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# Enhancing access and understanding of ancient manuscripts: the 3D Digital Edition of the Codex Cospi

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ABSTRACT

Engaging museum visitors with ancient manuscripts poses challenges due to preservation requirements, incomprehensible language, and fragile nature, which prevents physical handling. Innovative approaches and technologies are emerging to enhance accessibility and comprehension for both specialist and general audiences. This study addresses two research questions: RQ1, how can 3D enhance traditional 2D representations of ancient manuscripts? RQ2, how can a reliable and engaging 3D knowledge space be created to facilitate their understanding? These questions are explored by creating the 3D Digital Edition (3DDE) of the Codex Cospi, a Mesoamerican divinatory manuscript with a complex leporello structure. The project highlights the effectiveness of 3D digitisation in capturing and presenting intricate layouts, enabling users to better explore the manuscript's dual sides and contextual layers beyond the limitations of in-site exhibitions and 2D formats. To enrich the artefact representation, the 3DDE seems the best format to integrate interdisciplinary research into a cohesive, interactive virtual space, and employ storytelling techniques to engage a diverse audience. Aimed at both public and academic dissemination, the 3DDE of the Codex Cospi serves as a tool for knowledge production and cultural valorisation, bridging the gap between accessibility and scholarly reliability. Its adaptability makes it suitable for museum exhibitions, education, and research, offering an immersive and enriched understanding of the manuscript's historical and cultural significance.

## 1. Introduction

Conveying the significance of manuscripts to museum visitors presents several challenges. Preservation requirements often necessitate dim lighting, the language of the texts can be incomprehensible, and the fragile nature of manuscripts prevents physical handling. As a result, visitors tend to engage with these works primarily for their aesthetic value, particularly when adorned with intricate decorations. While some museums offer 2D digital galleries to showcase manuscript pages, these tools frequently lack engaging storytelling elements or interactive features, which hinders deeper visitor engagement and understanding (Schreibman and Papadopoulos, 2019; Pietroni et al., 2023).

Over the last three decades, the cultural heritage sector has increasingly adopted interactive 3D models as tools for knowledge production. These technologies allow scholars to make complex two-dimensional data more comprehensible and to simulate conditions (spatial, temporal, or material) that cannot be addressed through conventional methods (Schreibman and Papadopoulos, 2019). The ability to digitally manipulate a representation of an object faithful to its physical characteristics introduces new opportunities for access, discovery, and valorisation of fragile and inaccessible artefacts, particularly when combined with effective storytelling techniques and contextual information (Bekele et al., 2018; Rizvic et al., 2024). A successful digital representation should go beyond mere photorealism to provide insights into an artefact's creation, historical relevance, and social or cultural significance. In this context, while photorealism aligns with public expectations and is often associated with historical accuracy, user evaluations suggest that intuitive and consistent interaction in a digital environment is more effective for learning than a focus on photorealistic detail (Pujol-Tost, 2019).

According to Huurdeman and Piccoli (2021), the use of 3D models as research tools enables a potential iterative three-step process of knowledge creation, sharing, and discovery.

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1. New insights emerge during the creation of a 3D reconstruction (interpretative visualisation).
2. This knowledge is presented to viewers through an online or immersive platform (expressive visualisation).
3. Users interact with the 3D environment, gaining, discovering, and even contributing new knowledge by exploring underlying linked data.

Based on these premises, this work seeks to address two key research questions.

- RQ1: How can 3D enhance traditional 2D representations of ancient manuscripts?
- RQ2: How can a reliable, accessible, and engaging 3D knowledge space be created to facilitate their understanding?

This paper focuses on the interdisciplinary study and on the creation of the 3D Digital Edition (3DDE) of the Codex Cospi, a Mesoamerican divinatory manuscript. The aim is to integrate existing research from various fields into a single, accessible, and interactive virtual space, leveraging storytelling techniques to engage multiple audiences across reliable sources. The 3DDE of the Codex Cospi aspires to serve as an accessible tool for knowledge production, cultural valorisation, and public and academic dissemination. The article will be structured as follows: section 2 gives a brief overview of the current state of the art in using innovative technologies to study and valorise ancient manuscripts from an international point of view, while also highlighting approaches to ensuring digital objects are accessible and reusable, in line with FAIR principles. Section 3 will introduce the methodology employed for the manuscript's digitisation within the CHANGES project (Spoke 4) and the development of the 3DDE using the methodological framework and infrastructure created by the PURE3D project. Section 4 presents the planned future improvements of the prototype presented. Finally, in Section 5, we discuss the main results obtained in our research.

## 2. Related works

The need to explore new approaches for accessing, enriching, and presenting ancient manuscripts (and generally texts) emerged after the development of the World Wide Web (Schreibman and Schoueri, 2024). Digital Scholarly Editions (DSEs) were among the earliest scholarly artefacts created by humanists to address this need, which stems from a long tradition of editing texts for print publication (Apollon et al., 2014; Driscoll and Pierazzo, 2016). DSE can be defined as assemblages or machines of knowledge which have introduced new modalities for annotation, extending beyond text to encompass audio, video, and images, linking data across internal and external, cross-media sources. Most of these editions were primarily text-based, employing the conventions of the Text Encoding Initiative (https://tei-c.org/) (e.g., The Rossetti Archive (https://www.rossettiarchive.org/), The Walt Whitman Archive (https://whitmanarchive.org/), among others), while a smaller number focused on image-based editions, such as The Blake Archive (https://www.blakearchive.org/). DSE redefined the role of text-based editions, shifting them from static, confined environments (such as books) into expansive, interconnected digital spaces.

This transformation allows for the creation of digital archives that assemble texts around specific themes, individuals, or topics, extending their context into a multimodal and dynamic space for exploration (Schreibman and Papadopoulos, 2019). However, these editions often maintain a predominantly critical focus, without developing storytelling methodologies to make their content more engaging for a wider audience. Furthermore, they frequently fail to fully leverage the potential for interdisciplinary collaboration, concentrating primarily on critical, philological, literary, and historical aspects. In this context, projects like MINIARE, at the Fitzwilliam Museum, Cambridge (https://fitzmuseum.cam.ac.uk/research/projects/miniare), focus on supporting the collaboration between humanities and hard sciences by enhancing understanding of book artefacts through non-invasive diagnostic techniques. Its web platform enables users to explore manuscripts by accessing insights into the techniques and materials used by illuminators, alongside codicological, palaeographic, and historical-artistic descriptions of the volumes. However, the project presents its content in a static, archival format, focusing on detailed analyses without interactive features or storytelling tools, limiting engagement for non-specialist audiences.

