Education and Information Technologies (2024) 29:10009–10042
https://doi.org/10.1007/s10639-023-12151-3

Digital modes of interpretation of Pictish sculpture

Sharon Pisani[1] · **Alan Miller**[1] · **Mark Hall**[2]

Received: 21 November 2022 / Accepted: 9 August 2023 / Published online: 23 September 2023

Abstract
Cultural heritage is no longer something that can only be experienced in a museum exhibition. Digital tools have facilitated the distribution of material relating to artefacts, both in its representation and in presenting its context. This paper describes how digital modelling techniques can be synthesised with 3D scanning to digitally restore artefacts and create authentic replicas of their original states. The digital artefacts can then be used to assist the process of interpreting these artefacts in diverse forms, both in the museum and outside the museum. The study looks at Pictish sculpture as a case-study, restoring 3D models of two stones, and creating varying opportunities for their interpretation. As part of this study, new interactive tools, a virtual reality environment, and a virtual tour are built to assist immersive interpretation of the Pictish sculpture. The application of these digitised objects serves as an opportunity for informal learning. These applications were evaluated during a drop-in session. Findings show that all participants enjoyed the immersive mode of learning with 89% also showing a willingness to learn more about the topic.

Keywords Digitisation · 3D modelling · Heritage interpretation · Immersive learning · Virtual reality · Digital heritage

1 Introduction

The digitising of historical artefacts — in this case-study early medieval, Pictish sculpture — is a crucial aspect of the conservation, preservation, and interpretation of culture. Advancements in technology have made it possible to create

✉ Sharon Pisani
sp259@st-andrews.ac.uk

Alan Miller
alan.miller@st-andrews.ac.uk

Mark Hall
mahall@culturepk.org.uk

[1] School of Computer Science, University of St Andrews, St Andrews, UK

[2] Perth Museum and Art Gallery, Culture Perth and Kinross, Perth, UK

reconstructions of the past which go beyond a photograph or digital image. Increasingly, museums are digitising their collections, turning them into 3D models through object scanning, and using them as "digital surrogates" to make the artefact accessible in the digital world (Hindmarch et al., 2019). Scans of objects can be used to interact with the artefact in new ways: rotating, zooming in, and digitally handling the artefact, something which is not common in traditional museum settings. This closeness to the digital model provides opportunities for people to get close to artefacts. However, it is often still presented in an environment that is not representative of its original context and use, or how that may have changed over time.

Digital modelling has been beneficial in developing replicas of the past. 3D modelling software and gaming engines can build objects and environments from the ground up. This has given new opportunities to interact with the past. Presenting artefacts as realistic 3D models can help the viewer understand their historical relevance as they can be visualised better. This could further be heightened by placing them in their historical setting. The importance of 3D models in increasing public engagement, accessibility, and experience has been observed in many settings (Jeffs et al., 2017). Additionally, the creation of digital forms of cultural heritage means that cultural heritage can be included in immersive informal learning activities, outside of a school's curricula and within museums and homes.

This research takes a practice-led approach with two objectives:

- To discuss how digital modelling techniques can be synthesised with 3D scanning to digitally restore artefacts and create authentic replicas in their original states.
- To present different modes of interpretation using authentic digital replicas.

Whilst the project focuses on Pictish sculptures, namely, the St Madoes Cross-Slab (Fig. 1) and the Inchyra Symbol Stone (Fig. 2), the techniques developed can be applied to other artefacts. The stones, which had already been photogrammetrically scanned, were restored using digital modelling software (Fig. 3 and Fig. 4) and then used in various immersive experiences, eliciting varying interpretations, and assisting in the cultivation of new learning on the Picts.

This article builds on a conference paper presented at the iLRN conference in 2022 (Pisani et al., 2022). The framework presented in this conference is described in this article, and then strengthened through evaluation carried out on the immersive applications built as a result of the initial case-study. The project outlined in this article contributes to the Immersive learning Knowledge Tree (Beck et al., 2021) by providing an exemplar case study which is novel in nature. This case study furthers research in the use of immersive learning in the cultural heritage field of inquiry.

This study makes a novel contribution to the field by combining the technical object restoration methods with the creation of digital resources that can be used in cultural heritage education. To the best of our knowledge, this is the first practice-led study which documents the entire process from restoring digitised artefacts to giving back their context by placing them in authentic environments. This process helps to make immersive learning experiences in informal education a more valuable experience. This work shows that immersive learning approaches can be applied to create

Fig. 1 St Madoes Cross-Slab (Front and Back)

alternate uses of digitised artefacts which can help museums include their digitised collections in educational material within their museums, in schools, or online.

The next section provides a background into the various parts of this project. Firstly, by providing an analysis of digitising techniques and how restoration of digital models can take place, and then by looking at the literature to note how other projects have utilised different immersive experiences to divulge historical information. Section 3 describes the methodology for this research. The results are evaluated and discussed in Section 4.

2 Literature Review

This section provides an overview of techniques for digitising and restoring historical artefacts and the areas of virtual reality where digitised artefacts can be used in. This follows the practice-led methodology and informs how the creation of these assets can be used for immersive learning by creating a package of tools around digitised artefacts. In practice-led research, the content and processes generate the knowledge

Fig. 2 Inchyra Symbol Stone (Front and Back)

Fig. 3 Restored St Madoes Cross-Slab (Front and Back)

(Edith Cowan University Library, 2022). Therefore, the final outcomes were achieved by working from the ground up and exploring how the separate digitisation and restoration techniques (Section 2.1 and Section 2.2) can work together to create digital interpretations of heritage through virtual reality (Sections 2.3 and 2.4). Section 2.5 includes the historical research that applies specifically to this project.

2.1 3D Digitisation Techniques

Creating a 3D model through digitisation can preserve a lot of information that a flat photograph cannot, such as size, texture, structure, and surface shape. Once a model has been created there are a variety of ways to interact with it: from the use of the model in virtual gallery, virtual reality or augmented reality to 3D printing and handling in physical interactions. The 3D scanning of artefacts enables non-intrusive preservation, research, restoration, and exploration of theories about their use and

Fig. 4 Restored Inchyra Symbol Stone (Front and Back)

appearance. Accurate data in 3D can be captured through photogrammetry, structured light scanning, and laser scanning.

In photogrammetry, data points are taken from photographs, and thus include colour information. This helps to create a digital model with accurate textures (McCarthy et al., 2020). With the increase in computing power, it has become possible to handle hundreds of photos of one object. Digital cameras are readily available, and free and easy-to-use software make community-based projects a possibility (McCarthy, 2014), making photogrammetry a practical tool to create authentic assets.

When scanning small artefacts, structured light scanning is more favourable than photogrammetry as it can capture more details (Shurik, 2018). This is also the case in finely detailed artefacts (Ruiz et al., 2021; Mathys et al., 2013). The downside to structured light scanning is that it cannot be used on well-lit areas or in outdoor environments where ambient light overpowers the projected light.

The popularity of laser scanning has recently surged due to LiDAR and ToF scanners in consumer portable products. This has facilitated crowd-sourced projects, such as the Earth Archive project which aims to scan and map the entire surface of the Earth to digitally preserve the Earth's surface for future use (Altaweel, 2020). Terrestrial laser scanning has successfully been used to preserve monuments and buildings (Pritchard et al., 2017). Accurate replicas can be made which can help rebuild damaged buildings, like the Notre Dame Cathedral (Praticò et al., 2020), and to analyse their conservation state (Pesci et al., 2012; Costanzo et al., 2015). Spatial 3D models are increasingly used in virtual museums and many times, some form of laser scanning is used to achieve this.

Often, projects make use of a mix of scanning technologies, depending on the object being scanned, and the intended use of the digital model. Textures obtained from photogrammetry could also be laid over more detailed point clouds obtained through LiDAR scanning (Emmitt et al., 2021).

In the last 20 years digitisation techniques have become more accessible. The equipment required to make the digitisation is available at commodity prices. A photogrammetry kit consisting of lights, camera, and tripod and laptop is within the reach of most museums. Consequently, there are new digital pathways for museums to engage with their communities and audiences (Cassidy et al., 2018). The creation of 3D cultural heritage assets is an important step in developing authentic experiences which can be used in immersive informal learning applications.

The digital models of the Inchyra Stone and St Madoes cross-slab were created using photogrammetric methods and were made available through SketchFab and international Image Interoperability Framework galleries.

2.2 Digital Restoration Methods

Theories about an artefact can be explored on a digital model. Non-invasive restoration and reconstruction show how an artefact looked through time. 3D scanning has been used to repair physical artefacts by 3D printing missing pieces (Jo et al., 2020). Restoring an artefact could bring to light new ideas and link the artefact to its context.

Working digitally facilitates an open workflow which keeps 3D visualisation projects sustainable and accessible as encouraged by the London Charter (Denard, 2012).

