Theorising 3D visualization systems in archaeology: Towards more effective design, evaluations and life cycles.

Fabrizio Galeazzi[1] and Paola Di Giuseppantonio Di Franco[2]

1. Department of Archaeology, University of York
2. McDonald Institute for Archaeological Research, University of Cambridge

Summary

3D visualization in archaeology has become a suitable solution and effective instrument for the analysis, interpretation and communication of archaeological information. However, only few attempts have been made so far for understanding and evaluating the real impact that 3D imaging has on the discipline under its different forms (offline immersive and not immersive, and online platform).

There is a need in archaeology and cultural heritage for a detailed analysis of the different infrastructural options that are available and a precise evaluation of the different impact that they can have in reshaping the discipline. To achieve this, it is important to develop new methodologies that consider the evaluation process as a fundamental and central part for assessing digital infrastructures. This new methods should include flexible evaluation approaches that can be adapted to the infrastructure that need to be assessed.

This paper aims at providing some examples of 3D applications in archaeology and cultural heritage and describing how the selection of the infrastructure is related to specific needs of the project. This work will describe the different applications and propose guidelines and protocols for evaluating their impact within academia and the general public.

1. Introduction

3D visualization in archaeology and cultural heritage has a long history stretching back to the 1980s (Arnold *et al*. 1989; Reilly 1989; Reilly and Shennan1989), as foreseen by Wilcock in 1973 when discussing the possibility of computer reconstructions of temples and monuments (Wilcock 1973: 20). During the 1990s, methodological and theoretical issues relating to the use of 3D reconstruction and visualization in archaeology were discussed and considered in the field (Reilly 1991; Wood and Chapman 1992; Forte and Siliotti 1997; Sims 1997). By the beginning of the 21st century the spread of 3D visualization into archaeology was sufficiently widespread to allow consideration of best practices in the field (Frischer *et al*. 2002; Fernie and Richards 2003). Today, 3D visualization is so well established that it has given rise to a new breed of professionals with hybrid backgrounds combining humanities and social sciences with ICT (Information Communication technologies) skills for the creation and development of 3D platforms. Three types of platforms can be identified: 1) Applications concerned with documentation and analysis for use by cultural heritage professionals; and 2) Applications with a component of dissemination. 3) Applications that combine the previous two purposes.

These platforms have impacted methods of preservation, data sharing, and the communication of heritage today. For instance, digital archives and libraries of ancient artefacts are considered necessary comparative collections for scholars with limited or non-existent access to original collections. Such access issues are primarily due to laboratories and archaeological sites or laboratories and artefact storage facilities being far apart (Martinez-Carrillo *et al*. 2009; Weber and Malone 2011). 3D visualization is also an effective means by which to introduce aspects of artefact study to large numbers of students, and can also be used in museums for virtually re-contextualizing objects preserved inside display windows where their past functions and meanings can be explained (Simon *et al*. 2009; Forte *et al*. 2010). Scholars and institutions (e.g. ICOMOS and UNESCO) recognise the value of 3D visualization for preserving ancient material culture in contexts where artefacts and monuments are at risk of degradation or destruction due to urban development, and, especially of late, conflicts (Emberling 2008; Forte *et al*. 2010; Di Giuseppantonio Di Franco and Galeazzi 2013).

Far from being a comprehensive analysis of the state of the art of 3D visualization in archaeology, this essay describes different kinds of infrastructures and approaches for the exploration and analysis of 3D cultural heritage data, based on our own personal experience. This work aims to be a practical guide, describing some of the infrastructures currently available in the archaeological and heritage sectors and proposing some guidance on how to select them based on the specific needs of individual projects.

The paper is organized as follows: Section 2 describes off-line visualization systems and their main characteristics through the presentation of some case studies. Section 3 describes cyberinfrastructures that allow the integration of 3D visualization and data archiving, focusing primarily on a case study, the ADS 3D viewer, to discuss best practices for the design and development of web-based applications. Section 4 describes possible evaluations of these kinds of systems and also proposes novel evaluation methods borrowed from the cognitive sciences, which favour the assessment of perception, 'presence' and human–object interaction in the virtual world. The last section discusses some advantages and limitations in the use of the different 3D visualization systems and proposes strategies for their design and long-term preservation.

2. Immersive visualization systems in archaeology and cultural heritage

2.1. Introduction

The role of immersive visualization systems has become a major theme in the 3D reconstruction of archaeological sites. Virtual reality systems and collaborative virtual environments (CVE) can involve the users in a collaborative learning process between them and the virtual environment. A collaborative virtual environment is an application that uses a virtual environment to support human–human and human–system communication. Within such virtual environments, multiple users can convene, communicate and collaborate. Interaction with the different virtual 3D reconstructions can, in fact, increase our understanding of cultural heritage through experience and 'presence' in the virtual environment. The main scope of these displays is to provide a sensorial experience with tangible heritage that simulates real-life experience. Immersive large-scale display systems, such as the Powerwall (Camporesi and Kallmann 2013; Galeazzi *et al*. 2010), next generation semi-immersive and immersive CAVE systems (Levy *et al*. 2010; Forte 2014: 22), and 360-degree 3D panoramic spaces (Kenderdine *et al*. 2012) are considered places for enhancing innovative studies of cultural heritage, providing researchers with new ways to interpret material culture (Kenderdine 2009; Kunert *et al*. 2014). These systems can also be viewed as non-mediated places where a user can interact with a simulated past either independently or with other virtual users and create both personal and collective narratives of past environments thanks to an embodied experience with the virtual space (Kenderdine *et al.* 2009; Forte 2008). Embodiment is one of the key components of immersive systems which have been implemented and used in archaeology, based on the idea that interpretation processes of the past are mediated by our embodied experience with past remains (Dant 1999; Malafouris 2004). 3D immersive systems have therefore been designed following theories of embodiment. According to these theories, cognition depends on our bodily, sensory motor capacity to experience the material (Varela *et al.* 1991: 172–3). Immersive systems allow for a sense of presence, as defined by John V. Draper, David B. Kaber and John M. Usher (1998: 356): 'a mental state in which a user feels physically present within the computer-mediated environment'; and by Dawson et al. 2011 as involving 'feelings of being transported to another place and time ('you are there')' (389). Moreover, immersive systems rely on a sensory-motor learning system that is based on perception and action, since ancient artefacts and works of art 'are fundamentally visual objects, and any verbal treatment of them implies a translation of their most essential intrinsic characteristics, which are of a visual and perceptual nature, into a textual form' (Antinucci 2007: 84).