Over the years, advancements in interactive and digital technologies have offered textual scholars a diverse toolkit for remediating textual records and an expanding array of other knowledge transmission mediums. Among these, virtual technologies prove to be a valuable and engaging asset in providing 3D representations of complex artefacts, adding details and layers of understanding that cannot be achieved through a 2D format (Pallud, 2017; Li, 2021). Projects like Turning the Page (https://ttp.onlineculture.co.uk/) primarily focus on simulating the experience of flipping through a book, digitally reproducing pages in 2D or with basic 3D animations. While this approach provides access to rare manuscripts, it lacks sophisticated narrative tools that could convey the historical, cultural, and artistic contexts surrounding the manuscripts. The emphasis remains on access rather than on creating a deeper, engaging experience.

On the other side, recent projects blend advanced technology to enrich engagement with ancient manuscripts. The MUBIL project, initiated by NTNU University Library and PERCRO in Pisa (Angeletaki et al., 2014), uses 3D technology and gamified environments to promote ancient manuscripts interactively, fostering accessibility and engagement. The USC Virtual Reality Exploration of 15th Century Illuminated Manuscripts (https://dornsife.usc.edu/xrlab/neh-vr-exploration-of-illuminated-manuscripts/), developed by the USC Advanced Visualisation Lab, immerses users in the artistry and materiality of illuminated texts through VR, fostering interaction and narrative-driven discovery. The Manuscripts of Lichfield (https://lichfield.ou.edu/content/project) employs 3D imaging to digitise medieval texts, enhancing public access using 3D galleries and interactive features for scholarly exploration. Finally, Codex4D (https://codex4d.it/), developed by the CNR-ISPC, integrates 3D models of manuscripts into virtual and mixed-reality environments, combining hidden textual layers, subsurface details, and material diagnostics to create an interdisciplinary and web-based interaction powered by ATON framework (https://osiris.itabc.cnr.it/aton/) (Fanini et al., 2021; Schettino et al., 2023; Pietroni et al., 2023). Except few cases, 3D models are presented through videos with audio narration, shared on platforms (e.g., YouTube) or displayed in museums. While this approach is accessible and widely disseminated, it limits the 3D models' integration into the broader public and scholarly ecosystem (Schreibman and Papadopoulos, 2019). Moreover, the few accessible 3D models are mostly presented through interfaces with limited functionality, where the assets are only occasionally supplemented with predominantly textual content. Despite the milestones achieved by the mentioned projects, the lack of robust design strategies (such as storytelling techniques) highlights the need to adopting a methodology capable of making content accessible to a broader audience beyond the academic community.

Finally, while text-based editions benefit from decades-old standards and established research communities, such as the Text Encoding Initiative, working with more complex sources like 3D models presents several challenges (Moore et al., 2022). At the same time, it remains essential to ensure reliable and accessible content, while ensuring accurate digital representations through transparent documentation following, as much as possible, the FAIR principles (Knazook et al., 2023). The FAIR principles state that research data should be *Findable, Accessible, Interoperable,* and *Reusable*, and consist of fifteen recommendations that are "related, but independent and separable" (Wilkinson et al., 2016). The authors intentionally remain general, leaving it to individual research communities to determine how the

principles can be implemented within their specific disciplines and workflows (Harrower et al., 2020). Over time, the original list of FAIR principles has been adapted to different types of research objects. For instance, Koster and Woutersen-Windhouwer (2018) proposed a version tailored to library, archive, and museum collections, where accessibility presupposes that digital objects are permanently available through sustainable storage, open and universal access protocols, version management, and regular backups. Expanding on these adaptations, Barzaghi et al. (2024) proposed an extended version of the FAIR principles for 3D cultural heritage data, where a resource is considered *accessible* when its availability is ensured through version management, the use of open and standard formats, and a clear plan for depositing data objects in a trusted repository (such as Zenodo), accompanied by machine-readable metadata.

Web-based 3D viewers play a crucial role in making 3D data widely accessible, as they support visualisation, interaction, and metadata enrichment. Several 3D viewers have been developed for this purpose, including Voyager (https://smithsonian.github.io/dpo-voyager/) by the Smithsonian Institution, 3DHOP (https://3dhop.net/) by the Visual Computing Laboratory (CNR-ISTI), and the ATON framework by the Institute of Heritage Science (CNR-ISPC) (Fanini et al., 2021). A self-hosted viewer offers greater control over the displayed data and avoids limitations related to model size. Nonetheless, many models still require optimised or simplified versions for web distribution, to meet hardware constraints and ensure reasonable loading times. Champion and Rahaman (2020) analysed the most widely used commercial and institutional platforms for downloading, trading, sharing, and hosting 3D models, identifying key features relevant to 3D digital heritage research. Despite the increasing number of 3D models available, there are still few online repositories that the GLAM sector can reliably use. Moreover, the existing platforms often offer limited functionalities, lack interoperability, and do not provide sufficient metadata or links to related resources for research and reuse. Most commercial platforms, such as TurboSquid (https://www.turbosquid.com/it/), CGTrader (https://www.cgtrader.com/), and ShareCG (https://www.sharecg.com/), generally lack both Open Platform Interfaces (OPI) and Machine-Readable Persistent Identifiers (MRPI). Surprisingly, even many institutional and commercial solutions do not include integrated 3D viewers; instead, they typically provide only 2D images or video previews prior to download.

In this context, the absence of a stable web-based environment and widely accepted community-based standards, particularly concerning schemas, metadata, and paradata, poses additional challenges for the analysis, study, and dissemination of 3D digitised manuscripts and, more generally, digitised cultural artefacts (Moore et al., 2022; Schreibman and Schoueri, 2024; Papadopoulos, 2024).

## 3. Methodology

### 3.1. The codex Cospi

The Codex Cospi is a pre-Hispanic Mesoamerican pictorial manuscript now in the University Library in Bologna (inv. 4093) (Anders et al., 1994; Laurencich Minelli, 1992). Probably painted in the Eastern Nahua regions of Puebla-Tlaxcala (Mexico) between the fifteenth and early sixteenth centuries, it was brought to Bologna in 1533 by the Dominican friar Domingo de Betanzos (Domenici and Laurencich Minelli, 2014). The manuscript is a tonalamatl, or "book of destinies", a ritual object used in divinatory performances related to calendrical and astronomical events. It consists of a 364 cm-long strip of animal skin, likely deer, made up of five pieces and folded into a *leporello* format to form 20 plates. Both sides are covered with plaster and painted, though in different regions and with distinct color palettes primarily based on organic dyes (Miliani et al., 2012). The obverse of the codex, read from left to right, contains a 260-day divinatory calendar, predictions tied to Venus's heliacal rise, and depictions of the four quarters of the ritual year. The reverse, read from right to left, likely served as divination tables or as instructions for the proper disposal of offerings during rituals associated with several animals, with the content oriented 180° from the obverse. The leporello structure, typical of pre-Hispanic Mesoamerican manuscripts, allows the reader to open a varying number of plates so that a complete section could be displayed during the ritual action. Yet, the codex's dual-sided nature, and complex layout are difficult to convey in a 2D edition. In this context, we envisioned that a 3D format could enhance understanding by situating information within its spatial context, offering insights into the codex's complex format, and enabling users to intuitively appreciate its intricate structure and ritual functionality through enriched contextual information.