Repainting Many sculptures were once painted with no physical remnants left today. Paint restoration work has previously been applied to digital models of Pictish stones (McCarthy et al., 2020). Their work on medieval stone crosses had a focus of restoring the narrative function of the crosses. Audiences were shown unpainted and painted models in virtual reality. Painted models were better understood by audiences. This work shows that 3D models can be used to enhance physical interaction and disseminate the historical narrative to a wider audience, immersing them in this narrative. A recoloured reconstruction of the St Madoes cross-slab was previously used in a mixed reality exhibition, *Picts and Pixels*, at Perth Museum and Art Gallery in 2017 (Hall, 2020). A video was used to show the stone slab and it contributed to positive reactions from the audience. However, the model was painted in strong colours. Certain details were lost, and the damaged top part of the stone was not reconstructed. The new version of the colour model has been created for use in the new Perth Museum, set to open in 2024. The colour scheme will be intermittently projected onto the actual cross-slab and supporting interpretation made available on a digital console. Visitors will also be able to play around with colour selection to create their own colour models.

Reconstruction Recreating missing pieces can prove challenging depending on the affected area and the information available. Commonly, a similar item or area of the object is scanned, and the resulting model is added to the missing part of the model being restored. This involves fitting the reference surface around the area of the damage by adjusting their point clouds (Kesik et al., 2017). While this method provides accurate repairs, it is difficult to achieve if the content of the missing area is uncertain. The reference material must also be very similar to the object being restored. Automated mesh editors have been developed using mathematical Poisson-based gradient field manipulation to combine meshes (Yu et al., 2004). However, this is limited to the framework used in their experiment. Other algorithms can enable intuitive cut-and-paste operation when editing surface meshes, where a detail from a reference mesh can be pasted onto a target surface, provided that there is a continuous one-to-one mapping (Biermann et al., 2002).

This article proposes more straightforward workflows which make editing a 3D model accessible by implementing 3D modelling techniques using computer graphical software. Digital software that allows manipulation of a mesh has been utilised before, such as in reconstructing missing bones in palaeontological scans (Lautenschlager, 2016). However, our approach goes further by reconstructing missing pieces of the digital mesh and then restoring the object to its original appearance. The St Madoes stone was restored using Adobe Mudbox—a digital painting and sculpting software, while the Inchyra symbol stone, which had larger areas for restoration, was completed using Blender—an open-source 3D creation suite. The use of these programs is discussed in Section 3.1.

The issue of authenticity is one that arises when artefacts are digitised but there is a gap in the literature which describes how research that is done when restoring an artefact is presented to the public. The concept of authenticity is discussed with relevance to “identical reconstructions” and their “falsification’ of history” (Piazzoni, 2020). Once a 3D model of an artefact is created and restored, it becomes an artefact in itself. Interpretation should therefore include both the historical interpretation relevant to the real object, as well as the findings and decisions that were part of the restoration process. There are already established strategies that help show uncertain data in reconstructions, such as through media that describes the processes or reliability of the result, comparisons of versions, differently coloured renders, etc. (Pietroni & Ferdani, 2021). Piazzoni stresses that people’s desires and emotions are what makes heritage. With this in mind, interpretation around the authenticity of reconstructions should incorporate the public and their conclusions of what might have been real. Traditional methods, like the ones mentioned earlier, are often laid out by the exhibition creator, and do not allow space for the public to think about and explore the researchers’ decisions.

2.3 Exploring Virtual Environments

Museums are striving to incorporate virtual and augmented reality as an immersive tool for visitor learning and engagement. This is particularly pertinent in Perth at present where the new Perth Museum is in development, as mentioned above. Amongst its new displays will be the assemblage of Pictish sculpture from Perthshire, never before seen as a group. One of the ways the Museum is seeking to make this material further accessible is through digital approaches to communicate sensory perceptions around colour and place, as discussed above. Some of the ideas were trialled in temporary exhibitions, notably in 2015–16 with *The Cradle of Scotland* (working in partnership with The Glasgow School of Art and the Hunterian Museum & Art Gallery) and in in 2017, with *Picts and Pixels* (working in partnership with St Andrews University and SmartHistory).

Virtual reality communicates these sensory perceptions by creating immersive narratives of the past in a complete realistic ecosystem (Cerato & Pescarin, 2013). Interaction in the virtual world leads to story progression with the object changing or coming alive in the virtual world. This is often representative of an emphatic storyline, where the user progresses through the experience and develops an emotional connection to it. Virtual environments have also been used and documented as part of virtual museums, showcasing models and reconstructions both in museums and online (McCaffery et al., 2015).

Virtual worlds have applications beyond museums. They are being used in education, entertainment, and by experts to navigate new theories (Cerato & Pescarin, 2013; Miller et al., 2012). Immersive applications provide opportunities of experiential learning that is difficult to achieve through traditional artefact viewing, thus it is one of the modes of interpretation that are developed in this study. It allows cultural heritage to transcend “space and time” (Cecotti, 2022) making it available across countries and recreating heritage across time periods. As Cecotti shows, such applications can be used in educational formal learning and also through other social experiences in informal learning settings.

People engage differently when presented with a new world of information. Some will explore the extents of the world, others will stop and look at everything they see, interacting with each object. However, where data is uncertain, it should be communicated in a transparent manner. This can be achieved by documenting all sources and material and allowing them to be accessed from within the virtual environment (Fleury & Madeleine, 2012). Having this transparency ensures that a coherent virtual world can be creatively developed around an artefact even when there is partial contextual data available.

System and narrative immersion can be heightened by challenge-based immersion (Nilsson et al., 2016). Both are present in virtual environments that recreate the past. Challenge elements within a virtual environment work with the narrative elements in the immersive system to absorb the user further into the environment and disassociating them from the physical world. This relates to Agrawal et al.'s definition of immersiveness and highlights the fact that cultural heritage applications can contribute to the development of immersive learning in informal settings (Agrawal et al., 2020). Means of adding a challenge include treasure hunt activities (Martina, 2014) or other interactive elements, such as configuring or creating new objects in the environment. Configuration allows further exploration as users interact with the environment in a creative way.

The effects of using virtual reality in both formal and informal educational environments have already been discussed in several studies. Virtual reality has been found to increase motivation through heightened attention and satisfaction (Casu et al., 2015). Students also feel that material presented in VR is more relevant to their studies, whilst in informal contexts, the use of virtual environments was proven to heighten engagement by linking the content to the lived experiences and knowledge of visitors (Kersting et al., 2020).

Virtual environments also increase acceptance of the material and the methods used to present it (Ch'ng et al., 2020). Such studies made use of objects reconstructed from referenced museum artefacts. However, the selection of real-life digitised objects used in reconstructions was generally low, when compared to generic or remodelled artefacts. In Ch'ng et al.'s work, for instance, only 9 out of the 27 items used were digitised or modelled on museum artefacts. This is despite recording a stronger sense of presence and a sense of meaningfulness when interacting with the museum objects. Hence, the significance of incorporating museum objects into immersive cultural heritage education becomes evident, underscoring the imperative for further investigation and development of authentic and life-like digital surrogates.

2.4 Accessible Virtual Tours

Here, virtual tours refer to two broad types of tours: immersive 360° tours which require a VR headset, and 360° tours which can be viewed on a 2D screen, such as laptop or smartphone. In both cases, photos or videos of a location need to be taken using 360° cameras. Videos can create more immersive output; however, 360° photos can also allow exploration of the scene and include various hotspots to move between scenes.

Despite not being completely in a digital environment, users still find virtual tours immersive and engaging (Argyriou et al., 2020). Such tours can capture the location without needing to recreate it in a gaming engine. The final package is often less substantial than the entire environment, thus requiring less powerful and more easily available hardware to run. Such virtual tours can also include narrative and gamified elements through mission-like walkthroughs or knowledge-based games as presented in Argyriou et al. This study also showed that movement and navigation can be simulated through walking videos. Virtual tours can also combine the tangible with intangible heritage (Mah et al., 2019). This allows both the physical cultural heritage site and intangible information to be documented and made accessible and communicated throughout the tour. Mah, et al. combine images and photographs in addition to 360° photos to create a virtual tour of the Tampines Chinese Temple which also shows ritual practices and highlights the significance of artefacts within the temple. The added accessibility of virtual tours means that this is a viable mode of interpretation that can be explored.

The content of such tours could also be replicated in tours which do not require VR headsets. Whilst this reduces the immersiveness aspect, it makes the content available outside of VR. Tours which require VR headsets are appropriate in a museum setting, where a headset and system can be installed. There are also options to make VR accessible at home by creating web-based VR tours or applications. However, the majority of people do not own a VR headset at home, despite the availability of lower-priced and portable models that have become available in recent years. There is also a question of device compatibility – where a VR app is built for a museum, the device is known, and the application can be designed and developed accordingly. At home, there is a greater availability of different devices so the shared experience might not be compatible with user devices. This creates a requirement for a different system which can allow the exploration of a virtual environment by a wider audience.

Additionally, 360° photos and videos can be taken in a reconstructed environment to capture the location and make it available outside the environment in a non-VR headset dependant method. Whilst virtual environment can be experienced in different immersive layers (Khorloo et al., 2022), exports presented in tours can let the user experience pre-defined routes within the environment. Furthermore, it allows the combination of real-life information and imagery to be combined with the virtual environment, facilitating the comparison of the two environments. Such tours can be built using online tools such as Kuula. These allow 360° media to be experienced on a screen. Although removing the fully immersive element that one can experience when wearing a headset, these tours are more accessible. They can also represent a high-resolution snapshot of a real-life or recreated location using panorama imagery. Online services such as the ones mentioned above, typically have free versions and are easy to use by members of the public, without the need for coding experience or high-power devices. This is important for the cultural heritage sector as adoption challenges of virtual worlds remains one of the biggest obstacles

(Gaspar et al., 2020) in any educational setting. Thus, creating virtual tours to showcase cultural heritage artefacts can be one way that a museum with limited resources can create immersive learning opportunities for its audience.

