan, 2008; Klopfer et al., 2009; Kafai et al., 2010; Clark et al., 2016). The learning gain from video games that enable visualization, which is not possible or logistically impractical in the real world, is particularly significant in subject areas requiring spatial understanding (David, 2012). Moreover games, whether digital or not, provide opportunities to develop and practice problem-solving strategies, cement competence, and hone multi-tasking in complex activities (Squire & Jan, 2007; Squire and Klopfer, 2007). Learning through video games has also been suggested to be particular suitable for the "digital generation," owing to their familiarity with virtual environments and digital environments (Prensky, 2001), and thus has application to the teaching of current undergraduates.

The Kinlochleven VFT is not *senso stricto* a video game, since a game is defined as a rule-based vehicle for play, where the motivation for participation is based on entertainment. As a compulsory course component, designed to meet learning objectives, the Kinlochleven VFT is conceptually closer to a simulation of a real-world experience and thus falls under the definition of a serious game (Prieto and Medina-Medina, 2016), although with elements shared with other epistemic games, because it teaches discipline-dependent problem-solving through experience, rather than the delivery of factual knowledge (e.g., Perkins, 1997).

Measuring the success of a pedagogical strategy involves an evidence-based assessment of the learning gain compared with alternative techniques. Assessment of specific ILOs was made from the maps, cross-sections and notebooks produced by the students. The accuracy of boundaries on maps is a measure not only of interpreting field observations to reconstruct geological boundaries (ILO 4), but also the identification of lithology and extrapolation of structures (ILO 1). Field data coverage on maps provides a proxy for efficiency and work time-management (ILO 5) whilst the accuracy of outcrop positions is a measure of positional awareness and map reading ability (ILO 6). The quality of field notes and sketches (ILO 2, 3) are directly assessed from hand-in work. Assessment of these criteria suggested parity between outdoors and virtual fieldwork. Awareness of field safety (ILO 7) is perhaps the one outcome that is impossible to measure from student behaviour in a consequence-free virtual world.

One quantitative criteria to evaluate the virtual Kinlochleven fieldtrip is the marks distribution for the course compared with previous outdoors fieldtrips. The student cohort in this case is particularly apt since their educational experience up until Kinlochleven was identical to previous cohorts, and marking was undertaken by the same educators, using the same criteria. The over-all average mark for the course was within the range of marks obtained by students who attended the outdoors course over the last 5 years suggesting parity. However, this approach to assessment of the performance of the fieldtrip is dependent on the subjectivity of markers who might subconsciously compensate for the different delivery methods.

An independent approach in comparing the virtual and outdoors field course is to compare student evaluation surveys of the course in 2019 and 2020. Imperial students complete a course and educator evaluation survey every term (SOLE survey) in order to monitor the quality of courses. The SOLE survey allows a comparison of student satisfaction with the quality of the course content and delivery and reveals that in 2019 and 2020 the value differed by only 2%. Student satisfaction surveys, however, are difficult to interpret since they are influenced by varying commensurate workload, differing cohort culture and expectations. Although the results suggest the students were as satifisfied with the VFT it could be they were simply more satisfied than they expected, given the remote nature of the course, thus compromising a direct comparison to previous years.

An alternative method of comparing the quality of assessed work completed during the course may provide a more rigorous insight into the learning gain compared with the outdoors fieldtrip. Anonymised electronic versions of 10 field maps from each the 2019 and 2020 course were selected at random and were assessed by an independent marker - who has experience with marking geological maps for independent mapping projects. The marker was simply asked to identify which maps were produced during the VFT without any assessment of their quality. The result suggests that the geological maps produced during the VFT were indistinguishable from those produced in the outdoors equivalent. Although this assessment does not compare actual learning gains, it is a comparative measure of the attainment of core competences, and thus given the equivalent cohorts, a measure of the effectiveness of the course.