The Codex's 3D digital representation was created as part of the digital twin developed for the temporary exhibition *The Other Renaissance': Ulisse Aldrovandi, the Wonders of the World* (Balzani et al., 2024), following a FAIR-compliant and solid methodology consolidated during the pilot case (Barzaghi et al., 2024, 2025). This work was carried out within the CHANGES project ("Cultural Heritage Active Innovation for Next-Gen Sustainable Society"), an EU-funded national initiative. More specifically, it was part of SPOKE 4, the thematic sub-project dedicated to employing virtual technologies for the promotion, preservation, exploitation, and enhancement of cultural heritage in museums and art collections.

Due to the preservation state of the Cultural Heritage Object (CHO), it was not possible to use traditional photogrammetric acquisition or scanning techniques to acquire it, as was commonly done in the other cases. Instead, a direct 3D modelling approach was adopted, using specialised software to accurately represent the CHO. For this specific case study, two versions of the model were preserved.

- The Digital Cultural Heritage Object (DCHO): A high-resolution model that represents the most complete version in terms of data density. In this specific case, given the simplicity of the manuscript's shape and geometry, the data density mainly concerns resolution of the textures, which were created to ensure maximum legibility and photorealism of the model.
- The Optimised Digital Cultural Heritage Object (DCHOo): A more performant 3D model version optimised for real-time interaction on web-based platforms.

Every stage of the process required to create the two versions was documented to ensure full transparency and reproducibility (see Barzaghi et al., 2024; Barzaghi et al., 2025).

### 3.2. 3D digitisation process

The Digital Cultural Heritage Object (DCHO) was generated and modelled in Blender (https://www.blender.org/), a free and open-source 3D creation suite, using precise measurements provided by the owning institution and documenting materials about the temporary exhibition where the CHO was exposed. The Codex was depicted fully open to ensure both comprehensive visibility and structural understanding. This approach also faithfully replicates the artefact's positioning and condition as determined by the curatorial decisions made for the temporary exhibition.

Starting from the RAW version of the photos provided by the University Library of Bologna, some editing operations have been done in GIMP (https://www.gimp.org/), an open-source and cross-platform software for image editing, to remove the distortion due to the camera lens to obtain orthogonal images. Then, UV mapping was performed in Blender organising carefully the UV islands to guarantee a detailed texture building using GIMP. UV mapping is the process of linking three-dimensional mesh coordinates to two-dimensional image coordinates. This involves unwrapping each polygon in the mesh onto a flat surface and applying a texture to it. The texture is an image applied to the surface of a 3D model to accurately reproduce the colours, details, and

surface characteristics of the real object.

To obtain the highest resolution possible, five textures of 16K each were created (Fig. 1), and the UV islands of each of the five UV maps were manually aligned to obtain perfect correspondence between geometry and visual sequencing of textures and, consequently, the plates of the object. To enhance the photorealism of the materials, a 4K normal map was created based on open-access textures based on the appearance of ancient manuscripts made from animal skin. In addition, roughness and occlusion maps were produced to highlight certain painted details of the manuscript. This process provides the DCHO, which represents the maximum completeness in terms of texture data quantity and quality, finally stored in OBJ or FBX format. The DCHO, with 16k diffuse textures and 4k normal maps, has a total file size of 1.85 GB. Since the shape of the manuscript was very simple and regular, no geometric optimisation processes were carried out, maintaining a count of 52,128 triangles for both DCHO and DCHOo. This number allowed for final sculpting operations on the model, aimed at achieving an appearance consistent with that of deerskin. To obtain the DCHOo, the additional performant version for web-based and real-time interaction, the DCHO's textures were finally optimised: the five diffuse textures were resized to 4K, while among the additional maps, only the normal map, resized to 2K, was retained, resulting in a model of 12.5 MB.

It is important to emphasise that the optimisation and compression of 3D models critically depend on the intended use and the performance requirements related to the density and complexity of the virtual environment in which they are embedded. In this specific case, while the DCHOo version ensures the proper functioning of the 3D digital edition, there are situations in which a further, more optimised version may be required. For example, in the context of the Aldrovandi exhibition's digital twin, an even more optimised version was developed alongside the existing ones. This was necessary to enable the model to coexist efficiently with other elements during navigation. In this version, the five textures were merged into one through a process of UV mapping and subsequent baking, and geometry was reduced to a minimum. Aside from these specific cases, our research output emphasises the use of DCHOo on web-based platforms (i.e., ATON framework, Voyager, etc.) allowing real-time interaction. The DCHOo is stored in glTF format (https://www.khronos.org/Gltf), an open and royalty-free specification designed for the efficient transmission of 3D scenes and models between engines and applications (Robinete et al., 2018). The DCHOo was finally published on Zenodo (https://zenodo.org/) (Bordignon, 2024), an open-access repository for publications and data by researchers. While Zenodo is not specifically designed for 3D or cultural heritage data and metadata, it was selected for its strong alignment with Open Science principles: it offers a DOI for every deposited item, supports advanced metadata schemas such as the DataCite Metadata Schema and Dublin Core, and is highly regarded within the research community.

### 3.3. 3D digital edition

#### 3.3.1. Creating multifaceted resources

Each artefact contains a story. In our case, we chose to craft one centred on the Codex Cospi. The PURE3D project (https://pure3d.eu/) provided the ideal framework and methodology to achieve this goal, adding a layer of depth to the featured exhibition piece. PURE3D is an open-source infrastructure initiative led by the Maastricht University, The Netherlands. It focuses on revolutionising the presentation, preservation, and evaluation of 3D cultural heritage and scholarly works.

Unlike conventional methods, where 3D models are often presented independently of their academic narratives, PURE3D integrates these models as core scholarly outputs. By embedding them within rich contexts of annotations, multimedia elements, and metadata, PURE3D turns these models into multifaceted resources that cannot be replicated in traditional print formats. This resource, conceived as a 3D Digital Scholarly Edition, introduces an innovative approach by positioning 3D models as the central "text" within the traditional concept of DSE. This paradigm creates a multimodal space for research and annotation, enhancing accessibility while preserving both the models and their interpretative frameworks as integral components of the scholarly discourse. Creating such an edition involves constructing an intertextual network that integrates the 3D model with its accompanying annotations and apparatus, offering a foundation for the reader to actively