2.5 Historical Research

The historical research is what drives the subsequent developments in practice. The reliability of these approaches lies in the fact that the proposed development is rooted in research, thus providing authentic replicas. When in an immersive environment, users tend to acquire factual knowledge of what they are seeing. Therefore, it is necessary to ensure that all development is based on historical research. (Makransky & Petersen, 2021). This section details historical research that was vital to the development of the assets of this study.

The approach presented in this article was applied to reconstructions of two Pictish sculpted stones: the St Madoes cross-slab and the Inchyra symbol stone. These were chosen as key pieces of sculpture in the Museum's collection, with a critical significance to understanding the Picts in the Perthshire region. The cross-slab is a largely intact monolithic sculpture of the eighth century (Fig. 1), whilst the symbol stone is a possibly sixth/seventh century sculpture carved episodically in different orientations, with Pictish symbols, to which at least three sets of ogham inscriptions have been added (Fig. 2). More images of the stones can be found in (Hall, 2012). The sculptures are part of the collections of Perth Museum and Art Gallery.

A Pictish colour palette was composed to establish cohesiveness between the restored models and to ensure future reconstructions on other Pictish stones. The objective was to create a range of colours that would have been available to and likely be used by the Picts. Therefore, concurrent historical sources were investigated to make decisions on the colour selection. These sources included pigment remains on stone and illuminated manuscripts contemporary with the Pictish period.

Roman stonework has revealed a colour palette rich in reds and yellows, with traces of white lead (Campbell, 2020). These colours have also been observed on post-Roman, Insular sculptures including the Anglo-Saxon Lichfield Angel. Here, the core colours used were mixed to create different hues, as well as adding black and white to create different shades (Geary & Howe, 2009). Red pigment was found on sculpted interlace of the Pictish Portmahomack sculptures, while white, which was possibly used as a base layer, was found on the Goodlyburn cross-shaft[1] (Hall, 2020). These findings reveal that reds, yellows, and white should be present in a Pictish colour palette. They also give an indication of which areas were painted and what effect could have been desired; most notably, using a white background to create contrast with the intricate designs.

More information was drawn from illuminated manuscripts, especially the Book of Kells (Fig. 5), created circa 800AD, and the Lindisfarne Gospels, created circa 715-720AD. These Insular artworks include intricate and colourful patterns

[1] The white pigment on the Goodlyburn cross-shaft was identified by eye only. It is currently awaiting XRF confirmation.

Fig. 5 The Temptation of Christ from The Book of Kells (The Book of Kells, c. 800 CE)

in bright colours and a range which goes beyond red and yellow, to include blues and greens as well. These are the core hues that would have been available to Picts through natural minerals and plants. A reconstruction of the Forteviot burial monument reproduced similar colours from the manuscripts (Fig. 6) (Hall, 2020). From these colours, a 10-colour palette was created which is shown in Fig. 7. The 10

Fig. 6 Forteviot burial monuments (Campbell & Driscoll, 2020, Figure 10.2)

hues can be lightened or darkened and can capture accurate colours in any Pictish reconstructions.

With regards to the restoration of the sculptures, Inchyra has the most damage. The wider part of the stone is broken off–-destroying one of the fish symbols at that end of the face. This could be reconstructed by looking at the complete fish symbol

Fig. 7 Reusable Pictish colour palet

incised on the other side. Most of the remaining restoration was in reconstructing pieces of the stone that had chipped off. Interestingly, two symbols on the Inchyra stone, on the side of the intact fish, appear not to have been finished by the sculptor (Stevenson, 1961). These were only lightly incised in the final restored version and left unpainted to reflect their incompleteness.

The symbols on the St Madoes cross-slab have seen some erosion and damage and needed fine-tuning of their detail. The panels at the back of the stone are harder to make out but previous research had established what the symbols originally were (Hall, 2020). The largest piece to be reconstructed was the top, where a pair of crouching lions were identified (Hall, 2012). The reconstruction draws mostly from the lions carved on the Pictish sarcophagus found at St Andrews which was sculpted in the same period.

2.6 Research Aims

Since their re-discovery of the St Madoes and Inchyra stones in the nineteenth and twentieth centuries respectively they have generally been treated as individual artefacts. In actuality, they come from the same temporal period and were found within the same landscape, something that is not immediately apparent due to the markedly changed landscape in which they once resided (Hall, 2012).

Whilst there are many separate studies that look at restoring museum artefacts from a technical perspective or building immersive tools for cultural heritage education, there is a lack of studies that document the entire process of authentically restoring artefacts and building multiple modes of interpretation around them. There is also great potential in creating and using virtual environments as a platform for presenting and experiencing digitised cultural heritage artefacts and how these impact understanding of past cultural landscapes.

The research, therefore, aims to digitise and restore the collection of stones found to give visitors a better sense of their sensory perception through re-imagining how they were coloured and to present them to an audience who might not know of their link and the environment where they were found. As demonstrated in the literature, virtual reality can facilitate this knowledge transfer by situating a restored stone in its environment. Virtual tours then make this experience accessible to a wider audience, even outside the museum. This is done in this research by combining digitisation and restoration techniques to create new modes of interpretation. In addition, we will investigate how enabling learners to interact with authentic replicas can increase engagement with the historical material. Through the different modes of interpretations created and their evaluation, this research will answer how presenting the stones in their original environment can increase the knowledge and understanding of this unique environment. It is, of course, but a first step, but the advantage of the digital environment is the relative ease with which it can be updated as our understanding deepens.

3 Methodology

Following a practice-led methodology, our objectives were to restore the Pictish stones, place them within their contextual environment and create diverse modes of interpretation. The adoption of this methodology is justified as the process of creating digital interpretations is considered integral to the research process and contributes to the generation of new knowledge in the domains of Pictish sculpture and heritage education. The research involves exploring how digitization and restoration techniques can work together to create digital interpretations of heritage artifacts. This process involves experimentation and iteration, which are key components of practice-led research. This methodology is not solely based on existing literature or theory, but rather on the processes involved in creating digital interpretations of heritage artefacts prioritizing the practical intricacies associated with them.

The procedures within this methodology followed an explorative approach with each component prescribing the next, and with multiple reiterations of the steps that make up each component. Figure 8 shows this process.

Data collection occurred twice. Once through interviews and discussion with other heritage professionals after the first stone was restored. The second data collection occurred after the digital modes of interpretation were created. Through a drop-in focus group session, surveys were collected. These were analysed through qualitative methods which offer an effective way of understanding the behaviour, knowledge acquisition, and opinions of the participants after experiencing the various interpretations. Though the outputs can be implemented informal and formal education, this research looks specifically at informal out-of-syllabus learning, such as in the museum or at home. Therefore, the sample of people recruited for the focus group were not educators of this subject, but rather, people who might be interested in learning more about it.

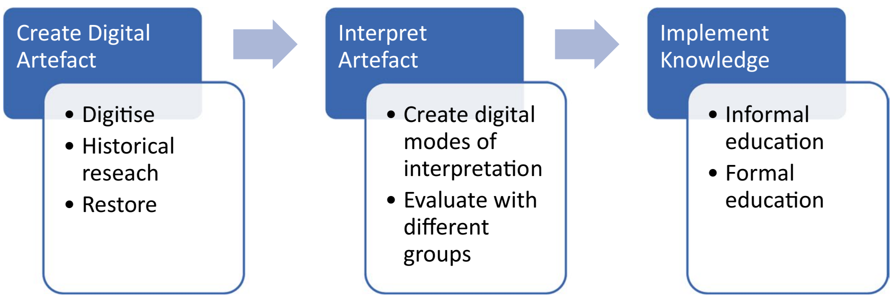

Fig. 8 Methodology to create authentic digital replicas and modes of interpretation

3.1 Creating and Restoring Artefacts

After the necessary historical research was done, the 3D models of the stone could be digitally restored. A workflow for artefact restoration was developed and applied to both sculptures. This is detailed below:

1. Conduct historical research and form a colour palette.
2. Plan a colour scheme for each artefact.
3. Import digitised 3D model.
4. Sculpt missing sections.
5. Restore selected areas by painting and refining detail.
6. Export model for use in future applications.

This workflow can be applied to any artefact, irrespective of its historical period. The concepts in the workflow can be adapted according to the artefact; for instance, if an artefact does not have missing fragments, that step can be skipped. Working with a digital model which has been obtained through 3D scanning methods allows the final digital model to have realistic textures and accurate details. These would not be possible if a digital model is recreated from scratch. Conversely, relying entirely on the digitisation process means that the digital artefact only represents the heritage object as it is now. Synthesis of modelling and digitisation allows both realistic details and the rejuvenation of the artefact, so we can visualise and manipulate the artefact as it may have been when first in use. The following section will describe some techniques that can be applied. It is not a comprehensive list, but the tools can be reused on any 3D model, as deemed fit.