By combining a sense of presence and sensory-motor learning, 3D immersive systems can also be developed to incorporate hyperlinks that offer additional information on the 3D models and environment in real-time. This is possible using just the two main aspects involved in the creation of immersive 3D viewers for the analysis of the archaeological records: the archaeological content that the users will visualize in the viewer; and the way in which the content will be visualized, ie. the interface and the media (text, picture, video, etc.).

2.2. Case study 1

This discussion concerns the Western Han Dynasty Virtual Museum project. The project started in 2008 with collaboration between the Xi'an Jaotong University and the School of Social Sciences, Humanities and Arts, University of California, Merced. This collaboration was later extended to the Xi'an Municipal Cultural Relics Conservation and Archaeological Research Institute (China), and the Italian National Research Council (CNR-ITABC,). For this project, researchers digitally documented Western Han Dynasty relics of the Shanxi Province, with two primary purposes, the first being the preservation of some of the most representative artefacts of the Dynasty, which are at risk of destruction due to urban development. In fact, the city of Xi'an, ancient capital of the Western Han Dynasty (under the name of Chang'an), is experiencing such rapid urban development that every year archaeologists discover hundreds of monuments during emergency surveys on construction sites that they cannot preserve due to lack of economic resources. The second purpose was to disseminate information about the Western Han Dynasty through 3D reproductions and reconstructions of its material past (for a detailed description of the project, see Forte *et al*. 2010; Galeazzi *et al*. 2010; Di Giuseppantonio Di Franco and Galeazzi 2013).

The final outcomes of the overall project were two different off-line digital installations placed in two locations: the University of California, Merced (Forte *et al*. 2010) and the City University of Hong Kong (Kenderdine *et al*. 2012). Later developments of the project involved the creation of an immersive system for research and analysis of Western Han tombs (Forte and Kurillo 2010). 3D replicas of Western Han Dynasty monuments and artefacts were displayed in three different immersive displays: the Powerwall at the University of California, Merced (Galeazzi *et al*. 2010), a 360-degree 3D panoramic space (Advanced Visualization Interaction Environment – AVIE) at the University of Hong Kong, China (Kenderdine *et al*. 2012), and a 3D real-time environment (Forte and Kurillo 2010).

The Powerwall is a high-resolution display wall at the University of California, Merced that is used for projecting large, computer-generated images. It is complemented by a Vicon full-body optical tracking system that allows full-body immersion in a virtual environment (Camporesi and Kallmann 2013). *The Virtual Museum of the Western Han Dynasty* for the Powerwall was developed using an open source 3D graphics engine, OGRE (http://www.ogre3d.org/). This platform seemed the best option for the development of immersive applications in research institutions, because it is free and allows the developers easier access and sharing of resources and results. The Powerwall was used to visualize the 3D reconstruction of one of the 3D reconstructed tombs of the Western Han Dynasty, (M27), which was complemented by a 3D mind-map (*cybermap*) revealing all the spatio-semantic relationships of the paintings found in the main tomb chamber (Galeazzi *et al*. 2010; Fig. 1-2). M27 is the logical and practical result of the revolutionary historical moment in which it was built – the end of the Western Han Dynasty – and its paintings partially narrate and describe this period. They are visual narratives composed of scenes and themes.

Figure 1. Cybermap of the Western Han mural tomb M27 (Xi'an, China): Powerwall visualization and motion capture facility at UC Merced.

The paintings are realized on a white clay stratus which hides the material support, giving the sense of an immaterial whole with intangible boundaries constituted by the frescos' contents and spatial and semantic relationships.

We thought that a better understanding of the tomb's contents would be facilitated by removing these intangible boundaries through a simulation process that allowed the potential semantic re-composition of the tomb, creating new metaphors of learning and communication. From our perspective, a cybernetic approach to the interpretation of the tombs, realised through the cybermap, could emphasise the iconographic complexity and the strong symbolism that springs from the scenes of the tomb frescos. The cybermap was conceived as a guide for a virtual tour, showing the main iconographic themes and paths; it therefore helps people to recreate narratives, moving from one scene to another in the right sequence. If the material monument represents the tangible remains of Western Han heritage, the frescos' spatial relations are traces of its intangible heritage. The map schematizes the themes and simplifies the information, as well as revealing the Chinese way of storytelling through paintings on ancient monuments and how it differs from the Western approach (Di Giuseppantonio Di Franco and Galeazzi 2013). Westerners are used to storytelling in a linear path per superimposed registers (Borra *et al*. 2006), while the path of the frescos in the Western Han tombs is circular and in continuous movement (Di Giuseppantonio Di Franco and Galeazzi 2013). According to Nisbett, 'Chinese people think the world is a circle; "westerners" that is a line. The Chinese believed in constant change, but with things always moving back to some prior state' (2003: 5).

Figure 2 (VIDEO): Cybermap of the Western Han mural tomb M27 (Xi'an, China): Powerwall visualization and motion capture facility at UC Merced.

Following the Powerwall experience, the Western Han Dynasty Virtual Museum was also displayed in the application *Rhizome of Western Han* at the Applied Laboratory for Interactive Visualization and Embodiment (ALiVE) at the City University of Hong Kong, using AVIE (Advanced Visualization and Interaction Environment). The AVIE 360-degree stereoscopic interactive visualization system is a cylindrical projection screen that uses camera tracking of visitors' movements to create interactive relationships between the visitor and the reconstructed/simulated environment (Kenderdine *et al*. 2012:145–6; Fig. 3). This system allowed an immersive experience with Western Han Dynasty material culture through two different scenarios:

- a 1:1 reproduction of tomb M1 that the user could navigate to scale and explore. This scenario was completed with a cybermap that guided users through the complex semantics of the tomb's frescos.
- a system called Object Viewer (OV) which displayed virtual reconstructions of the artefacts. The objects float around the user, who can manipulate and magnify each object independently. Each object can also be explored through its mesh (i.e. 3D model without original colours).