The quantitative measures of successful learning outcomes are also subject to other factors dictated by the technical requirements of virtual worlds. The limits on memory, for example, restrict the number of outcrops that can be included, and although this is still a large number, it is much less than in outdoor environments. The complexity provided by an excess of information, in particular when some is contradictory, makes interpreting polyphase structures easier in a virtual environment than in the outdoors. In virtual environments only elements chosen by the creators are present, providing less diversity and an essentially narrated experience. It is simpler, therefore, to attain the required outcome in a virtual environment, and impossible to completely replicate the degree of uncertainty experienced in outdoor fieldwork. Whilst increased cognitive load is often stated as a major issue in VFTs owing to the additional load associated with operating the activity (Garcia et al., 2023), we suggest that the reduced complexity decreases cognitive load compared with outdoors fieldwork. The training and the quantitative measure of outcomes for the virtual course are thus both somewhat compromised leading to a less valuable learning experience for the student.

Impact on Inclusivity

The inclusivity of the learning activity must also be considered in evaluating its suitability as a replacement for outdoors fieldwork. Video games have been assumed to be particularly suitable as educational tools for current and future generations of undergraduates since they have been considered a digital generation who are accustomed to virtual worlds and interaction (Prensky, 2001). A survey of students who participated in the course, however, revealed that whilst only 25% described themselves as “gamers,” suggesting a high level of engagement with virtual worlds, 30% had never or rarely played video games. Indeed, amongst feedback comments for the course a few students expressed concerns that gamers had an advantage because they were already used to the concepts and movement controls within virtual environments. The assumption that undergraduates are digital natives in all environments is, therefore, flawed. Indeed, some research shows even students who have digital skills struggle to transfer those to study (Kopp et al., 2019).

A greater concern in terms of inclusivity, however, is the influence of social-economic group or gender on familiarity with virtual environments. Social-economic factors are likely to mean a greater proportion of students from more affluent backgrounds are gamers, owing to the costs of equipment and game purchase. Open source data from Statistica suggests 9% of respondents in economic groups A, B and C1 in the UK downloaded games in May 2018, compared to 5% in the less affluent economic groups C2, D, and E. More directly students from affluent backgrounds with more capable computer systems will obtain an enhanced experience, since although efforts were made to ensure virtual activities work on low-specification machines, they perform best on capable systems. Consequently, whilst participation in VFT is more equitable since it reduces the economic outlay on travel expenses, outcomes can be influenced by familiarity with the technological basis of these activities. Furthermore, a gender-bias likely exists in the familiarity of students with virtual environments, Data from Statistica suggests the proportion of males identifying as gamers worldwide (in 13 countries) in 2020 was 59% of the total. Klippel et al. (2019) also showed that VFT delivery has gender bias with female students benefiting from headset-based VR.

Finally, virtual environments also impact on inclusivity for neurally divergent students, in particular those with neurodevelopmental disorders such as ADHD, which can influence spatial awareness and interrupt immersion through attention disruption (e.g., Lou et al., 2019). Students with ADHD diagnoses reported issues with location and spatial awareness within the virtual environment. They also reported difficulties with 3D visualization of outcrop models owing to a lack of stereoscopic stimulus. Several adaptations were implemented to improve inclusivity: (1) glowing trails of footprints, allowing students to more easily trace their path through the virtual environment, (2) the placement of user-defined location markers, and (3) sidewards camera displacement to better simulate head movement. Students reported an improvement after the adaptations, however, the issues were not completely addressed. Therefore, whilst outdoors fieldwork excludes students who cannot participate owing to physical, mental or financial considerations, virtual fieldwork also suffers from inclusivity issues and is less effective, albeit accessible, for less affluent, neurally diverse and female students when viewed as a group. A digital divide thus still exists in virtual field training.

Limitations of Virtual Fieldwork

The limitations of virtual learning in synthetic environments mean virtual courses are not suitable replacements for outdoors fieldtrips since although they can provide many of the required cognitive outcomes, there are some critical attainments they cannot provide.