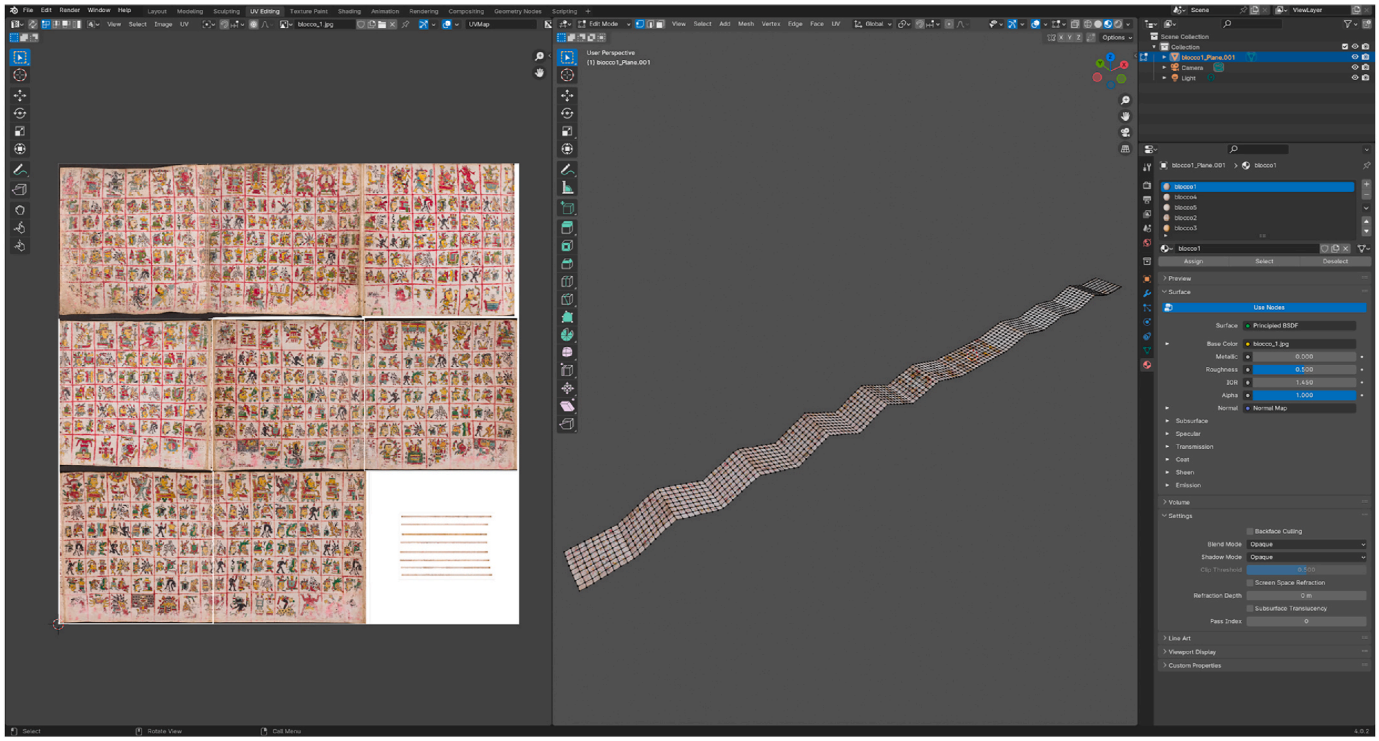

**Fig. 1.** Edit view in Blender of the Codex Cospi. On the left, one of the five textures created.

participate in the process of knowledge creation (Schreibman and Papadopoulos, 2019). The creation of the 3D Digital Edition required a multidisciplinary approach to integrate different bodies of knowledge. Once the 3D model was created, the authors discussed together the type of textual and visual information to be added, as well as the optimal format and language.

According to Schreibman and Schoueri (2024), 3D digital scholarly editions can be conceptualised as comprising three interoperable layers.

1. The Viewer Layer: The visual interface presented to the user.
2. The Database Layer: Contains the version of the model used in the interface, along with the annotation data and information about object behaviours.
3. The Preservation Layer: Stores all versions of the model created, as well as associated metadata and paradata.

The viewing layer is powered by Smithsonian Voyager (https://smithsonian.github.io/dpo-voyager/), a software developed by the Smithsonian Institution to offer immersive online exploration of its 3D digitised collections. The database layer, currently being developed by CLARIAH (https://www.clariah.nl/), will enable 3D scholarly editors to create, edit, and publish 3D editions for their audience. Lastly, the preservation layer, guided by DANS (Dutch Data and Archiving Networking Services) (https://dans.knaw.nl/en/), ensures long-term accessibility of the 3D edition and its data, even if the viewing or database layers are no longer maintained.

### 3.3.2. *Empathy maps and conceptualisation phase*

First, following the methodological framework offered by PURE3D, an empathy map was developed to define the target audience through the creation of personas. Personas are fictional characters that represent groups of similar users, this approach enables to simplify and organise large volumes of user information into more digestible segments (Katifori et al., 2018; Almeshari et al., 2019). In this phase, the main goal is to imagine and learn more about the user and their problems, wants, needs, and the environment or context in which they will experience the design (Fig. 2).

Then, conceptualisation was needed to identify the main thematic strands on which to structure the edition contents (Fig. 3). Specifically, we identified three main topics based on the available and accessible sources about the Codex Cospi.

1. Biography: focusing on the history of the object and its journey from Mesoamerica to the University Library of Bologna, where it is now preserved.
2. Contents: covering all aspects related to the interpretation of the manuscript's contents based on research conducted to date.
3. Materials: examining the material composition of the object, informed by analyses using innovative technologies conducted thus far (Miliani et al., 2012).

Subsequently, we used a PowerPoint presentation to draft the content and keep track of the available materials to enrich each topic. This phase was instrumental in organising the tour's structure and drafting the articles, including their titles, media, captions, and other elements. It also included notes-to-self on how to use hotspot annotations and the 3D space to convey the narrative effectively, such as planned camera movements, viewpoints, and interactions with the 3D model.

### 3.3.3. *Implementation*

In 3DDE, annotations can extend beyond text to include multimodal elements and linked data, connecting the edition to knowledge generated externally on the web. Moreover, a dynamic 3D environment offers the unique capability to adjust camera angles and viewpoints, enabling the orchestration of perspectives to highlight and annotate specific physical characteristics of an artefact or its spatial and temporal context. Although the database and preservation layers support the life cycle of a 3DDE, its development and conceptualisation primarily focus on the viewing layer, where both explicit and implicit annotations are integrated with a 3D model of historical or cultural significance (Schreibman and Schoueri, 2024). Huurdeman and Piccoli (2021) suggest that implicit annotations, such as camera views, hypothesis layers, certainty index layers, and texture materials, are created through user interactions with the model and supported by the viewing environment. These annotations differ from explicit ones, such as text, images, sound, or video, as they are less overt or immediately recognisable as editorial