The choice of software is an important one and for this project Adobe Mudbox and Blender were utilised and compared. Mudbox is a software dedicated to sculpting and painting a 3D mesh. It was appropriate for St Madoes as most of the restoration involved manipulating the existing mesh. This was possible using the sculpting tools which alter the model similarly to real-life sculpting. Since Inchyra required more extensive reconstruction, it was restored using Blender, which offers a suite of features that go beyond sculpting and editing. These include Boolean operators which seamlessly add new parts of the mesh. Moreover, Blender comes with multiple modifiers such as Remesh and Decimate. These tools help to fine-tune the final meshes, especially when new pieces have been added. The Remesh modifier can be controlled to reduce the number of faces without reducing the quality of the details. The mesh can also be Triangulated and Decimated to ensure smoother sculpting. Additional areas can be added and then joined to the model using the Boolean Union operation to remove unused vertices. The Remesh modifier can be reapplied to cohesively join additional fragments to the original mesh and clean it up before further sculpting takes place.

Once the structural changes have been made, the sculpting of details and painting can commence. Painting and refining should be done in a cyclical approach which ensures that areas of the model are viewed from every angle. Painting can be done on top of textures obtained through photogrammetry. Models which have been remeshed require a new UV projection to distribute the 3D vertex points onto the 2D texture.

One of the uses of a digitised cultural artefact is to preserve it for future generations and to catalogue it digitally. As such, a high level of detail which encompasses every aspect is required. However, for the model to be usable in other immersive applications, a balance must be reached between quality and size. This was a challenge while restoring. If the model has a small number of faces, it becomes difficult to sculpt details accurately. Higher-resolution meshes are required if the model is going to be displayed in life-size or bigger dimensions. On the other hand, this increases the number of faces and the size of the model. The final model becomes unusable in other applications due to a slow loading time. Computers or portable devices with less graphical power would struggle to smoothly interact with the model.

In Blender, file size can be reduced in multiple ways. The Decimate modifier reduces the number of faces with minimal shape changes by reducing unnecessary vertices in `flat' areas where there is not much change in the topology. This is critical to ensure that detail is not lost. Blender also supports geometric mesh compression and can export the restored model in different formats to suite the intended use: FBX is a binary 3D format which can store multiple subdivision surfaces in less space and is ideal for use of the model in gaming engines; the glTF format, on the other hand, is optimised for real-time transmission, making it better suited for web-based applications. Because of its efficient size, it is widely used for VR and AR applications, as well as many digital heritage projects and public domain catalogues (Bradshaw & Crabb, 2020).

3.2 Digital Modes of Interpretation

The goal of restoring 3D artefacts is to bring them closer to the community. Immersive learning opportunities can be constructed through having accurate 3D digital replicas and restoring them in an authentic manner. Immersive applications provide an opportunity to learn about artefacts and their context and are also a non-invasive means of understanding sculpture further as they require, for example, no actual application of colour to the sculpture. The restoration of these two stones has brought them together and they can be presented in meaningful ways.

The following sections will detail several modes of interpretation that have been developed which make use of the authentic restored reconstructions. Moreover, these digital tools can be experienced in multiple locations. This ensures that interpretation can happen at the museum, at home, or anywhere in between. The audience is also varied. Therefore, in the case of the Pictish sculpture presented here, interpretations can be done by museum visitors, students, local people in Perthshire, tourists, scholars, etc. These backgrounds diverge through their experience of the digitised material, creating diverse interpretations.

3.2.1 Interactive Configurator Tool

There is always room for interpretation when repainting historical/cultural artefacts, especially when little concrete evidence is present. This is something that ought to be communicated to the audience, without detaching from the learning experience. An online interpretation tool which enables the application of different colours on the artefact is effective. This is presented as part of a web interface that introduces the stones, their history, and context. The website is not overloaded with information to keep the content direct and meaningful. Additionally, it raises interest and allows the user to start forming their own thoughts and theories about how the stones might have looked. A 3D visualisation is embedded which lets the user configure the different colours of the stone to reflect their own perceptions (Fig. 9).

The configurator was built using the JavaScript library Three.js, ensuring it can work on any modern browser. It accepts 3D models in the GLTF format and can decode compressed models as well. The application builds the scene including the object, lights, and camera on an HTML canvas. Once the model is loaded, three.js extensions provide orbit controls which allow panning, rotating, and zooming via mouse or touch. The user can then recolour the stone by selecting any part of the stone and choosing from the swatches of the provided Pictish colour palette. The configurator can be accessed through the interactive web interface at https://cineg.org/painting-the-picts/imagine/.

The 3D configurator is a valuable learning tool which emphasises the fact that the colouring of the stone is an exploratory task. This is shown to the viewer in a subtle manner which does not detract from the richness of the experience. Restricting the colour palette to the colours available to the Picts establishes their historical accuracy, whilst the freedom to create their own colour scheme certifies that the colour

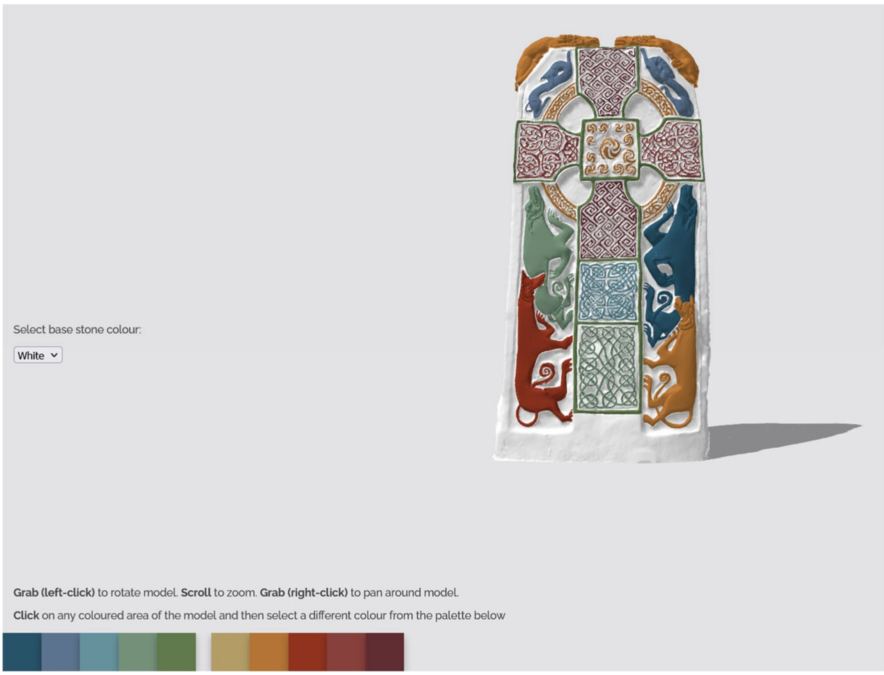

Fig. 9 Colour configurator tool showing the St Madoes Stone. Users can recolour the stone by clicking on the stone areas and selecting the new colour

scheme of the model is not an exact replica. The benefit of this tool is that when presented in a virtual environment, the additional thinking provides a challenge-based approach to immersion as defined by (Nilsson et al., 2016).

3.2.2 Virtual Environment

Building a virtual environment of St Madoes in the early medieval period was an essential next step in disseminating an interpretation of the historical environmental context in which the Pictish stones had operated. The landscape has drastically changed due to a railway and motorway that presently pass through it. Archaeological, topographic, and onomastic evidence indicates that St Madoes was a significant place and had been since the Bronze Age, with some element of curated ritual continuity. Known features and finds include Bronze Age burial mounds and standing stones and a Roman coin hoard and brooch. The Inchyra stone was found adjacent to a Bronze Age burial mound and itself horizontally capped a burial. The St Madoes stone was found in the church burial ground, which when founded in its Pictish use may have encroached upon the remnants of a prehistoric cemetery and/or ritual space. From the churchyard came a further piece of Pictish sculpture currently lost and the recent find of another fragment of symbol stone indicates a concentration of Pictish sculpture in the area. This makes St Madoes/Inchyra a prime location for recreating a historical virtual landscape. There has been no archaeological excavation in or around the St Madoes churchyard or close to where both sculptures were found, which means there is no solid, archaeological date for reconstructing the environment beyond the stones themselves and the morphology of sites in the landscape. Comparison with related sites that have been excavated thus becomes an important source of comparator data, e.g., the excavation of the Pictish landscape at Forteviot (Campbell & Driscoll, 2020).