When compared to the Powerwall experience, the AVIE's multimodality gives an increased immersivity, due to the visualization in 360 degrees. Instead of being in front of a screen with the reconstructed environment, with AVIE the user stands in the centre of the reconstructed monument. The sense of immersivity is not complete though, as this structure lacks the immersive interaction with ceiling and floor that one would have inside immersive CAVE systems (Forte 2014: 22; Gaugne *et al*. 2014; Christou *et al*. 2006).

Figure 3. *Rhizome of Western Han*: AVIE 360-degree stereoscopic interactive visualization system (Kenderdine and Hart 2011: Fig. 13)

In a subsequent study by Maurizio Forte and Gregory Kurillo, M27 was inserted in a newly designed tele-immersive real-time system, to facilitate remote collaboration between scholars, with up to five users at a time sharing the same virtual space while being able to interact with 3D replicas in real-time (Forte and Kurillo 2010). With this kind of system, each user navigates and interacts with the simulated environment in the first-person perspective (which is represented in real-time in the immersive environment), and can select and manipulate objects, measure them, and obtain metadata of the objects from drop-down menus. This immersive system was used for re-contextualizing and studying all the artefacts found in one of the reconstructed tombs (M1) during the excavation. As Forte and Kurillo (2010: 160) explain, 'the tentative repositioning of the objects, after the restoration, is very important since it is possible to study their volumetric relations with the funeral chamber, the rituals and their social symbolic value'. In other words, this kind of tele-immersive system allows international scholars to collaborate actively on the study and interpretation of the past through its virtual material remains (Fig. 4).

Figure 4 (VIDEO). *Tele-immersive Western Han*: tele-immersive real-time system (https://www.youtube.com/watch?v=LZtssNwAfMQ).

3D immersive systems such as those described above are rarely used in museums or similar facilities due to economic constraints and the need for specialized technical support to develop and maintain the necessary infrastructure. Consequently, museum and heritage specialists who are keen to use immersive systems for the virtual display of cultural contents tend to rely on cheaper, user-centred infrastructures that provide immersivity through multi-user virtual reality installations, such as the one described in the following case-study, *The Virtual Museum of the Ancient Flaminia.*

2.3. Case study 2. The Virtual Museum of the Ancient Flaminia

Like the Western Han Dynasty Virtual Museum, *The Virtual Museum of the Ancient Flaminia* (Forte 2008; Dell'Unto *et al*. 2007) was aimed at the 3D documentation of sites and monuments along the ancient Flaminia Road, using integrated technologies for their long-term preservation as well as the development of a virtual-reality environment that would allow access and understanding of these sites for the general public. The circumstances of the project were also similar: the public institutions involved welcomed the opportunity to test the use of innovative digital tools in their daily documentation practice, and in both situations we dealt with the post-excavation documentation of the archaeological context. This project was first developed for public access in 2008 thanks to a multi-user virtual reality stereo installation specifically designed to be integrated in the visitor experience of the Diocletian Baths in the National Museum of Rome (Fig. 5). A multi-disciplinary team of archaeologists, art historians, computer scientists, architects and cultural heritage specialists worked on the optimization of the 3D reproductions and reconstruction of the sites for their integration into a complex 3D real-time application developed using Virtools, a game development environment software (today 3DVIA Virtools: http://www.3dvia.com/).

A digital protocol was developed to preserve all the data acquired during the project and related metadata in a multi-dimensional and multi-disciplinary virtual environment. To manage the fragmentary nature of the archaeological remains along the Flaminia road due to recent urban development, archaeological evidence was re-contextualized within a virtual environment with three main levels of visualization:

- a 3D holistic vision of the road landscape from Rome to Rimini, where the user can navigate the territory using a flying view (DEM resolution: 100 m);
- a 3D holistic vision of a higher resolution reproduction (DEM resolution: 10 m) of the first section of road starting from Rome (first 20 km between Milvio Bridge and Malborghetto), always using a flying view approach;
- monographic levels of visualization of high-resolution reproductions of selected sites (6–50 mm) realized using data collected during a topographic acquisition survey by laser scanning, laser total station, photogrammetry, and Digital Geographic Positioning System. The users can navigate the virtual environment by walking between and interacting with the 3D virtual reproductions of the sites and monuments.

In the multi-user virtual environment developed for the National Museum of Rome's Diocletian Baths, the users, represented by avatars, could meet and interact in the virtual space and co-operate in the creation of common narratives. The application was characterized by four interactive mono display platforms where visitors could interact with the application (i.e. one visitor per display). A larger HD stereo display screen allowed other visitors to have a real-time 3D stereo visualization of the narratives developed by the four users inside the virtual scenario with related information and video material. The users interact with a space made 'alive' through a virtual storytelling of metaphors, virtual characters, and both floating and learning objects (Pietroni and Rufa 2008).

Figure 5. Virtual Museum of the Ancient Flaminia: multi-user virtual reality stereo installation (Pietroni e Rufa 2008: Fig.

Following the creation of the platform, in 2006 Dassault Systèmes acquired Virtools (http://www.3ds.com/), resulting in a change in the commercial policy of the company. This fact, combined with the availability of more innovative and powerful 3D technologies and software, encouraged the developers of the *Virtual Museum of the Ancient Flaminia* to build a new application, which re-used the data and information developed in the original project. This new initiative, entitled *Livia's Villa Reloaded* (Pietroni *et al*. 2015), involved the development of a virtual-reality application in Unity 3, which uses mid-air, gesture-based interaction and combines different media and languages (real-time exploration, cinematographic paradigms, virtual set practices). The application was opened to the public in the same location as the original one, the National Museum of Rome's Diocletian Baths (Fig. 6). *Livia's Villa Reloaded* re-used the 3D models of the first *Livia's Villa* project without the need of any major reworking. The porting of the models in Unity 3 and the reorganization of the original database resources required two months of work from a digital archaeology specialist with specific expertise in 3D data modeling and optimization. The new platform was developed in 6 months involving four researchers (see table 1 for additional information on the time required for the migration of the data and the implementation of the new application).