Although the quantitative measures suggest the virtual Kinlochleven field course was as effective as the outdoor equivalent at delivering the key learning objectives of the course, they measured only the broadest intellectual outcomes and not in-depth or comprehensive understanding. Indeed, there are some obvious limitations to virtual environments that preclude acquiring a complete understanding since although multi-scale observations can be presented in part, observations at the smallest scale, in particular of mineralogy and fabrics, lacks the spatial context that is crucial to fully interpret polyphase folding. Pervasive cleavage is perhaps the most difficult to represent in the virtual environment since it often needs to be observed with a hand lens in the field. Pervasive cleavage is not adequately recorded in photographs, and even the orientation of crenulation cleavages can be subject to greater uncertainty in the virtual environment. Some different approaches arguably provide a more seamless integration for multiscale data, for example, streaming LOD models provided by the V3Geo repository ([1]; Buckley et al., 2022). However, these solutions differ from an immersive field experience and lack the spatial relationships between localities, nor do they provide high resolution images to supplement models. They are, however, invaluable for single locality investigations.

Despite the provision of a large number of localities within the VEP, virtual fieldwork also cannot provide the diversity of examples found in the outdoors. Owing to the limitations of computer memory and application performance the most crucial localities are prioritised greatly reducing complexity. In polyphase structural geology, for example, minor folds with opposing symmetries are common-place and their relative abundances must be evaluated to identify the nature of larger scale structures. The reduced number of examples that can be provided as detailed models in a VFT makes this exercise difficult to replicate. Thus, whilst fine-scale detail is more challenging to evaluate in virtual fieldtrips, the lesser diversity and choice of localities makes integration of data in interpretation less challenging and does not fully prepare students in addressing the levels of uncertainty encountered in outdoors fieldwork.

Finally, although virtual fieldwork does build competence and confidence in field skills, it remains a synthetic exercise. Students who participated in the 2020 Virtual Scotland Fieldtrip had less outdoor field experience than other cohorts and

---

[1] https://v3geo.com/

exhibited less confidence in their abilities when they were able to participate in outdoors fieldwork. In particular, students expressed concerns about performance on later field courses owing to the perception that they had less field experience. Finally, there may also be an impact on career prospects with some employers considering outdoors experience essential.

The Benefits of Virtual Fieldwork

The main benefits of virtual field experiences, as highlighted by several previous studies, are their low running costs and logistical simplicity (Cliffe, 2017; Klippel et al., 2019). Unlike outdoors field courses a virtual activity can be run in a practical session associated with a lecture providing a greatly enhanced learning experience compared with field photographs and maps. The accessible nature of virtual activities also mean that students can practice skills by self-study, meaning outdoor field time can focus on deeper understanding rather than practice of methods. Furthermore, activities in virtual environments require no travel time or equipment preparation, thus distance is not a factor in the logistics of VFTs and allows students to experience the best localities on Earth.

IMPLICATIONS

The Use of Virtual Worlds in Fieldwork Support

After the pandemic the Kinlochleven virtual fieldtrip has been used to support the outdoors fieldtrip. During the 2022 and 2023 outdoors Kinlochleven fieldtrips laptops with the VFT preloaded were taken to the field area. Several students who were unable to fully participate in the outdoors fieldwork, for medical and wellbeing reasons, were able to conduct the mapping exercise using a mixture of outdoors and virtual mapping. On those days where students were not able to work in the outdoors, they conducted their mapping in the virtual world enabling their participation in the field course. The VFT thus provided a useful means of supporting student wellbeing by providing a suitable alternative that facilitated choice without inducing anxiety about performance. The VFT has also been used as a preparatory tool for the outdoor field course, a role recommended by Cliffe (2017), allowing an introduction to the area and its geology to be performed, meaning outdoors field time can be used more efficiently to focus on complex concepts.