The Unreal Gaming Engine was used to create the virtual environment. The landscape maps were obtained from Digimap and used to create the digital landscape. The restored stones were imported and placed in their imagined appropriate location. A medieval chapel was recreated. No reference remains have been found, but other historically contemporary buildings indicate that the chapel was most likely built of wood with a thatched roof. The model is relatively simple, without the precise detail that is present in the stones. The door and windows do not open, and the textures are two-dimensional. This highlights the fact that it is in part a creatively drawn reproduction reflective of its time, and not an authentic reconstruction based entirely on direct, archaeological evidence (though informed by reconstructions made based on sites excavated elsewhere). Barrows were added to indicate the burial mounds and a cemetery built near the church and the cross-slab (Fig. 10). As the St Madoes and Inchyra sculptures were unlikely to be the only stones created for the site (a further cross-slab fragment was found in the nineteenth century and then lost (Hall, 2012, pp. 89–90, Fig. 7.2) and an additional Symbol stone was reported on recently (Hall, 2019)), suggestions for a range of other burial monuments were added referencing the known designs of stones from other parts of Pictland (Fig. 11). The scene was populated with estimates of typical flora and completed with indications of settlements.

Fig. 10 Pictish environment showing the St Madoes Stone, cemetery, and Pictish church in the background

Fig. 11 Inchyra Stone placed in the environment with additional non-player characters

The virtual environment provides opportunities to walk around the scene with a first-person perspective. As a learning environment, users can freely explore the environment, intrinsically finding answers to their questions about the stones. As this can be applied to any artefact, users can learn about the people who built and used historical artefacts through seeing and interacting with the worlds they lived in, and not just through reading information. Parallels and contrasts between the current environment and the historical one can easily be drawn which assist in the understanding of this cultural landscape and its evolution. The realistic ecosystem created here ensures that an immersive narrative can be realised (Cerato & Pescarin, 2013). Through this, the sensory perceptions that allow the audience to understand how the stones looked and how they were situated can be communicated.

3.2.3 Location Tours

Museums have increasingly been implementing virtual tours of their collections. This mode of interpretation can be transferred to locations as well. One of the aims of this project was to represent the cultural landscape in Perthshire and how it has changed over the years. A set of location tours was created to encourage interpretation around this aim. The virtual environment described above was reused. Several 360 photos were taken around important points of the landscape. These were exported and a Kuula tour was created, highlighting areas of interest and providing more information about the locations. Additionally, 360 photos were taken in the real world, in approximately the same location of the 360 photos exported from the environment. These were added to another Kuula tour. Similar hotspots were added, calling attention to the differences in the environment.

The idea behind this mode of interpretation is to present the environment and generate thoughts on how the landscape has changed by comparing the two in a similar manner. People already familiar with the Perthshire landscape can view the landscape in a new light. On the other hand, people who are unfamiliar with the area, can better visualise the extent of this settlement. The importance of why this work was carried out becomes apparent as the stark contrast between the two environments can be seen.

By eliminating well-known landmarks, such as the motorway and railroad which divide the landscape, a new understanding of how the Picts lived across the area can be achieved. The locations now considered as three distinct villages, become one large area of settlement. The whole area was once probably considered a significant and influential area. This can be presumed from the multiple burial sites, which were reused over the ages. Bronze age remains were found around Forteviot and Inchyra and it seems the Picts continued to consider the areas to be sacred and important, using the locations as their own burial grounds. Today, the landscape is ordinary and very little is seen from its considerable history.

This kind of interpretation and understanding can be achieved through tools such as virtual tours and made available to an international audience through the internet. This overcomes the obstacle of adopting virtual environments (Gaspar et al., 2020) by making it more accessible. Programs which create interactive virtual tours, such as Kuula are easy to use. As discussed in Section 2.4, open-source or free alternatives make this mode of immersive interpretation accessible to museums and heritage centres.

4 Evaluation

Evaluation was carried twice, once after the model was restored, and once after the modes of interpretation were created. The work was initially shared with several history and museum professionals who provided feedback. This first round of feedback was collected specifically on the restoration and colourisation of the stone. This helped define the kind of interpretations that could be developed in the next stage. The debate of whether the Picts painted on a white base layer or directly onto the stone was prominent. The configurator tool was modified to reflect this by including a choice of both options. The consulted experts were satisfied with how the surfaces were digitally restored during the process of sculpting on the 3D model. There were positive comments on how the colour interplays with reliefs in the stones, bringing out unseen detail. They commented on how more insight into the appearance of the stones, for instance at different times of the day, can be obtained by using the stones in a virtual environment. This highlighted the importance of developing various modes of interpretations around one subject, with each mode of interpretation providing different layers of knowledge and learning about the subject.

The second round of evaluation was done after the virtual environment was built. This involved testing of the virtual environment in VR. A webpage introducing the Picts and the topic of recolouring ancient artefacts was first presented to the subjects. This assisted in conveying key information about the Picts. Additionally, the webpage contained the interactive colour configurator tool. Participants were allowed to play around with this tool to become more familiarised with the coloured artefact. Following this stage, they were given instructions on how the VR experience will work. The participants were shown the controls for moving forward in the environment and for jumping to the next scene. They were instructed to explore the environment as they would like, as well as skip to the preconfigured scenes whenever they want. They were not given any time limit. Afterwards, they were asked to fill in a survey to describe their experience.

The data collection was held in a lab in the school of Computer Science and participants were voluntarily recruited through flyers and email. The email was sent to the university museum team to recruit museum professionals. The participants recruited are representative of a public who had very little or no knowledge of the subject topic, mirroring how museum visitors come in contact with artefacts in a museum that they know little about. A total of 17 participants took part in the study, with the majority being students, but also including lecturers and museum curators. The age varied between 18 and 64 years, with 53% of the participants falling in the 18–24 years category. The participants mostly had some experience of working with digital technologies, but most of them had never or only once used VR. The VR application was viewed through an Oculus Rift S connected to a PC. An external TV displayed the experience for people accompanying the participant. Another PC and monitor were used to access the informative webpage during the first part of the study.

To evaluate the effectiveness of the immersive modes of interpretation designed, four evaluation themes were created: the system's ease of use, user engagement, learning ability, and its significance to the cultural heritage. The survey contained 12 statements which asked participants whether they strongly agreed, agreed, neither agreed or disagreed, disagreed or strongly disagreed with each statement on a 5-point Likert scale. These statements gather information about the specified themes (Fig. 12). These questions were followed by three free text questions asking participants to describe their experience, what they enjoyed the most, and any areas of improvement.

The results from the Likert-style questions are summarised in Fig. 12. Overall, the response was positive. The questions are grouped according to their evaluation theme. The free-text questions were coded and collated into topics outlined in the tables below.

Table 1 contains all the coded responses listed by the different users with the percentage reflecting how many times it was mentioned. Figure 13 and Fig. 14

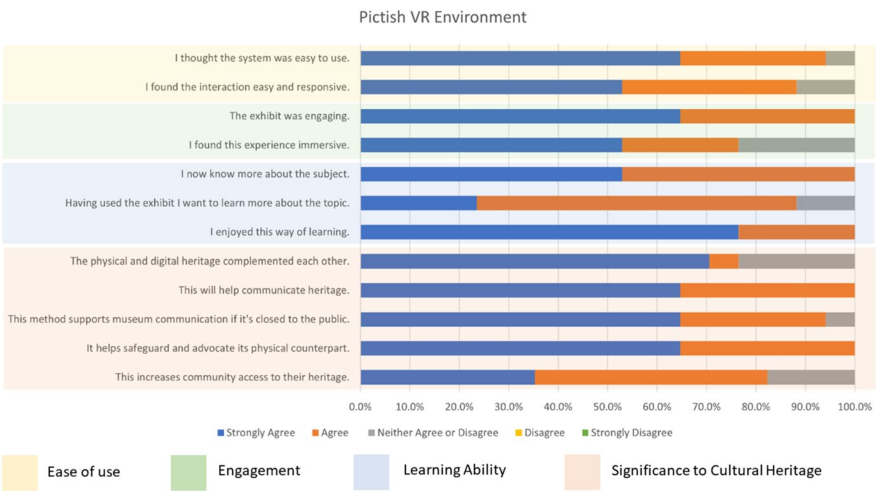

Fig. 12 Responses to survey evaluation statements

Table 1 List of coded responses for “What three words best described your experience with the exhibit?” ordered by their frequency

What three words best described your experience with the exhibit?			
interesting	18%	intriguing	4%
immersive	14%	impressive	2%
engaging	12%	Picts	2%
fun	12%	motion-sickness	2%
interactive	8%	captivating	2%
different/original/new	6%	visual	2%
exciting	6%	realistic	2%
informative	6%	colourful	2%

were coded through an inductive approach to reflect all the categories that the users mentioned in their responses. This is especially helpful to categorise the improvements suggested by the users.

The four core themes of the survey are evaluated below against the results summarised above.