**Fig. 2.** Example of user persona.

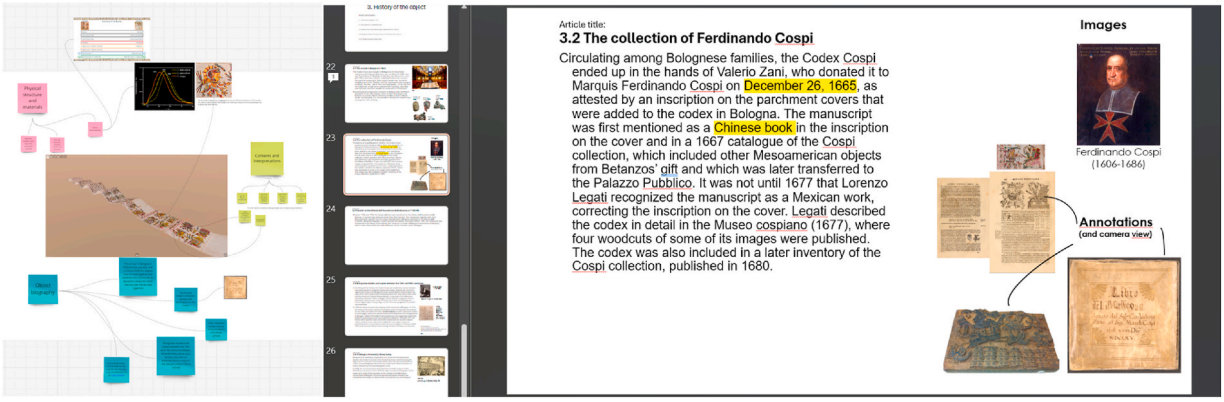


**Fig. 3.** Conceptualisation phase.

contributions.

Voyager, as a 3D web viewer, not only offers tools for inspecting 3D assets (such as zooming, measuring, cross-sectioning, and visual rendering) but also emphasises features that enhance digital storytelling through four interconnected modalities, enabling both linear and nonlinear exploration.

1. Annotation Labels: Expandable hotspot text providing spatially aware annotations.
2. Articles: HTML-based pages incorporating text and multimedia, displayed either as overlays on the 3D model or positioned alongside it.
3. Guided Tours: A versatile mix of annotations, articles, camera movements, and analytical features, including alternative material shaders, lighting adjustments, measurement tools, and slicers.
4. Audio Narration: A single audio clip is available for playback at any point during the experience.

Designed with a general audience in mind, the Codex Cospi 3DDE places a strong emphasis on guided tours. Tours not only offer a step-by-step narrative but also create a rich annotative environment, integrating text, multimedia, and guided camera views to effectively direct the reader's focus. The edition features three thematic tours (Contents, Biography, and Materials) each offering a structured narrative complemented by a richly annotated environment of text and multimedia. These annotations, which include pre-set camera views, are designed to focus the reader's attention on key aspects of the Codex Cospi.

The information, based on the most recent scholarly literature, has been presented in a language accessible to a wide and diverse audience, making it available in both English and Italian. This need for simplification, without sacrificing scientific accuracy, was particularly effective in dealing with the manuscript's materiality, a task that required making available highly specialised knowledge acquired through spectroscopic analysis. Indeed, in the Materials Tour, the edition integrates a wide array of multimedia resources derived from the analytical campaigns on the manuscript (Miliani et al., 2012). These resources (photos, videos, and scientific papers) are incorporated as explicit annotations, using Voyager's hotspot annotation system, and expanded upon through in-depth articles (Fig. 4). In terms of implicit annotation, the flexible features of Voyager's guided tour enabled us to set specific camera views around the manuscript. These camera movements, combined with object-based contextual annotations (Schreibman and Schoueri, 2024), proved to be the most efficient way to focus attention on the model, highlighting the results of the analysis campaigns conducted on the manuscript. This approach emphasised, based on the color palettes used, the distinct technological traditions of the regions where the two sides of the manuscript were painted (Fig. 4).

Similarly, within the annotations created for the Content tour, it was possible to directly integrate into the 3D model the interpretations made by scholars regarding the identification of figures and the meaning of the signs or symbols depicted (Fig. 5). Numerous resources (including textual analyses, images, videos, and publications) are interlinked to provide context and narrate the historical and cultural significance of the manuscript. This structure allows users to explore the content through multiple pathways, such as selecting tours, articles, or annotations. Fig. 6 illustrates an example of transitioning from an annotation within the Biography Tour to a detailed textual explanation, triggered by clicking the *Read more* function, where additional photos and insights are presented to the user. To support first-time users accessing Voyager from home, a textual pop-up is displayed upon loading the edition's page, inviting users to consult the introduction, and providing guidance on changing the language if required. The introduction is presented as