The Kinlochleven VEP has also been used to support students who have not been able to attend the field course owing to physical barriers, enabling them to perform the same work as the rest of their cohort with support from an educator. Video calls with an educator from outcrops in field were used to provide these students with additional perspectives. Whilst students explored selected virtual outcrops they could discuss interpretations with an educator at the real-world outcrop, including a guided examination of the outcrop by video. Although these mechanisms are time-intensive they provide not only enhanced learning outcomes, but also enhance engagement and a sense of participation with the cohort, thus encouraging positive wellbeing outcomes.

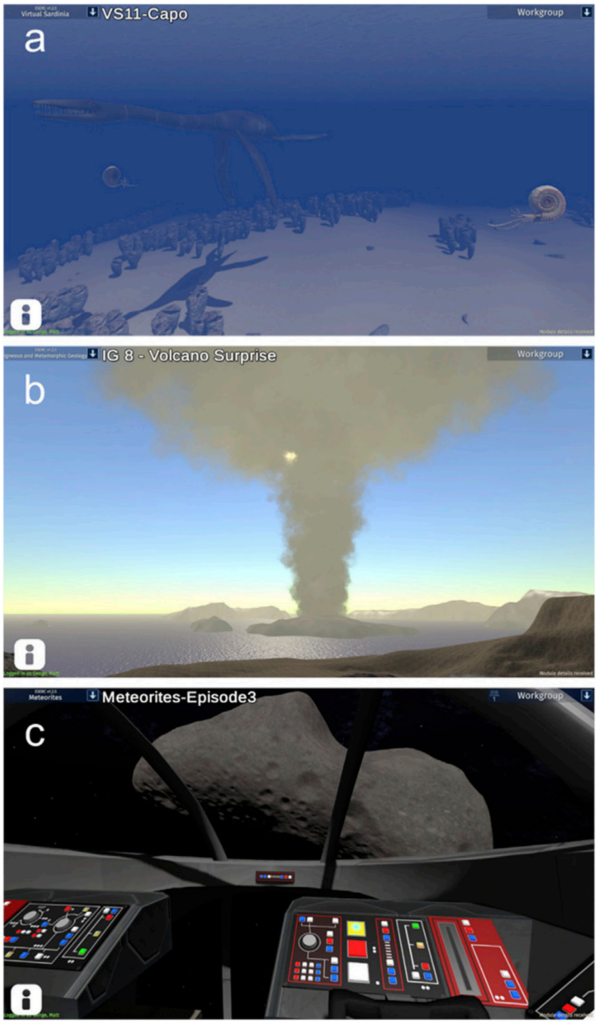

FIGURE 6 | Examples of virtual environment applications illustrating their value to enhance Earth Science teaching. **(A)** Exploring a Cretaceous palaeoenvironment. **(B)** experiencing a volcanic eruption at Santorini, and **(C)** studying asteroids in an extrasolar planetary system.

Virtual Class-Room Activities

Subsequent development of virtual field activities after the Virtual Kinlochleven fieldtrip illustrate their versatility in delivering new learning experiences. Several activities were developed that provided students with experiences that are not possible in the real world. In the Virtual Sardinia field course students were transported from a summary at an outcrop of Mesozoic limestone, into the Cretaceous Tethys Ocean to explore the sedimentary environment and fauna (**Figure 6A**). In their second year Igneous Petrology course students were taken during the practical session to Meglachlori Quarry on Santorini to explore the pyroclastic deposits of the Minoan eruption. This activity culminated in a Plinian eruption of Nea Kameni (the active volcano in the centre of the Caldera; **Figure 6B**). Finally, in the final year Meteorites course practical sessions were entirely undertaken in a virtual environment based in an extrasolar planetary system. Groups of students were given their own futuristic spacecraft and could fly to asteroids, investigate their morphological features and spectroscopic properties, and collect samples that could be examined in the science lab of the ship – a lab complete with optical, petrological and scanning electron microscopes (**Figure 6C**). Virtual field-like activities, therefore, can provide a versatile supplement to traditional teaching techniques that offer enhanced engagement with the subject through unique experiences.