Table 1. Time required for the migration of the data and the implementation of *Livia's Villa Reloaded*.

Tasks	**Time**	**N people**
Creation of the Digital Terrain Model (DTM)	1 week	1 (digital archaeology specialist/3D data modelling)
Porting of the models in Unity 3 and reorganization of the original database resources	8 weeks	1 (digital archaeology specialist/3D data modelling and optimization)
Creation of camera animation in 3D Studio Max then imported in Unity 3	2 weeks	1 (digital archaeology specialist/3D data modelling)
Light mapping, scene editing, and rendering effects in Unity 3	3 weeks	1 (computer scientist)
Software development in Unity 3	6 weeks	1 (computer scientist)
3D modelling of furniture	4 weeks	1 (digital archaeology specialist/3D data modelling)

The main difference between the two projects rely on the infrastructures, as well as on lighting and rendering effects, which considerably affected the final visual outcome of the reconstructed landscape and architecture. Considerable improvements in real-time rendering were achieved in the new application compared to the 2008 experience. In this new application the use of 'Lightmapping' calculation and Colour Correction Image Effect (provided in the new the graphics engine) gave rich colour tones to the virtual environment, thereby creating a more evocative atmosphere. Users can interact with the reconstructed environment using simple and natural gestures of the body. Here the use of mid-air, gesture-based interaction allowed this project to overcome the limitations of the traditional input interfaces and devices based on the WIMP (Windows, Icons, Menus and Pointing devices) paradigm, where the visitors struggle with interfaces that are not immediate and simple to use for all users, such as a mouse, joystick, keyboard, or console. The *Livia's Villa Reloaded* gesture-based application was developed using Microsoft Kinect (Microsoft 2015) first generation that does not require the user to wear any marker nor expensive licences to operate (Pietroni *et al*. 2015: 4–5). The application, implemented using Unity 3D, allows the visitor to navigate (using the hotspots 'GO FORWARD' and 'STOP AND ROTATE') and interact with the system via a main menu (hotspot 'MENU') that allows users to select both language (Italian or English) and scenarios:

- Introduction movie about via Flaminia;
- Introduction movie about Livia's Villa;
- Virtual exploration of today Livia's villa;
- Virtual exploration of the reconstruction in the Augustan age. (Pietroni *et al*. 2015: 5).

Livia's Villa Reloaded is a good example of both the re-use of datasets and the application of natural interaction as a new way of re-configuring and re-considering the boundaries between 'real' and 'virtual' worlds. Natural interaction can increase embodiment, thus enhancing communication between the public and all artificial entities present in the virtual space.

Figure 6 (VIDEO). *Livia's Villa Reloaded* (video from vimeo: https://vimeo.com/80151975).

3. Evaluating 3D visualization applications in archaeology and cultural heritage: visualization and cognition.

3.1. Introduction

The case studies above utilise some of the most commonly used immersive 3D visualization systems for the analysis and interpretation of the archaeological record. Even though archaeologists and heritage specialists have long experimented with these new technologies in the fields of archaeology and heritage, some scholars suggest that these models lack information that can only be obtained through real-world human–object interaction (Lederman and Klatzky 1990; Renaud 2002). These concerns raise a question about the significance of digital object representations in both research and education. To address this concern, we decided to evaluate how people interact with 3D visualization systems. This section presents the findings of recent studies aimed at analysing some aspects of how people interact with ancient material culture through different media. We aimed to answer two specific questions through our studies: how people perceive inner qualities of ancient artefacts, when they experience these objects through media that are different from the tactile experience obtained with the original (3.2); and how human–object interaction changes based on the medium used to reproduce and present ancient artefacts (3.3). In order to investigate how different senses interact during perception and how individuals think while interacting with things, we videotaped volunteer participants interacting with ancient artefacts through different media (3D digital artefacts, 3D prints, 2D photographs, etc.). To analyse these videos, we used a multi-disciplinary approach and borrowed methods of evaluation from the cognitive sciences; we then combined the different data sources, which are described in Table 2. While we believe that the methodology used for our research design is an effective way to evaluate how 3D visualisation systems affect human–object interaction dynamics, other methods of evaluation have also been used; these have focused principally on learning processes, recollection of information, rating of heritage experiences through the use of new technologies, and other aspects of ‘physical’, ‘social’, and ‘cultural’ presence (see Pujol and Champion 2012, and Dawson et al. 2011, which also provide a definition of ‘presence’; see also Forte *et al*. 2006; Petridis *et al*. 2003, 2006; Di Blas *et al*. 2005).

Table 2.

Data source	**Intended purpose of data**
Surveys of participants	To gain demographic details and information about participants’ previous experience (as professionals or as visitors to historical, anthropological, and/or archaeological museums) with ancient artefacts and their familiarity with 3D digital reproductions of artefacts.
Transcripts from video-interviews	To understand how people describe artefacts with specific regards to word choice, how they focus on innate qualities of artefacts (i.e. shape, weight, material, etc.), and finally how they try to determine the function of these objects in the past.
Analysis of gestures	To understand to what extent gestures give bodily support to

	participants’ discourses, to observe which medium produces the highest number of gestures, and to see when participants use gestures and which kind of gestures.
Observations of participants’ behaviour while 'interacting' with each medium	To gain insights into how people interact with the medium, to understand the findings better (speech and gestures).
Questionnaires combining multiple-choice questions and Likert scales	To gain insights into participants' overall experience with the media selected for the experiments.

In an inspiring article about the relationship between images, text and human cognition, anthropologist and sociologist Bruno Latour argued that when studying changes in the way scientists have used images in association with text, the focus needs to be only on those situations in which 'we might expect changes in the writing and imaging procedures to make any difference at all in the way we argue, prove and believe' (Latour 1986: 4).
We believe that this statement applies equally to new technologies being introduced today and that it is time to start thoroughly evaluating the effects 3D technologies produce on human–object interaction.