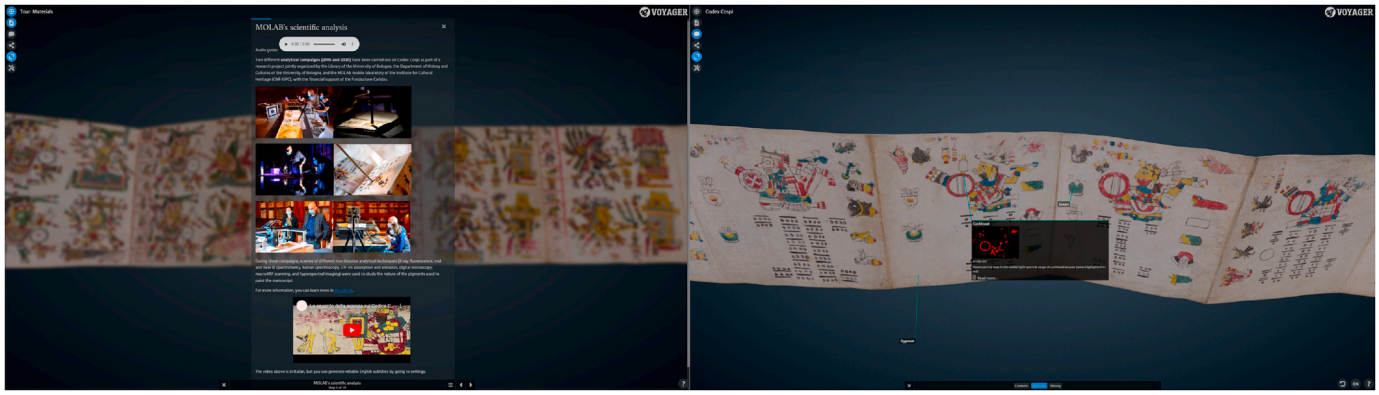


**Fig. 4.** Article and object-based annotations about Materials.

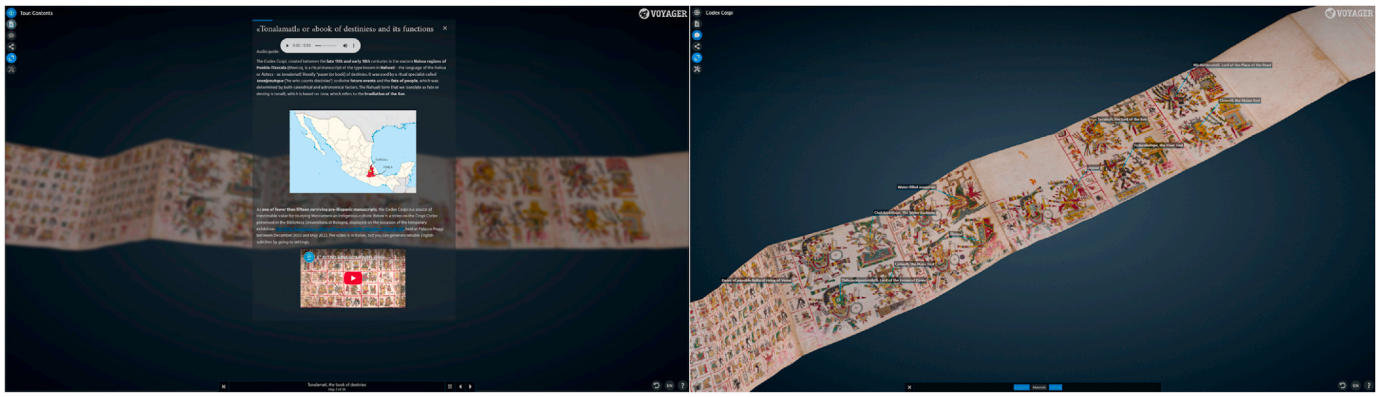


**Fig. 5.** Article and object-based annotations about Contents.

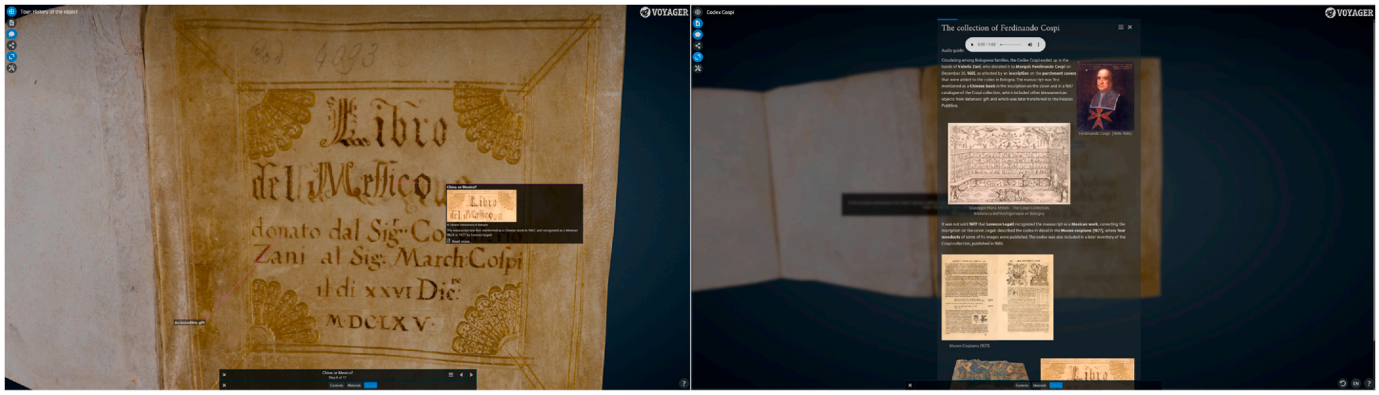


**Fig. 6.** Example of interactive transition between different sources.

an article offering a concise overview of the edition, the context of its development, and instructions for navigating its content. At the conclusion of each virtual tour, users are directed to a dedicated article compiling all references underpinning the edition. To facilitate focused study, these sources are organised thematically. Furthermore, for users interested in methodological details, an additional section provides references for further study on the manuscript's digitisation process and the underlying editorial approach.

Finally, to improve sensory accessibility for individuals with visual impairments, MP3 audio files were included for each article, providing an audio version of the content in both English and Italian. In addition, basic alternative text was included for images to support screen reader interpretation. The audio files were generated using Speechgen. io (https://speechgen.io/it/), an online AI-powered text-to-speech reader. The platform offers a wide range of synthetic voices and allows users to create and download high-quality audio narrations for free, without licensing issues. Although the project did not adopt specific sensory accessibility standards, the inclusion of audio versions aligns with the principles of inclusive design as promoted by the Web Content Accessibility Guidelines (WCAG 2.1) (W3C, 2025), as well as with the European Accessibility Act (European Parliament and Council, 2019), which require that information be perceivable through multiple sensory channels.

### 3.4. Accessibility and reusability

Voyager supports a variety of formats for 3D model integration and interaction, including glTF and glb for general 3D model rendering, as well as its proprietary SVX format. The SVX format is a structured JSON file designed to manage complex data, including 3D models, annotations, and associated metadata. Its structure is similar to glTF but tailored to the specific needs of Voyager's ecosystem, enabling rich, multimodal content to be embedded alongside the 3D models. This flexibility allows for the integration of interactive features, like camera views and hotspots, while ensuring that both the models and their interpretative frameworks are preserved and accessible. This makes Voyager's infrastructure highly replicable for similar projects, as it can support a wide range of digital assets, from text-based annotations to dynamic multimedia resources, all within a streamlined platform for research and engagement.

The Codex Cospi 3DDE was published online following a peer review process managed by PURE3D platform (https://editions.pure3d.eu/index.html) (Bordignon and Domenici, 2025). The publication is available in two languages (Italian and English) under a CC-BY license, ensuring compliance with the FAIR principles. In addition to the visibility and inclusion of the metadata, all the contents of the edition can be downloaded: the article texts — including any links to external resources — multimedia files (images and audios), 3D models, and the JSON file, which maintains the connections between the various resources, allowing users to reuse Voyager to further integrate or expand the original edition. Once downloaded the edition, it is possible to replicate it both in the Voyager standalone version (https://3d.si.edu/voyager-story-standalone), available online, and through local hosting of Voyager. The standalone version allows users to interact with the content directly via the web, offering the possibility to test the edition's editing interface and not just its viewing mode; meanwhile, local hosting provides a more flexible and stable option for offline access, as well as for edition editing and integration. By hosting Voyager locally, users can run the platform on their own servers, allowing full control over the data and offline access. This setup enhances the replicability of the project, enabling deployment in various environments, from academic research labs to museum exhibitions, while preserving all the interactive and

multimodal features.

In this context, the permanent reinstallation of the Poggi Palace Museum in Bologna is currently underway, with official implementation scheduled for January 2026. According to the final plan, the Codex Cospi will be physically exhibited in the museum's second room, accompanied by a medium-sized touch screen (50–55″) running the 3DDE of the Codex, thus allowing direct interaction with visitors. To prevent potential disruptions arising from network malfunctions, the application will be deployed locally, ensuring full offline functionality. Meanwhile, throughout 2025, the prototype was exhibited and presented at various events and conferences. Regarding usability, these occasions provided an opportunity to conduct direct observations of users interacting with the prototype (Kamińska et al., 2022). Depending on the context, the 3D digital edition attracted considerable interest: in public events not exclusively aimed at an academic audience, younger users enjoyed exploring and reading the manuscript's content under our guidance, highlighting the educational potential of the tool (Fig. 7). In academic sessions, the prototype was valued by researchers for its scientific significance and ease of use. It should be noted that, due to the largely informal and uncontrolled nature of these exhibition contexts, no formal usability data collection campaigns, such as structured surveys or questionnaires, were conducted at this stage. Direct observation nonetheless provided valuable preliminary insights into user engagement, comprehension, and navigational behaviour. These findings can inform the design of future, more systematic and controlled usability studies, aimed at collecting both quantitative and qualitative data to further refine and improve the edition.