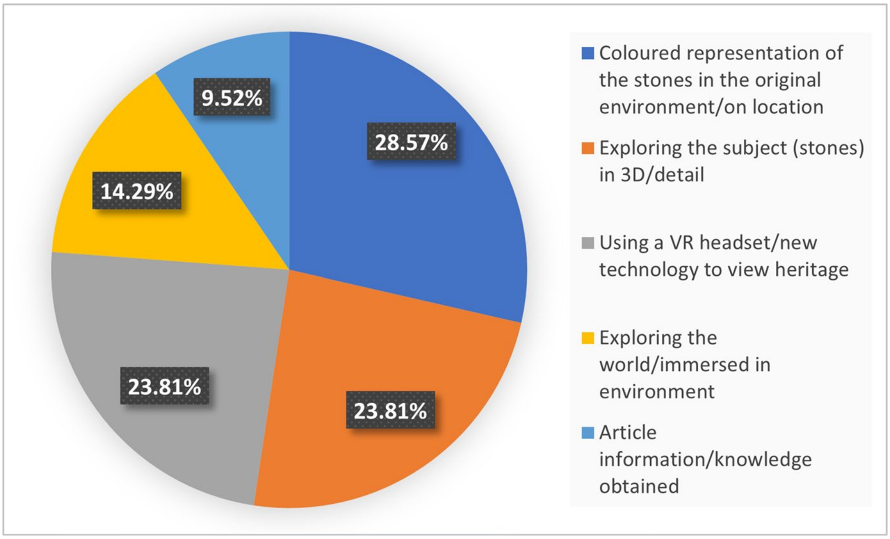

Fig. 13 Coded results for: What did you enjoy most about the experience?

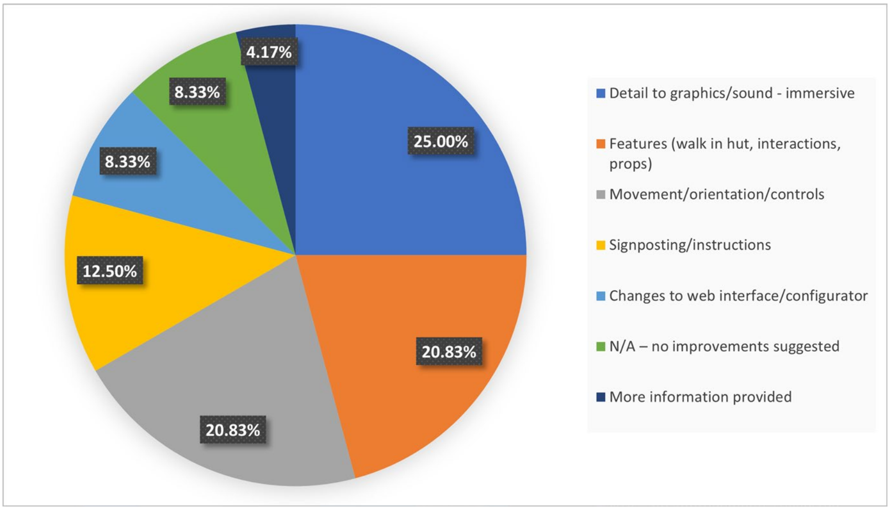

Fig. 14 Coded results for: How could the experience be improved?

4.1 Ease of Use

This theme looks at whether the participants found the system and interactions easy to use and responsive. Whilst the respondents were in the majority strongly agreeing with the statements, 18% of the respondents were neutral. Looking at the responses on what improvements they would like to see in Fig. 14, 20.8% of responses were regarding the movement in the environment and an additional 12.5% suggested more signposting or instructions. Movement in a virtual world can be problematic. The aim is to make the experience as immersive as possible, but sometimes this might not be intuitive whilst within the VR world, especially for inexperienced users. This reduces the engagement, enjoyment, and learning possibility. The tested system's mode of movement which was to go forward in the direction the user is looking, is realistic and mimics real-world walking. However, for the participants, it was not always intuitive as they had to turn around whenever they wanted to go somewhere that was not directly in front of them. This could be improved by using the joystick on an Oculus controller to indicate direction (instead of using the trigger to indicate forward). Another way to facilitate movement around objects would be to include hotspots, marked perhaps by a glow on the ground, which the user can point at in order to move to that point of view. This can make it much easier to move around the stones, for instance, to see them from different angles. This should be kept in mind when designing immersive learning applications.

4.2 Engagement and Immersiveness

All the participants agreed that the exhibit was engaging and 76.5% of the participants agreed that the experience was immersive, with the rest neutral. 45.8% of the improvements suggested by participants fall into categories which can further improve this. Adding more detail to the graphics, as well as the inclusion of sound can make the environment more immersive. New features such as interacting with props or going into the buildings would make the experience more interesting and engages the user for a longer period.

The immersive element was greatly enjoyed by the participants. The most common theme when asked what they enjoyed the most was seeing the coloured representation in the original environment. This satisfies one of the project's objectives of representing the context of the stones and bringing their history alive. Another highlight for the participants was using the VR headset to explore heritage. This reflects other research that measures engagement in similar virtual reality learning apps (Bodzin et al., 2020) but stresses the effectiveness of using innovative technologies to create modes of interpretation of historical artefacts.

4.3 Learning Ability

One of the aims of this study was to use different modes of interpretation to expedite learning about elements of history or culture, in this case Pictish sculpture. The different modes tested here — web interface, colour configurator, virtual environment — were successful in engaging the participants in learning about a topic they knew little about. The participants agreed that they knew more about the subject and enjoyed learning in this experience. Besides, 88.2% showed a willingness to learn more about the subject. This is an important condition. Museums' focus on teaching the public about their collections goes beyond what is physically in the museum. One participant commented that they would have liked more information displayed within the experience, indicating that the experience was not over-saturated with information and was a good platform for the dissemination of this knowledge.

The objective of such interactive experience is to ignite an interest in the user to keep on learning about the subject. Whilst this experience might have been an introduction to the topic, leaving the participants interested even after the exhibition is over can lead to future consumption of related material. Because "interesting," "fun," and "exciting," were amongst the most frequently used to describe the experience (Table 1), there is a higher chance that it is memorable, creating future connections and learning opportunities.

Despite this, out of the 88.2%, only 23.5% 'strongly agreed' to learning more about the subject outside of the environment. This is also reflected in the fact that the "article information/knowledge obtained" was the least source of enjoyment (Fig. 13). What this could indicate is that the quality of the provided interpretive information should be of better quality. This is to ensure that participants understand and learn enough to continue seeking more information, and to make the knowledge acquired just as much of a highlight as the immersive experience itself.

A response from a participant: “I enjoyed seeing the recreations of the carvings and symbols as if it were in person. I liked learning about the exhibit beforehand and then entering the virtual experience and being able to visualize what I had just read about,” encapsulates how it is the combination of these modes of interpretations that heightened the learning aspect, rather than the most immersive or enjoyable one on its own.

4.4 Significance to Cultural Heritage

Another important objective is that this work is significant to the cultural heritage it represents. Overall, this had a positive reaction from the participants, where they believe that the digital experience provided appropriate interpretations of the physical artefact. Interestingly, the lowest scored statement in this section was that the experience increases community access to their heritage. This could be due to the fact that the participants came from an international background, and so, they might not have considered this work as improving access to “their” heritage. In fact, a forthcoming work from the University of St Andrew’s research team indicates that similar work is important in promoting the experience of culture as part of the community it is representing. The work utilises a similarly built virtual environment of North Uist and evaluates it within a community of people from North Uist and a statement similar to the one presented here, received a higher score.

5 Discussion

Advancements in technology, such as 3D modelling and virtual reality, have introduced new possibilities for studying and interpreting heritage. This research demonstrates the potential of these technologies in the field of cultural heritage, emphasizing their value in preserving, studying, and presenting historical artifacts in innovative and engaging ways.

One innovative method presented involves restoring a digitised model and creating multiple modes of interpretations around it. Embedding the 3D model of St Madoes Stone in a gallery-type representation hosted on Sketchfab or in a IIIF gallery on a web page enables the user both to manipulate the stone and to have access to its context and relevant narrative. Furthermore, the user can also manipulate the stone by choosing colour schemes from an appropriate palette. This addresses the issue of how to make clear what is known and what is not known. On their learning journey, the user is empowered to explore the colour space that was available to the Picts.

Synthesizing 3D digitization and modelling techniques to recreate objects as they appeared in the past, with precise detail obtained from physical digitization, represents a new field. This approach builds upon existing digital reconstruction and 3D digitization literature, benefiting from the increased accessibility of commodity computers, graphics engines, and cameras. The methods showcased in this research demonstrate the feasibility of reconstruction from digitization and have broader applicability.

This development is significant in both the heritage and the educational fields because it enables the creation of highly accurate and detailed reproductions for use in a multitude of digital tools. The digitisation reconstruction techniques shown here are accessible because they require little or no coding knowledge and use open-source software which continues to improve. This should become the standard in reconstructions, allowing the wealth of objects digitised through museums and organisations to be used effectively. Incorporating highly realistic artefacts in reconstructions is the future of heritage education, especially considering the rise of artificial intelligence. Digitization plays a crucial role in preserving and conserving historical artifacts, allowing for the creation and restoration of authentic digital surrogates, as demonstrated with real-life data in this research and potentially with AI in the future. This is particularly valuable when preserving physical objects that are at risk of damage due to climate change or conflicts.

This research addresses the issue of limited access to cultural heritage education. Geographical, financial, physical, or other barriers often prevent individuals from visiting heritage sites in person. By making heritage accessible through various digital means, a wider audience can engage with and learn about these artefacts. This research focuses on immersive learning opportunities for informal education, utilizing interactive tools, virtual reality environments, and virtual tours. These approaches enhance the educational experience and promote a deeper understanding of the cultural heritage, particularly in settings where traditional teaching methods may not be as effective or engaging. For instance, these multiple modes of interaction benefit educators teaching children with Special Educational Needs and Disabilities (Pitchford et al., 2018).