CONCLUSION

A geoscience VFT to Scotland to teach geological mapping was constructed as an immersive field experience and its performance against the equivalent physical fieldtrip assessed. The field course was evaluated to have met the same learning outcomes as the in-person outdoors fieldtrip with the immersive elements improving outcomes by encouraging engagement with the activity. Several limitations were identified that represent challenges in replacing outdoors fieldwork with virtual equivalents. Technical compromises must be made to ensure accessibility that limit the resolution of observations that can be made at localities, decreasing the educational value in comparison with outdoors fieldwork. Likewise, the reduced diversity of observations imperfectly prepares students for the degree of uncertainty encountered in the field. Although VFTs have many benefits for inclusivity, in particular making participation more equitable, certain groups are negatively impacted owing to a lack of prior engagement with computer games or virtual worlds. This digital divide introduces difficulties with parity when it comes to activity progress. The limitations of virtual fieldwork make such activities imperfect substitutes for the real world courses, however, they remain useful tools in the educational arsenal in pre-fieldwork preparation, and in supporting student participation and wellbeing during field courses.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Imperial College Education Ethics Review Process (EERP2021-003). The participants provided informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MG developed the virtual Kinlochleven fieldtrip. The course was delivered by MG and VL. MS developed ESERC—the application in which the virtual package was delivered. PM, AS, and AW all participated in development and delivery of other VFTs at Imperial College. All authors contributed to writing the paper. All authors contributed to the article and approved the submitted version.

FUNDING

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ACKNOWLEDGMENTS

The Kinlochleven virtual fieldtrip would not have been possible without the work of Prof John Cosgrove and Dr Paul Garrard, who from the 1970s have developed the outdoors fieldtrip. Special thanks goes to Paul Garrard whose exceptional field maps and notes provided the factual baseline for the field course.

REFERENCES

Akenine-Möller, T., Haines, E., and Hoffman, N. (2018). *Real-time Rendering*. Boca Raton, Florida: CRC Press, 1198.

Barab, S. A., Zuiker, S., Warren, S., Hickey, D., Ingram-Goble, A., Kwon, E.-J., et al. (2007). Situationally Embodied Curriculum: Relating Formalisms and Contexts. *Sci. Educ.* 91, 750–782. doi:10.1002/sce.20217

Bond, C. E., and Cawood, A. J. (2021). A Role for Virtual Outcrop Models in Blended Learning – Improved 3D Thinking and Positive Perceptions of Learning. *Geosci. Commun.* 4 (2), 233–244. doi:10.5194/gc-4-233-2021

Buckley, S. J., Howell, J. A., Naumann, N., Lewis, C., Chmielewska, M., Ringdal, K., et al. (2022). V3Geo: A Cloud-Based Repository for Virtual 3D Models in Geoscience. *Geosci. Commun.* 5, 67–82. doi:10.5194/gc-5-67-2022

Bursztyn, N., Sajjadi, P., Riegel, H., Huang, J., Wallgrün, J. O., Zhao, J., et al. (2022). Virtual Strike and Dip – Advancing Inclusive and Accessible Field Geology. *Geosci. Commun.* 5, 29–53. doi:10.5194/gc-5-29-2022

Clark, D. B., Tanner-Smith, E. E., and Killingsworth, S. S. (2016). Digital Games, Design, and Learning: A Systematic Review and Meta-Analysis. *Rev. Educ. Res.* 86, 79–122. doi:10.3102/0034654315582065

Cliffe, A. D. (2017). A Review of the Benefits and Drawbacks to Virtual Field Guides in Today's Geoscience Higher Education Environment. *Int. J. Educ. Technol. High. Educ.* 14, 28. doi:10.1186/s41239-017-0066-x

Copine, A. (2011). *3D Art Essentials: The Fundamentals of 3D Modeling, Texturing and Animation*. Taylor & Francis: Publisher, 274.