In this regard, PURE3D allows continuous access to the edition's editing environment even after its publication. Upon authors' request, the edition undergoes a temporary *unpublishing* process, enabling the editor to incorporate updates and modifications in light of the feedback received. Once the editing phase is completed, PURE3D republishes the resource, which retains the same persistent identifier throughout the process.

## 4. Discussions and conclusion

The development and promotion of web-based 3D models, enriched with annotations and supporting materials, remain in an early stage of maturity. For ancient manuscripts, the need to provide digital access to these fragile resources must be complemented by offering detailed contextual information to enhance dissemination and understanding for a broader audience.

Addressing RQ1, this case study explores the potential contribution of 3D visualisation for ancient manuscripts, particularly those with complex layouts such as the Codex Cospi. Beyond potentially supporting comprehension compared to traditional 2D sources, the 3D representation is intended as a complementary tool for use in physical exhibitions. During the temporary exhibition *The Other Renaissance*, the placement of the Codex in its display case limited visibility of the reverse side (facing the case). This setup constrained a holistic exploration of the manuscript, an issue the 3D model aims to mitigate by enabling more comprehensive interaction with both sides of the object. Additionally, the development of a FAIR-compliant methodology for the manuscript's digitisation seeks to make the interpretative process as transparent as possible.

As for RQ2, the 3DDE is explored as a format with the potential to go beyond photorealistic representation, creating a cross-media resource that is both comprehensive and designed to be engaging. It is intended to enhance accessibility while preserving the models and their interpretative frameworks as integral components of scholarly discourse. The inclusion and interconnection of articles, annotations, and multimedia across various thematic strands, supported by storytelling techniques, positions the 3D edition of the Codex Cospi as a versatile, web-based interdisciplinary resource. Its adaptability is intended to support relevance across different contexts, from museums and entertainment settings to educational and academic environments.


**Fig. 7.** Presentation of the codex cospi 3DDE at Tourisma – Archaeology and cultural Tourism fair, florence (Italy), February 2025.

Owing to the flexibility of its editing and republishing process, the 3D digital edition of the *Codex Cospi* can be regarded as an ongoing project. Although most of the planned implementations have been completed, further modifications or enhancements remain possible. Future evaluation efforts, including the application of complementary user assessment methodologies, have the potential to inform the systematic collection of both quantitative and qualitative data, thereby supporting the continuous refinement and improvement of the edition.

## CRediT authorship contribution statement

**Alice Bordignon:** Conceptualization, Methodology, Visualization, Validation, Writing – original draft, Writing – review & editing. **Davide Domenici:** Investigation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Almeshari, M., Dowell, J., Nyhan, J., 2019. Using personas to model museum visitors. In: Adjunct Publication of the 27th Conference on User Modeling, Adaptation and Personalization. Presented at the UMAP '19: 27Th Conference on User Modeling, Adaptation and Personalization. ACM, Larnaca Cyprus, pp. 401–405. https://doi.org/10.1145/3314183.3323867.

Anders, F., Jansen, M., Loo, P. van der, Contreras Martínez, J.E., 1994. Códice Cospi: Biblioteca Universitaria De Bolonia, 4093. Libro Explic: Calendario De Pronósticos Y Ofrendas/Introd. Y Explicación: Ferdinand Anders; Maarten Jansen; Peter Van Der Loo Con Contrib. De José Eduardo Contreras Martínez, 1. Códices mexicanos. Akad. Dr.- u. Verl.Anst, Graz.

Angeletaki, A., Carrozzino, M., Johansen, S., 2014. MUBIL: creating a 3D experience of "Reading Books" in a virtual library laboratory. International Journal of Heritage in the Digital Era 3, 271–286. https://doi.org/10.1260/2047-4970.3.2.271.

Apollon, D., Belisle, C., Régnier, P. (Eds.), 2014. Digital Critical Editions, Topics in the Digital Humanities. University of Illinois Press, Urbana.

Balzani, R., Barzaghi, S., Bitelli, G., Bonifazi, F., Bordignon, A., Cipriani, L., Colitti, S., Collina, F., Daquino, M., Fabbri, F., Fanini, B., Fantini, F., Ferdani, D., Fiorini, G., Formia, E., Forte, A., Giacomini, F., Girelli, V.A., Gualandi, B., Heibi, I., Iannucci, A., Manganelli Del Fà, R., Massari, A., Moretti, A., Peroni, S., Pescarin, S., Renda, G., Ronchi, D., Sullini, M., Tini, M.A., Tomasi, F., Travaglini, L., Vittuari, L., 2024. Saving temporary exhibitions in virtual environments: the digital Renaissance of ulisse aldrovandi – acquisition and digitisation of cultural heritage objects. Digital Appl. Archaeol. Cul. Herit. 32, e00309. https://doi.org/10.1016/j.daach.2023.e00309.

Barzaghi, S., Bordignon, A., Gualandi, B., Heibi, I., Massari, A., Moretti, A., Peroni, S., Renda, G., 2024. A proposal for a FAIR management of 3D data in cultural heritage: the aldrovandi digital twin case. Data Intell. 6, 1191–1221.

Barzaghi, S., Bordignon, A., Collina, F., Fabbri, F., Fanini, B., Ferdani, D., Gualandi, B., Heibi, I., Mariniello, N., Massari, A., Massidda, M., Moretti, A., Peroni, S., Pescarin, S., Rega, M.F., Renda, G., Sullini, M., 2025. A reproducible workflow for the creation of digital twins in the cultural heritage domain. Transformat.: A DARIAH J. Workflows 14773. https://doi.org/10.46298/transformations.14773.

Bekele, M.K., Pierdicca, R., Frontoni, E., Malinverni, E.S., Gain, J., 2018. A survey of augmented, virtual, and mixed reality for cultural heritage. J. Comput. Cult. Herit. 11, 1–36. https://doi.org/10.1145/3145534.

Bordignon, A., 2024. Digital twin of the codex cospi. https://doi.org/10.5281/ZENODO.10944120.

Bordignon, A., Domenici, D., 2025. Codex cospi. https://editions.pure3d.eu/project/14/edition/1/index.html. (Accessed 20 October 2025).

Champion, E., Rahaman, H., 2020. Survey of 3D digital heritage repositories and platforms. Virtual Archaeol. Rev 11, 1. https://doi.org/10.4995/var.2020.13226.