3.2. Inner qualities of objects

Proponents of the extended (e.g. Clark 2003), enacted (e.g. Varela *et al*. 1991), embodied (e.g. Ratey 2002; Lakoff and Johnson 1980; 1999; Cole 1985), distributed (e.g. Norman 1988; Hutchins 2005), mediated, and situated (e.g. Suchman 1987; Lave 1988; Wilson and Myers 2000) mind accept the idea that when people engage with material things, they think with them. Some archaeologists (MacGregor 1999; Ingold 2007; Olsen 2010) also stress the importance of material qualities for the perception of artefacts. As Tim Ingold’s (2007: 11) puts it: 'materials are the active constituents of a world-in-formation' and can tell us about a place and a time (*hic et nunc*), about the people who created or used the artefacts, and also about changes over time. For Ingold (2007:14), the properties of materials, which also have to be considered constituents of an environment, 'are neither objectively determined nor subjectively imagined, but practically experienced'. In other words, it is important to understand how people experience material objects when they physically manipulate (i.e. touch) them and how this experience changes when the objects are digitally reproduced and the experience occurs within a virtual domain. Colin Wave highlights how visualization is an important instrument for the analysing and understanding cultural heritage by enhancing our perception of objects' affordances/agency (Wave 2004: 3). 2D visual representations are commonly used in archaeological and cultural heritage practice to represent, preserve and disseminate visual representation of ancient material culture, because they are simple, fast and cost-effective. However they are not always ideal forms of reproduction in order to grasp physical characteristics that sometimes are crucial for the understanding of the use(s) of these objects in the past. In a recent study, Galeazzi *et al*. (2015) compared 2D and 3D digital images to see how people's perception of artefacts changes based on the medium used to archive their visual representations. A set of experiments conducted with university students showed how 3D digital replicas of artefacts are a more effective means of digitally preserving tangible cultural heritage because 3D multi-visualization augments perception of the specific physical qualities that are crucial to grasp the functionality of these objects in the past. This allows an experience with the artefacts that is closer to a real-life one, since the possibility of interacting with the multiple levels of information encapsulated in the 3D representation (texture, mesh, vertexes, and wireframe) simulates, to some extent, real-life experiences better than 2D visual representations (Galeazzi *et al*. 2015: 20). In another study, titled *Experiencing Artefacts through Different Media* (Table 1) Di Giuseppantonio Di Franco *et al*. (2015) also analysed how the perception of inner qualities of artefacts is achieved in immersive systems. The results from this study reinforce the idea that presentation modalities affect how different characteristics of objects are perceived. In this study we compared perception through three different media:

- visual examination of an object displayed in a show-case (i.e. *Look* condition);
- interactive manipulation in the Powerwall immersive system (i.e. *Powerwall* condition);
- manipulation of a 3D print (i.e. *3D print* condition).

In the Powerwall condition, participants had the option to manipulate the objects interactively and select specific actions through a virtual floating menu. As shown in Figure 7, the user controlled a virtual pointer in the scene (red cone) directly mapped to the position in space of the remote controller. The virtual pointer appears to the user to be floating in front of the controller being held. Users manipulate objects by selecting them with the virtual pointer and then using manipulations that are very similar to everyday real life (Figure 7 a-b). Through a virtual menu that could be opened and removed at will (Figure 7c), two actions were possible (Figure 8): removing original colours (i.e. *texture*) to appreciate the 3D model geometry *mesh*, and changing light conditions (environmental or torch-light simulation, and light-source colours). No virtual scale accompanied the objects displayed during the experiment. After the users had interacted with the 3D digital replicas they completed a questionnaire to explain their experience with each object. The questionnaires were analysed in order to determine which type of interaction would be most suitable for research needs and for the presentation of archaeological material to the general public.

Each participant was only allowed to interact with just one of the three use-cases alternatives that were implemented (i.e. display case object, Powerwall, or 3D prints).