Placing the stone within a historic landscape improves our understanding of the landscape, and the stone's significance within it. The creation of the landscape is a learning process, but it also makes exploration of Pictish landscapes something that can be undertaken by the general public. The availability of gaming computers and virtual reality headsets, and improved digital literacies, means that this sort of exhibit and exhibition is possible in the home, schools and in museums. However, barriers still exist, as not everyone possesses game-capable computers or VR headsets. To address this, a virtual tour of the landscape, comprising a series of 360 images with hotspots accessible via an app or web browser, provides an accessible immersive learning experience. Evaluation responses indicate that users found the systems easy to use, enjoyable for learning, and effective in communicating heritage in an engaging manner. As supported by the literature review, emerging game technologies and virtual reality contribute to engagement with heritage while facilitating learning through various interactive interpretations. This evaluation reflects the positive impact of these technologies.

Additionally, this research introduces a new way of engaging the public, by granting them control over interpreting researchers' decisions. This addresses the authenticity gap found in the literature where heritage creators where heritage creators typically hold final authority in restoring artifacts and presenting specific discourses. Involving people in the interpretation process is crucial for fostering a deeper understanding and increased engagement with heritage. The colour configurator deals with this issue by acknowledging the uncertainty in knowing how the stones were coloured whilst giving the audience the chance to interpret it and make their own choice. What this suggests is that this tool, used with the other immersive tools, stimulates discussion and engagement with the topic at hand.

However, this study does not address whether similar responses can be observed in a formal educational environment. Evaluating the effectiveness of digital modes of interpretation for Pictish landscapes in classrooms would be a fruitful area for future research. A natural progression of this work is to analyse how non-player characters can be included in the scene to help pass on information about the topic, either replacing or supplementing textual information in the environment. Furthermore, enhancing the challenge-based immersive experience can be achieved by including the user's own configured and customized stone model within the environment. This approach strengthens the connection between the colouring of stones and how they were perceived in their original context.

This research makes a valuable contribution to the existing literature by presenting an integrated approach to creating multiple modes of interaction for heritage studies, using realistic reconstructions. While these modes of interaction may have been utilised individually in previous studies, their combined application offers a more immersive and cohesive experience. This integrated approach facilitates a departure from compartmentalized thinking and encourages a holistic understanding of the subject matter. The techniques employed in this research also demonstrate the feasibility of not only creating authentic replicas of artefacts but also digitising entire cultural landscapes by leveraging a combination of traditional and immersive media. By utilizing interactive tools, this research supports the adoption of co-creation approaches in the field of heritage research and education.

6 Conclusion

The study set out to:

- Discuss how digital modelling techniques can be synthesised with 3D scanning to digitally restore artefacts and create authentic replicas in their original states.
- Present different modes of interpretation using authentic digital replicas.

This paper has made several contributions which encourage the effective and innovative use of digitised historical, archaeological, and cultural artefacts. On a conceptual level, a workflow has been developed which synthesises 3D modelling techniques with digitised artefacts. This can be used to authentically restore artefacts in a non-invasive digital manner. This has been applied to the St Madoes and Inchyra Pictish stones. In the process, a Pictish colour palette was composed which can be applied to any future colourisation of Pictish stones. A colour configurator tool has been developed which boosts interpretation, and the stones were placed in a virtual environment, representative of their context. A virtual tour has been created to assist in making the immersive virtual environment available outside of a VR headset experience. The restored digital models have thus been utilised to create immersive and exploratory modes of interpretation which aid in the understanding of the stones' original landscape. This is crucial in immersive learning contexts, both formally and informally, where a holistic understanding of the contexts of artefacts can be achieved through interaction with such historically accurate reproductions.

Funding Author A has received partial financial support from the Scottish Funding Council.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Agrawal, S., Simon, A., Bech, S., Bærentsen, K., & Forchhammer, S. (2020). Defining Immersion: Literature Review and Implications for Research on Immersive Audiovisual Experiences. *Journal of the Audio Engineering Society, 68*(6), 404–417. https://doi.org/10.17743/jaes.2020.0039

Altaweel, M. (2020, June 23). *The earth archive project and 3D mapping the earth*. Accessed from GIS Lounge: https://www.gislounge.com/the-earth-archive-project-and-3d-mapping-the-earth. Accessed 20 Nov 2022

Argyriou, L., Economou, D., & Bouki, V. (2020). Design methodology for 360° immersive video applications: The casestudy of a cultural heritage virtual tour. *Personal and Ubiquitous Computing, 24*, 843–859. https://doi.org/10.1007/s00779-020-01373-8

Beck, D., Morgado, L., Lee, M., Gütl, C., Dengel, A., & Wang, M. (2021). Towards an Immersive Learning Knowledge Tree - a Conceptual Framework for Mapping Knowledge and Tools in the Field. 2021 7th International Conference of the Immersive Learning Research Network (iLRN) (pp. 1–8). Eureka, CA, USA: IEEE. https://doi.org/10.23919/iLRN52045.2021.9459338

Biermann, H., Martin, I., Bernardini, F., & Zorin, D. (2002). Cut-and-paste editing of multiresolution surfaces. *ACM Transactions on Graphics (TOG), 21*(3), 312–321.

Bodzin, A., Junior, R. A., Hammond, T., & Anastasio, D. (2020). An Immersive Virtual Reality Game Designed to Promote Learning Engagement and Flow. 2020 6th International Conference of the Immersive Learning Research Network (iLRN) (pp. 193–198). San Luis Obispo, CA, USA: IEEE. https://doi.org/10.23919/iLRN47897.2020.9155132

The Book of Kells. (c. 800 CE). *Trinity College Dublin MS 58*. https://doi.org/10.48495/hm50tr726

Bradshaw, R., & Crabb, A. (2020). *Khronos and Smithsonian collaborate to diffuse knowledge for education, research, and creative use*. Accessed from Khronos. https://www.khronos.org/news/press/

khronos-smithsonian-collaborate-to-diffuse-knowledge-for-education-research-and-creative-use. Accessed 20 Nov 2022

Campbell, L. (2020). Polychromy on the Antonine Wall Distance sculptures: Non-destructive Identification of pigments on Roman reliefs. *Britannia, 51*, 175–201. https://doi.org/10.1017/S0068113X20000124

Campbell, E., & Driscoll, S. (2020). *Royal Forteviot: Excavations at a Pictish Power Centre in Eastern Scotland (SERF Monograph 2)*. York: Council for British Archaeology.

Cassidy, C., Fabola, A., Miller, A., Weil, K., Urbina, S., Antas, M. N., & Cummins, A. (2018). Digital Pathways in Community Museums. *Museum International, 70*(1–2), 126–139. https://doi.org/10.1111/muse.12198

Casu, A., Spano, L. D., Sorrentino, F., & Scateni, R. (2015). RiftArt: Bringing Masterpieces in the Classroom through Immersive Virtual Reality. In A. Giachetti , S. Biasotti , & M. Tarini (eds.) *Smart Tools and Apps for Graphics - Eurographics Italian Chapter Conference* (pp. 77–84). The Eurographics Association. https://doi.org/10.2312/stag.20151294

Cecotti, H. (2022). Cultural Heritage in Fully Immersive Virtual Reality. *Virtual Worlds, 1*(1), 82–102. https://doi.org/10.3390/virtualworlds1010006

Cerato, I., & Pescarin, S. (2013). Reconstructing Past Landscapes for Virtual Museums. In C. Corsi, B. Slapšak, & F. Vermeulen (Eds.), *Good Practice in Archaeological Diagnostics: Non-invasive Survey of Complex Archaeological Sites* (pp. 285–296). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-01784-6_17

Ch'ng, E., Li, Y., Cai, S., & Leow, F.-T. (2020). The Effects of VR Environments on the Acceptance, Experience, and Expectations of Cultural Heritage Learning. *Journal on Computing and Cultural Heritage, 13*(1), 1–21. https://doi.org/10.1145/3352933

Costanzo, A., Minasi, M., Casula, G., Musacchio, M., & Buongiorno, M. F. (2015). Combined use of terrestrial laser scanning and IR thermography applied to a historical building. *Sensors, 15*(1), 194–213.