Domenici, D., Laurencich Minelli, L., 2014. Domingo de Betanzos' Gifts to Pope Clement VII in 1532-1533: tracking the Early History of Some Mexican Objects and Codices in Italy. In: Los Obsequios De Domingo De Betanzos Al Papa Clemente VII En 1532-1533: Siguiendo La Historia De Algunos Objetos Y Códices Mexicanos En Italia, Estudios De Cultura Náhuatl, pp. 169–209.

Driscoll, M.J., Pierazzo, E. (Eds.), 2016. Digital Scholarly Editing: Theories and Practices, first ed. Digital Humanities Series. Open Book Publishers, Cambridge, UK. https://doi.org/10.11647/OBP.0095.

European Parliament and Council, 2019. Directive (EU) 2019/882 on the accessibility requirements for products and services (European accessibility act). Off. J. Eur. Union L151, 70–115. https://eur-lex.europa.eu/eli/dir/2019/882/oj.

Fanini, B., Ferdani, D., Demetrescu, E., Berto, S., d'Annibale, E., 2021. ATON: an open-source framework for creating immersive, collaborative and liquid web-apps for cultural heritage. Appl. Sci. 11, 11062. https://doi.org/10.3390/app112211062.

Harrower, N., Maryl, M., Biro, T., Immenhauser, B., ALLEA Working Group E-Humanities, 2020. Sustainable and FAIR data sharing in the humanities: recommendations of the ALLEA working group E-Humanities. https://doi.org/10.7486/DRI.TQ582C863.

Huurdeman, H., Piccoli, C., 2021. 3D reconstructions as research hubs: geospatial interfaces for real-time data exploration of seventeenth-century amsterdam domestic interiors. Open Archaeol. 7, 314–336. https://doi.org/10.1515/opar-2020-0142.

Kamińska, D., Zwoliński, G., Laska-Leśniewicz, A., 2022. Usability testing of virtual reality applications—the pilot study. Sensors 22, 1342. https://doi.org/10.3390/s22041342.

Katifori, A., Karvounis, M., Kourtis, V., Perry, S., Roussou, M., Ioanidis, Y., 2018. Applying interactive storytelling in cultural heritage: opportunities, challenges and lessons learned. In: Rouse, R., Koenitz, H., Haahr, M. (Eds.), Interactive Storytelling, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 603–612. https://doi.org/10.1007/978-3-030-04028-4_70.

Knazook, B., Murphy, J., Barner, K., Cassidy, K., Claeyssens, S., Cortese, C., Manchester, E.J., Padilla, T., Reijerkerk, D., Robson, G., Schmidt, A., Sherratt, T., Warren, M., 2023. WorldFAIR Project (D13.2) Cultural Heritage Image Sharing Recommendations Report. https://doi.org/10.5281/ZENODO.7897243.

Koster, L., Woutersen-Windhouwer, S., 2018. FAIR principles for library, archive and museum collections: a proposal for standards for reusable collections. The Code4Lib J. 40. https://journal.code4lib.org/articles/13427.

Laurencich Minelli, L., 1992. Codice Cospi. Calendario E Rituali Precolombiani. Jaca Book, Milano.

Li, T., 2021. Interactivity in Museums: Options for the Aga Khan Museum. Toronto Metropolitan University. https://doi.org/10.32920/ryerson.14653479.

Miliani, C., Domenici, D., Clementi, C., Presciutti, F., Rosi, F., Buti, D., Romani, A., Laurencich Minelli, L., Sgamellotti, A., 2012. Colouring materials of pre-columbian codices: non-invasive in situ spectroscopic analysis of the codex cospi. J. Archaeol. Sci. 39, 672–679. https://doi.org/10.1016/j.jas.2011.10.031.

Moore, J., Rountrey, A., Scates Kettler, H., 2022. 3D data creation to curation: community standards for 3D data preservation. ALA.Chicago, Illinois, pp. 324–pp.

Pallud, J., 2017. Impact of interactive technologies on stimulating learning experiences in a museum. Inf. Manag. 54, 465–478. https://doi.org/10.1016/j.im.2016.10.004.

Papadopoulos, C., 2024. A leap of faith: revisiting paradata in 3D scholarship. In: Huvila, I., Andersson, L., Sköld, O. (Eds.), Perspectives on Paradata, Knowledge Management and Organizational Learning. Springer International Publishing, Cham, pp. 61–86. https://doi.org/10.1007/978-3-031-53946-6_4.

Pietroni, E., Chirivì, A., Fanini, B., Bucciero, A., 2023. An innovative approach to shape information architecture related to ancient manuscripts, through multi-layered virtual ecosystems. From Codex4D to DataSpace project. In: De Paolis, L.T., Arpaia, P., Sacco, M. (Eds.), Extended Reality, Lecture Notes in Computer Science. Springer, Nature Switzerland, Cham, pp. 247–267. https://doi.org/10.1007/978-3-031-43404-4_16.

Pujol-Tost, L., 2019. Did we just travel to the past? Building and evaluating with cultural presence different modes of VR-Mediated experiences in virtual archaeology. J. Comput. Cult. Herit. 12, 1–20. https://doi.org/10.1145/3230678.

Rizvic, S., Boskovic, D., Mijatovic, B., 2024. Advanced interactive digital storytelling in digital heritage applications. Digit. Appl. Archaeol. Cul. Herit. 33, e00334. https://doi.org/10.1016/j.daach.2024.e00334.

Robinete, F., Arnaud, R.' mi, Parisi, T., Cozzi, P., 2018. glTF: designing an open-standard runtime asset format fabrice robinet, re mi Arnaud, Tony Parisi, and Patrick Cozzi. In: GPU Pro 360 Guide to 3D Engine Design. A K Peters/CRC Press, pp. 243–260.

Schettino, P., Pietroni, E., d'Annibale, E., 2023. Re-Thinking visitor experience with ancient manuscripts via the holographic showcase: the case of the Codex4D project and its first public results from a mixed-method evaluation in situ. Heritage 6, 6035–6065. https://doi.org/10.3390/heritage6090318.

Schreibman, S., Papadopoulos, C., 2019. Textuality in 3D: three-dimensional (re) constructions as digital scholarly editions. Int J Digit Humanities 1, 221–233. https://doi.org/10.1007/s42803-019-00024-6.

Schreibman, S., Schoueri, K.G., 2024. 3D digital scholarly editions: the text as object. In: Kuzman Šlogar, K., Žugić Borić, A. (Eds.), Digital Humanities & Heritage. Presented at the DARIAH-HR International Conference, pp. 15–31. Zadar – Rijeka, Croatia.

W3C, 2025. Web content accessibility guidelines (WCAG) 2.1. https://www.w3.org/TR/WCAG21/#perceivable. (Accessed 14 October 2025).

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR guiding principles for scientific data management and stewardship. Sci. Data 3, 1–9. https://doi.org/10.1038/sdata.2016.18.