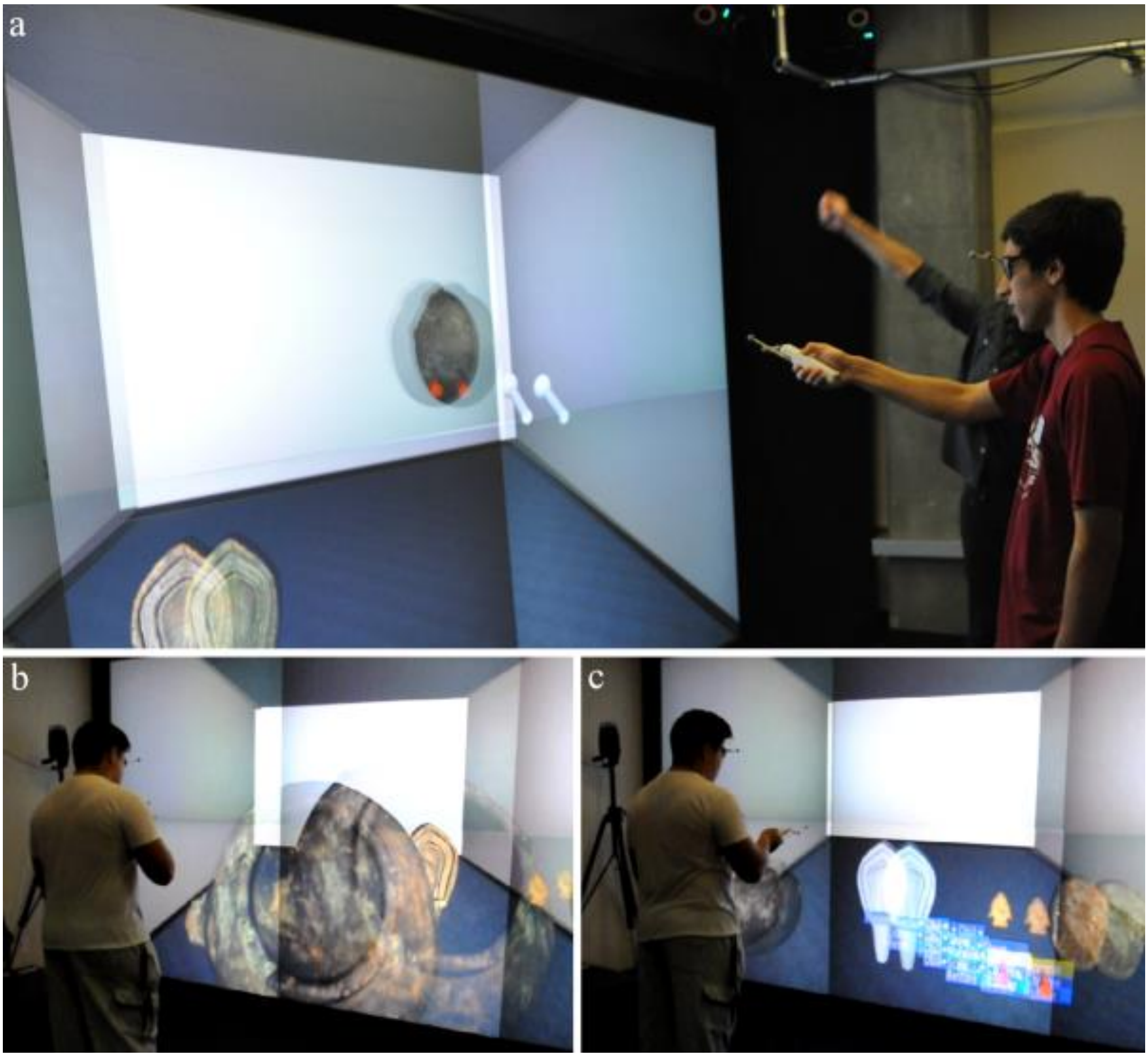

Figure 7. Powerwall condition. a) Changing light condition to explore objects. b) Manipulating objects (objects appear big on the screen due to off-axis parallax projection but the user perceives it as in real-life); c) Interacting with the objects without original colours (note the floating virtual menu in front of the user).

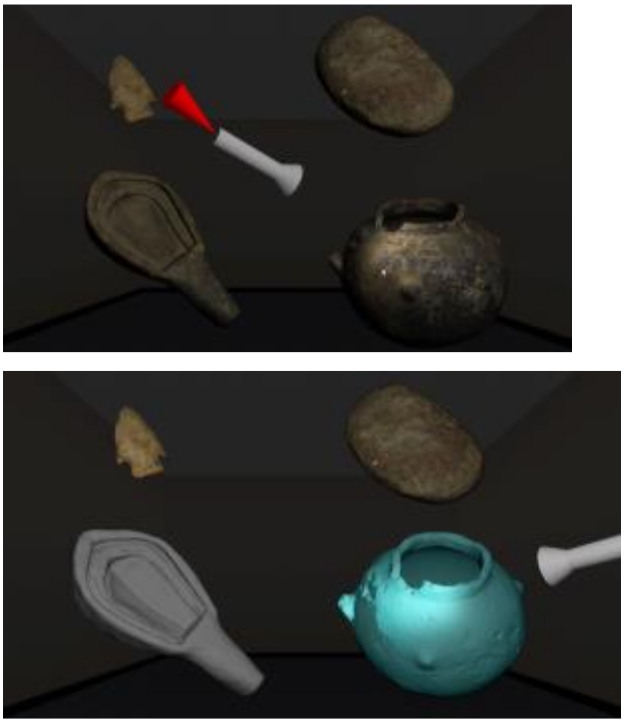

Figure 8. Highlight of object manipulation and visualization in the Powerwall in dark environmental light condition. The red cone represents the user’s pointer designed to interact with the scene (objects and menu 3D interaction and lights repositioning). Left: The user is moving the light source to enhance objects details. Right: similar situation where the objects' textures were removed to analyse the polygonal representation.

We chose four objects for the experiment: a ceramic vessel (i.e. pot), a grinding stone (i.e. mono), a projectile point, and a wooden Buddhist niche for figurines. Without dwelling too much on the detail, to give an example with respect to texture qualities, our findings suggest that in the case of small, bright, and light-coloured objects, such as the projectile point, visual cues are not enough to perceive texture qualities accurately. While participants in the *Look* condition could grasp the sense of texture of the objects based only on visual cues, participants in the Powerwall could rely on multi-visualization tools, such as different light settings and the possibility to zoom in and remove original colours from the 3D models, to grasp textural information.

3.3. Interaction and engagement with 3D digital objects

Latour also argues that both humans and non-humans achieve agency as a relational property, distributed across hybridized human–non-human networks, also called actor-actant dichotomies (Latour 2003: 31; 1999: 308). He calls things quasi-objects, hybrids of cultures-natures produced by and within networks of relations (Latour 1993: 54). Things are hybrids because of their linkages. But what happens when interactions between actors and actants happen in a mingling of physical and virtual reality? Are the actors and actants involved in the interaction subject to similar experiential phenomena as if they were interacting in the physical world? In a recent study, Di Giuseppantonio Di Franco *et al.* (2016) tried to answer these questions by investigating how people describe ancient artefacts using gestures. The authors were specifically interested in how people would interact with, understand, and describe objects presented in five different media conditions:

- tactile experience with authentic artefacts;
- visual experience with authentic artefacts;
- 2D pictures;
- 3D digital reconstructions;
- 3D prints.

Participants – both professional archaeologists and students – were videoed describing ancient artefacts. The analysis of gestures in the current study clearly shows that, in absence of a tactile experience, people reproduce stereotypical iconic gestures as if they were actually touching the object. Iconic gestures often convey spatial information; they help people mimic object manufacturing and function. Gestures can also be used to describe details of a form and help people estimate the size of an object. When people described objects they also produced 'beat' gestures. Beat gestures are brief, rhythmic hand movements that facilitate lexical access (see Krauss 1998) without conveying any particular semantic information. For instance, when describing an artefact a participant might try to recall information read in a book and, while struggling to recall it, produce a quick gesture (e.g., shaking one hand) to help her remember. Participants who interacted with digital 3D objects produced a significantly higher number of beat gestures. Following Krauss (1998), it is possible that the high number of beat gestures reflects a lack of certainty about artefact details (i.e. participants were less certain about what they were talking about). Another possible explanation of the high production of beat gestures in the 3D condition could be that beat gestures helped participants compensate for the lack of a tactile experience. The high number of gestures could indicate that participants recognized a difference, a frame, between the physical and the virtual world and tried to fill this gap using gestures. The use of gestures may have helped them have a more embodied experience with the artefact. Similar results were observed in follow-up study aimed at evaluating human-object interaction in a 3D immersive environment (Di Giuseppantonio Di Franco *et al*. 2015: experiment no. 3). We compared the interaction of the general public with the real-life object showcased on a screen and its digital and physical 3D reproduction (3D copy; 3D print). We video recorded them during their experience with the different media and then analysed their bodily interaction (gestures) with the objects. The results of our experiments suggest that in absence of a tactile experience with the original artefacts, the sample of people participating in our experiments favoured a tactile or semi-tactile experience with replicas to the visual experience with original ancient objects. They liked to engage with new technologies to understand ancient artefacts, suggesting how the integrated use of traditional displays, 3D immersive systems, and 3D prints as an effective way to increase perception, understanding, and engagement with artefacts (Di Giuseppantonio Di Franco *et al* 2015).