Denard, H. (2012). A new introduction to the London Charter. *Paradata and transparency in virtual heritage* (pp. 57–71). Accessed from https://www.london-charter.org/media/files/ch6_denard.pdf. Accessed 20 Nov 2022

Edith Cowan University Library. (2022). *Practice-based & practice-led research*. Accessed from Research Methodologies for the Creative Arts & Humanities: https://ecu.au.libguides.com/research-methodologies-creative-arts-humanities/practice-based-and-practice-led-research. Accessed 20 Nov 2022

Emmitt, J. J., Mackrell, T., & Armstrong, J. (2021). Digital Modelling in Museum and Private Collections: A Case Study on Early Italic Armour. *Journal of Computer Applications in Archaeology, 4*(1), 63–78. https://doi.org/10.5334/jcaa.63

Fleury, P., & Madeleine, S. (2012). Reviving ancient Rome: virtual reality at the service of cultural heritage. Progress in Cultural Heritage Preservation: 4th International Conference, EuroMed 2012 (pp. 159–169). Limassol, Cyprus: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-34234-9_16

Gaspar, H., Morgado, L., Mamede, H., Oliveira, T., Fernández-Manjón, B., & Guetl, C. (2020). Research priorities in immersive learning technology: The perspectives of the iLRN community. *Virtual Reality, 24*(2), 319–341. https://doi.org/10.1007/s10055-019-00393-x

Geary, A., & Howe, E. (2009). Three-dimensional documentation and virtual restoration of the Lichfield Angel. *Journal of the Institute of Conservation, 32*(2), 165–179. https://doi.org/10.1080/19455220903059875

Hall, M. A. (2012). Three stones, one landscape, many stories: cultural biography and the early medieval sculptures of Inchyra and St Madoes, Carse of Gowrie, Perthshire, Scotland. In S. Dudley, A. J. Barnes, J. Binnie, J. Petrov, & J. Walklate (Eds.), *Narrating Objects, Collecting Stories; Material Worlds Conference Proceedings and Festschrift in Honour of Prof. Susan Pearce* (pp. 85–102). Routledge.

Hall, M. A. (2019). Pictish carving, Glencarse, St Madoes. *Discovery & Excavation in Scotland, 20*, 161–162.

Hall, M. A. (2020). Show and tell: Re-articulating the monumentality of power, or Picts in the museum. In C. Thickpenny, K. Forsyth, J. Geddes, & K. Mathid (Eds.), *Peopling Insular Art: Practice, Performance, Perception: Proceedings of the Eighth International Conference on Insular Art 2018* (pp. 207–213). Oxbow Books.

Hindmarch, J., Terras, M., & Robson, S. (2019). The cultural heritage object in the age of 3D digital reproduction. In *The Routledge international handbook of new digital practices in galleries* (pp. 243–256). London: Routledge.

Jeffs, A., Insh, F., Matthes, E. H., Flynn, T., Pett, D., Ayers, T., et al. (2017). Disciplining the Digital: Virtual 3D Reproduction, Pilgrim Badges, and the Stuff of Art History. *British Art Studies, 6*, 1–42.

Jo, Y. H., Hong, S., Jo, S. Y., & Kwon, Y. M. (2020). Noncontact restoration of missing parts of stone Buddha statue based on three-dimensional virtual modeling and assembly simulation. *Heritage Science, 8*(103), 1–12. https://doi.org/10.1186/s40494-020-00450-8

Kersting, M., Steier, R., & Venville, G. (2020). Exploring participant engagement during anastrophysics virtual reality experience at a science festival. *International Journal of Science Education, 11*(1), 17–34. https://doi.org/10.1080/21548455.2020.1857458

Kesik, J., Montusiewicz, J., & Kayumov, R. (2017). An approach to computer-aided reconstruction of museum exhibits. *Advances in Science and Technology. Research Journal, 11*(2), 87–94. https://doi.org/10.12913/22998624/69419

Khorloo, O., Ulambayar, E., & Altantsetseg, E. (2022). Virtual reconstruction of the ancient city of Karakorum. *Computer Animation & Virtual Worlds, 33*(3–4), e2087. https://doi.org/10.1002/cav.2087

Lautenschlager, S. (2016). Reconstructing the past: methods and techniques for the digital restoration of fossils. *Royal Society Open Science, 3*(10), 160342. https://doi.org/10.1098/rsos.160342

Mah, O. B., Yan, Y., Tan, J. S., Tan, Y.-X., Tay, G. Q., Chiam, D. J., . . . Feng, C.-C. (2019). Generating a virtual tour for the preservation of the (in)tangible cultural heritage of Tampines Chinese Temple in Singapore. *Journal of Cultural Heritage*, *39*, 202–211. https://doi.org/10.1016/j.culher.2019.04.004

Makransky, G., & Petersen, G. B. (2021). The Cognitive Affective Model of Immersive Learning (CAMIL): A Theoretical Research-Based Model of Learning in Immersive Virtual Reality. *Educational Psychology Review, 33*, 937–958. https://doi.org/10.1007/s10648-020-09586-2

Martina, A. (2014). *Virtual Heritage: New technologies for edutainment (Doctoral Thesis)*. Accessed from Archivio Istituzionale della Ricerca: https://hdl.handle.net/11583/2541502. Accessed 20 Nov 2022

Mathys, A., Brecko, J., & Semal, P. (2013). Comparing 3D digitizing technologies: what are the differences? 2013 Digital Heritage International Congress (DigitalHeritage). 1, pp. 201–204. Marseille, France: IEEE. https://doi.org/10.1109/DigitalHeritage.2013.6743733

McCaffery, J., Miller, A., Vermehren, A., & Fabola, A. (2015). The Virtual Museums of Caen: a case study on modes of representation of digital historical content. 2015 Digital Heritage (pp. 541–548). Granada, Spain: IEEE. https://doi.org/10.1109/DigitalHeritage.2015.7419571

McCarthy, J. (2014). Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *Journal of Archaeological Science, 43*, 175–185. https://doi.org/10.1016/j.jas.2014.01.010

McCarthy, J., Sebo, E., Wilkinson, B., & Sheehan, F. (2020). Open workflows for polychromatic reconstruction of historical sculptural monuments in 3D. *Journal on Computing and Cultural Heritage (JOCCH), 13*(3), 1–16. https://doi.org/10.1145/3386314

Miller, A. H., Allison, C., & Getchell, K. M. (2012). Open virtual worlds: A serious platform for experiential and game based learning. *Proceedings of MCIS 2012. Association for Information Systems*. Accessed from https://aisel.aisnet.org/mcis2012/7. Accessed 20 Nov 2022

Nilsson, N. C., Nordahl, R., & Serafin, S. (2016). Immersion Revisited: A Review of Existing Definitions of Immersion and Their Relation to Different Theories of Presence. *Human Technology, 12*(2), 10–134. https://doi.org/10.17011/ht/urn.201611174652

Pesci, A., Bonali, E., Galli, C., & Boschi, E. (2012). Laser scanning and digital imaging for the investigation of an ancient building: Palazzo d'Accursio study case. *Journal of Cultural Heritage, 13*(2), 215–220. https://doi.org/10.1016/j.culher.2011.09.004

Piazzoni, F. (2020). What's Wrong with Fakes? Heritage Reconstructions, Authenticity, and Democracy in Post-Disaster Recoveries. *International Journal of Cultural Property, 27*(2), 239–258. https://doi.org/10.1017/S0940739120000119

Pietroni, E., & Ferdani, D. (2021). Virtual Restoration and Virtual Reconstruction in Cultural Heritage: Terminology, Methodologies, Visual Representation Techniques and Cognitive Models. *Information, 12*(4), 167. https://doi.org/10.3390/info12040167

Pisani, S., Miller, A., & Hall, M. (2022). Digitally restoring artefacts using 3D modelling techniques for immersive learning opportunities. Proceedings of the 2022 8th international conference of the Immersive Learning Research Network (iLRN) (pp. 149–156). Vienna, Austria: IEEE. https://doi.org/10.23919/iLRN55037.2022.9815895

Pitchford, N., Kamchedzera, E., Hubber, P. J., & Chigeda, A. L. (2018). Interactive Apps Promote Learning of Basic Mathematics in Children With Special Educational Needs and Disabilities. Frontiers in Psychology, 9(262). https://doi.org/10.3389/fpsyg.2018.00262

Praticò, Y., Ochsendorf, J., Holzer, S., & Flatt, R. J. (2020). Post-fire restoration of historic buildings and implications for Notre-Dame de Paris. *Nature Materials, 19*(8), 817–820. https://doi.org/10.1038/s41563-020-0748-y

Pritchard, D., Sperner, J., Hoepner, S., & Tenschert, R. (2017). Terrestrial laser scanning for heritage conservation: The Cologne Cathedral documentation project. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences, 4*(2), 213–220. https://doi.org/10.5194/isprs-annals-IV-2-W2-213-2017

Ruiz, R. M., Torres, M. T., & Allegue, P. S. (2021). Comparative Analysis Between the Main 3D Scanning Techniques: Photogrammetry, Terrestrial Laser Scanner, and Structured Light Scanner in Religious Imagery: The Case of The Holy Christ of the Blood. *ACM Journal on Computing and Cultural Heritage (JOCCH), 15*(1), 1–23. https://doi.org/10.1145/3469126

Shurik, A. K. (2018, November). Comparing 3 Techniques for 3D Digitizing Small Artifacts Photogrammetry Laser Scanning 3D Structured Light Scanning. Presentation at the American Anthropological Association Conference. San Jose, CA. https://doi.org/10.13140/RG.2.2.20800.89603

Stevenson, R. (1961). The Inchyra stone and some other unpublished Early Christian monuments. *Proceedings of the Society of Antiquaries of Scotland, 92*, 33–55.

Yu, Y., Zhou, K., Xu, D., Shi, X., Bao, H., Guo, B., & Shum, H.-Y. (2004). Mesh editing with poisson-based gradient field manipulation. ACM SIGGRAPH 2004 Papers (pp. 644–651). New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/1186562.1015774