David, L. T. (2012). Training of Spatial Abilities through Computer Games – Results on the Relation Between Game's Task and Psychological Measures That Are Used. *Procedia – Soc. Behav. Sci.* 33, 323–327. doi:10.1016/j.sbspro.2012.01.136

De Paz-Álvarez, M. I., Blenkinsop, T. G., Buchs, D. M., Gibbons, G. E., and Cherns, L. (2021). Virtual Fieldtrip to the Esla Nappe (Cantabrian Zone, NW Spain): Delivering Traditional Geological Mapping Skills Remotely Using Real Data. *Solid earth.* 13 (1), 1–14. doi:10.5194/se-13-1-2022

Fletcher, S., France, D., Moore, K., and Robinson, G. (2007). Putting Technology into Fieldwork Education: A Pedagogic Evaluation. *J. Geogr. High. Educ.* 31 (2), 319–330. doi:10.1080/03098260601063719

Garcia, M. B., Nadelson, L. S., and Yeh, A. (2023). "We're Going on a Virtual Trip!": A Switching-Replications Experiment of 360-Degree Videos as a Physical Field Trip Alternative in Primary Education. *Int. J. Child Care Educ. Policy* 17, 4. doi:10.1186/s40723-023-00110-x

Guillaume, L., Laurent, V., and Genge, M. J. (2023). Immersive and Interactive Three-Dimensional Virtual Fieldwork: Assessing the Student Learning Experience and Value to Improve Inclusivity of Geosciences Degrees. *J. Geoscience Educ.* 71, 462–475. doi:10.1080/10899995.2023.2200361

Ikeda, T. (1996). Structural Analysis of the Dalradian Rocks of the Loch Leven Area, Inverness-shire. *Scott. J. Geol.* 32, 179–184. doi:10.1144/sjg32020179

Jones, R. R., McCaffrey, K. J. W., Clegg, P., Wilson, R. W., Holliman, N. S., Holdsworth, R. E., et al. (2009). Integration of Regional to Outcrop Digital Data: 3D Visualisation of Multi-Scale Geological Models. *Comput. & Geosciences* 35, 4–18. doi:10.1016/j.cageo.2007.09.007

Kafai, Y. B., Quintero, M., and Feldon, D. (2010). Investigating the "'Why'" in Whypox: Casual and Systematic Explorations of a Virtual Epidemic. *Games Cult.* 5, 116–135. doi:10.1177/1555412009351265

Klippel, A., Zhao, J., Jackson, K. L., La Femina, P., Stubbs, C., Oprean, D., et al. (2019). Transforming Earth Science Education through Immersive Experiences – Delivering on a Long Held Promise. *J. Educ. Comput. Res.* 57, 1745–1771. doi:10.1177/0735633119854025

Klopfer, E., Scheintaub, H., Huang, W., Roque, W. D. R., and Roque, R. (2009). The Simulation Cycle: Combining Games, Simulations, Engineering and Science Using StarLogo TNG. *E-Learning Digital Media* 6, 71–96. doi:10.2304/elea.2009.6.1.71

Kopp, M., Gröblinger, O., and Adams, S. (2019). Five Common Assumptions that Prevent Digital Transformation at Higher Education Institutions. *INTED2019 Proc.*, 1448–1457. doi:10.21125/inted.2019

Lindstrom, P., Koller, D., Ribarsky, W., Hodges, L. F., Faust, N., and Turner, G. A. (1996). Real-Time, Continuous Level of Detail Rendering of Height Fields. *Proc. ACM SIGGRAPH* 96, 109–118. doi:10.1145/237170.237217

Lou, X., Guo, J., Liu, L., Zhao, X., Li, D., Li, H., et al. (2019). The Neural Correlations of Spatial Attention and Working Memory Deficits in Adults With ADHD. *NeuroImage Clin.* 22, 101728. doi:10.1016/j.nicl.2019.101728

Marshall, M. S., and Higley, M. C. (2021). Multi-Scale Virtual Field Experience: Sedimentology and Stratigraphy of Grand Ledge, Michigan, USA. *Geosci. Commun.* 4, 461–474. doi:10.5194/gc-4-461-2021