4. 3D web-based visualization and cyber-infrastructure in archaeology and cultural heritage

So far we have described some case studies exemplifying a range of off-line visualization systems available today. We will now consider recent efforts aimed at developing cyberinfrastructures for the on-line visualization of 3D archaeological data.

A workshop held at the National Sciences Foundation in February 2013 focused on the process of synthesis in archaeology, highlighting the need for investment in computational infrastructures that would assist in overcoming some of the archaeological 'grand challenges' that prevent synthetic research in archaeology. By which we mean problems of preservation, discovery and access, difficulties with data integration, the sheer variety and complexity of archaeological data and evidence, and the disciplinary norms and pragmatics of data sharing and collaboration (Kintigh *et al*. 2015: 4). This need to reconsider the nature of archaeological research was envisioned a few years ago by Ezra Zubrow, who stressed how I-archaeology would be relevant for an i-world, he argues that I-archaeology 'will change the way people conceive of the past for they will be connected to all of it all of the time if they so wish' (Zubrow 2010: 4).

Starting from the previous assumptions, it is critical to develop cyberinfrastructures that allow us to overcome the impediments to synthesis in archaeology described by Kintigh *et al*. (2015: 4). These cyberinfrastructures should allow access to a wide variety of data (i.e. 3D reproductions, 3D panoramic videos, RTI images, etc.) that reproduce the site or artefact as realistically and interactively as possible.

Such a 3D web-based visualization system (3D viewer) should not only address the visualization component but also be able to integrate a variety of datasets coming from fieldwork campaigns and include hyperlinks (i.e. links to pictures, 3D models, text, etc.). These should provide a range of audiences with varied information on the layers detected, excavation area, and methodologies used during fieldwork, and, in addition, links between the layers and artefacts or other material remains found on site etc. Mark Aldenderfer argues that 3D viewers should allow for simultaneous visualization of 3D contents and all inferences enhanced by 3D replicas and simulations:

> What I have in mind as a set of tools for visualization in service of archaeological simulation doesn't really exist yet in our field. We must develop tools and approaches that allow us to simultaneously 'see' (i.e., to create images that may represent a wide variety of information content across a variety of media types) and to 'know' (i.e., to be able to connect these disparate images to other kinds of data) such that inference is enhanced and enabled (Aldenderfer 2010: 55).

In other words, this kind of interactive application should give scholars and the general public the opportunity to access and visualize various datasets, favouring and enabling multiple interpretations of the same archaeological context and facilitating greater synthesis in archaeology as a result of better interconnectivity between researchers and practitioners in the fields of heritage and archaeology as well as other stakeholders interested in these fields of study.

The visualization of 3D contents was one of the main goals of the European-funded project CARARE (http://www.carare.eu/). CARARE gave users the capability to visualize 3D models in real-time, but the information on these models can only be seen separately from the 3D models. In other words it is not possible to visualize 3D models and site information simultaneously.

The development of a complex real-time system for the data management, analysis, and visualization of archaeological sites, using 3D realistic and metric reproduction of the archaeological units instead of schematic graphic representation, is a controversial and frequently discussed topic among digital archaeologists today. This is because the creation of a 3D web-based platform for the analysis and interpretation of archaeological data requires overcoming substantial technical and methodological challenges, including:

- the management of complex 3D models represents a key point for the creation of a usable and accessible visualization platform;
- the 3D real-time visualization system needs to be integrated with solid on-line information brokers and aggregators for different resources, since working in the context of 3D visualization for digital archiving requires sustainability and long-term preservation and dissemination of the data;
- the development of a 3D web-based collaborative research platform needs to build on the availability of complex cyber-infrastructures, which integrate a realistic 3D visualization of archaeological sites and related databases archived on-line;
- the collaborative platform should consider and solve the needs of scholars, researchers and practitioners from different fields working on the analysis and interpretation of all data collected on site.

As described above, complex visualization systems already exist, but they are mainly off-line platforms designed to present monuments and archaeological sites to the general public. The challenge now is to combine this interaction, alongside analysis and interpretation of these virtual environments, with related datasets on the wider web. The creation of standardized and complex databases for the preservation and sharing of the archaeological record is becoming more widespread in archaeology. Two of the most important and successful examples of data services supporting research and education in archaeology are the Archaeology Data Service (ADS: http://archaeologydataservice. ac.uk/) and tDAR (the Digital Archaeological Record: http://www.tdar.org/). The ADS was established in September 1996 at the University of York, while tDAR was developed at Arizona State University in 2008 as part of the Digital Antiquity initiative. There are also examples of European-funded projects that are trying to bring together and integrate existing archaeological research data infrastructures, such as the ARIADNE project (Niccolucci and Richards 2013; http://www.ariadne-infrastructure.eu/).

This on-going commitment of the European Research Council to support cyber-infrastructures that enhance and promote access and preservation of European Cultural Heritage requires further research and improvements in the integration of the 3D component on the web. Although there have been some attempts to create prototype management systems for the visualization of 3D representations of the archaeological record (Losier *et al.* 2007; Doneus *et al.* 2011; Stal *et al.* 2014; Trautner 2015), none of them is integrated within stable digital archives that allow for the long-term preservation and dissemination of those data.