Métois, M., Martelat, J.-E., Billant, J., Andreani, M., Escartín, J., and Leclerc, F. (2021). Deep Oceanic Submarine Fieldwork With Undergraduate Students: An Immersive Experience With the Minerve Software. *Solid earth.* 12 (12), 2789–2802. doi:10.5194/se-12-2789-2021

Michailidis, L., Balaguer-Ballester, E., and He, X. (2018). Flow and Immersion in Video Games: The Aftermath of a Conceptual Challenge. *Front. Psychol.* 9, 1682. doi:10.3389/fpsyg.2018.01682

Mikhail, E. M., Bethel, J. S., and McGlone, C. (2001). *Introduction to Modern Photogrammetry*. Wiley.

Millington, I. (2010). *Game Physics Engine Development*. Boca Raton, Florida: CRC Press, 552.

Peace, A. L., Gabriel, J. J., and Eyles, C. (2021). Geoscience Fieldwork in the Age of COVID-19 and Beyond: Commentary on the Development of a Virtual Geological Field Trip to Whitefish Falls, Ontario, Canada. *Geosciences* 11 (12), 489. doi:10.3390/geosciences11120489

Perkins, D. N. (1997). Epistemic Games. *Int. J. Educ. Res.* 27, 49–61. doi:10.1016/s0883-0355(97)88443-1

Polack, T. (2003). *Focus on 3D Terrain Programming*. Cincinnati, OH: Premier Press Game Development, 218.

Prensky, M. (2001). Digital Natives, Digital Immigrants Part 1. *Horizon* 9 (5), 1–6. doi:10.1108/10748120110424816

Prieto, De L. R., and Medina-Medina, N. (2016). A Comprehensive Taxonomy for Serious Games. *J. Educ. Res.* 55, 629–672. doi:10.1177/0735633116681301

Pugsley, J. H., Howell, J. A., Hartley, A., Buckley, S. J., Brackenridge, R., Schofield, N., et al. (2022). Virtual Field Trips Utilizing Virtual Outcrop: Construction, Delivery and Implications for the Future. *Geosci. Commun.* 5 (3), 227–249. doi:10.5194/gc-5-227-2022

Roberts, J. L., and Treagus, J. E. (1977). The Dalradian Rocks of the Loch Leven Area. *Scott. J. Geol.* 13 (2), 165–184. doi:10.1144/sjg13020165

Shulman, L. S. (2005). Signature Pedagogies in the Professions. *Deadalus.* 134, 52–59.

Squire, K. D., and Jan, M. (2007). Mad City Mystery: Developing Scientific Argumentation Skills With a Place-Based Augmented Reality Game on Handheld Computers. *J. Sci. Educ. Technol.* 16, 5–29. doi:10.1007/s10956-006-9037-z

Squire, K. D., and Klopfer, E. (2007). Augmented Reality Simulations on Handheld Computers. *J. Learn. Sci.* 16, 371–413. doi:10.1080/10508400701413435

Steinkuehler, D., and Duncan, S. (2008). Scientific Habits of Mind in Virtual Worlds. *J. Sci. Educ. Technol.* 17, 530–543. doi:10.1007/s10956-008-9120-8

Stephenson, D., Mendum, J. R., Fettes, D. J., and Leslie, A. G. (2013). The Dalradian Rocks of Scotland: An Introduction. *Proc. Geologists' Assoc.* 124, 3–82. doi:10.1016/j.pgeola.2012.06.002

Tibaldi, A., Bonali, F. L., Vitello, F., Delage, E., Nomikou, P., Antoniou, V. E., et al. (2020). Real World–Based Immersive Virtual Reality for Research, Teaching and Communication in Volcanology. *B. Volcanol.* 82, 38. doi:10.1007/s00445-020-01376-6

Whitmeyer, S. J., and Dordevic, M. (2021). Creating Virtual Geologic Mapping Exercises in a Changing World. *Geosphere* 17 (1), 226–243. doi:10.1130/ges02308.1