As part of European efforts to design and develop complex cyber infrastructure, the European-funded project *ADS 3D Viewer: a 3D Real-Time System for the Management and Analysis of Archaeological Data* (http://cordis.europa.eu/project/rcn/187 952_en.html) developed a 3D web-based resource for the management and analysis of archaeological data within the Archaeology Data Service. The ADS 3D viewer was created to take advantage of recent developments in web technology (Web Graphics Library: WebGL) by current web browsers. This project originates from an on-going collaboration between the ADS and the Visual Computing Lab (ISTI-CNR, Pisa; http://vcg.isti.cnr.it/) in the framework of the ARIADNE European project (Niccolucci and Richards 2013; http://www.ariadne-infrastructure.eu/). Combining the potential of the 3D Heritage Online Presenter (3DHOP; Potenziani *et al*. 2015), a software package for the web-based visualization of 3D geometries, with the infrastructure of the ADS repository, the ADS 3D Viewer project created a platform for the visualization and analysis of 3D data archived by the ADS (Galeazzi *et al.* in review). The methodology used in developing the 3D viewer was shaped by three main objectives:

1. *3D model optimization.* To provide a visualization that can be used to access supporting data in the 3D view, it is first necessary to optimize the 3D models. The optimization and management of complex 3D models acquired through laser scanning and image-based modelling is, in fact, the first challenge to overcome for the creation of usable and accessible visualization programs. This task required collaboration between an archaeologist with extensive expertise in 3D documentation and data processing and the ADS archivist. The constant feedback of the ADS archivist was essential for understanding whether the format developed for, and supported by, the ADS 3D Viewer (NEXUS 2015) was appropriate for the long-term preservation of the 3D information. This stage was also useful in understanding how to re-use and optimize the data acquired for other purposes in previous projects (Galeazzi 2015).
2. *3D viewer development.* The 3D models were imported into an off-line beta version of the 3D viewer to begin development of the different elements and tools of analysis of the infrastructure. In this second stage of the process the archaeologist/3D modeller received essential support from the 3DHOP developers and the ADS application developer for the creation of the infrastructure.

3. *Standardization of structures and formats: the ADS 3D Viewer on the web*. This part of the project involved integrating the off-line beta version of the viewer into the ADS on-line repository. A set of pilot tests was conducted on the off-line version of the viewer before its integration in the ADS infrastructure, in order to optimize it and facilitate its integration in the existing on-line aggregator's cyber-infrastructure. In this part of the project the archaeologist/3D modeller received support from various members of the ADS staff to archive a complex variety of data coming from the pilot case study used for the implementation of the viewer, including the digital archivists, the communications and access manager and the collections development manager.

The two versions of the viewer developed in this project, the Object Level 3D Viewer (implemented to extend the browsing capability of ADS project archives by enabling the visualization of single 3D models) and the Stratigraphy 3D Viewer (implemented so as to allow the exploration of a specific kind of aggregated data: the multiple layers of an archaeological stratigraphic sequence), are designed to answer the different needs of users. These platforms allow those unable to participate directly in the fieldwork to access, analyse and re-interpret the archaeological context remotely, and are likely to help favourably transform the discipline, by nurturing inter-disciplinarity, and cross-border and 'at-distance' collaborative workflows. We are confident that the ADS 3D Viewer is a tool that could play a significant role in the integration of both traditional and innovative digital acquisition methods in day-to-day fieldwork practice.

3D Viewer embedded in the paper

5. Discussion and conclusions

This paper has described 3D visualisation platforms designed and implemented within the archaeology and heritage fields. The case studies described above show the capabilities inherent to these immersive visualization systems when applied to cultural heritage. The virtual space can be populated by avatars (the users' virtual alter ego), characters with pre-recorded behaviours that simulate people from the past, and inanimate as well as animated objects (with pre-recorded information accessible through interactive hyperlinks). Interactions with the virtual world occur in different ways: real-life users can interact with objects and avatars in the virtual world using simply a mouse or a remote controller, or even their body (mid-air, gesture-based interaction). The virtual realm gives users the possibility to compare multiple interpretations and different simulations of reality in the reproduced space. This process increases the number of interactions the user can have with virtual objects and virtual characters.

Considering the complexity of these platforms, it is clear how cross-disciplinary efforts are essential to their efficient design and development. In fact, the combination of hybrid profiles, such as archaeologist/3D modeller, digital archivist/archaeologist, computer scientist/archaeologist, and manager/archaeologist, was crucial for the success of all the projects presented above. These hybrid profiles enhanced communication between the different partners and specialists, contributing to a reduction in the time needed for the completion of the different tasks of the projects. This allowed time for further discussions and developments between the projects' participants. Cross-disciplinary efforts might be achieved in a number of ways:

1) Individual researchers could be trained in the interdisciplinary perspective. Scientists possessing a strong background in heritage and/or archaeology, computer science and 3D modelling can formulate more appropriate theories to address issues related to digital preservation and communication of the archaeological record. This solution might have some limitations, since scientific practice requires a high degree of specificity and focus, and researchers might require high-level training in multiple alternative disciplines.
2) A second way is through interdisciplinary co-operation, which sees a team of investigators from different disciplines working together on a common project. This solution seems the most practised today, producing findings which are unlikely to have been obtained by departments and programs operating autonomously. This solution requires integration across discipline-specific methodologies. It has, however, some limitations, related to the very nature of inter- and multi-disciplinary collaborations. For instance, for scholars with a narrow, discipline-specific background, it might be difficult to generate research questions that cross the boundaries of their discipline.
3) One possible solution to overcome the limitations of the previous two approaches would be to combine a strong discipline-specific training with basic knowledge on the theories and methodologies of other disciplines (e.g. computer science) and then initiate interdisciplinary collaborations. This approach can overcome the limitations of a discipline-specific focus as well as increasing critical awareness in favour of a genuine interdisciplinary approach. Moreover, it speeds up research design and data analysis, since all stakeholders involved in

the study can easily problematize findings and interact to assess the original research design. The latter approach could generate results that can be applied to different disciplines, giving the opportunity to develop new research questions and theories.

From reducing visitor impact at fragile sites to creating a scientific record of conditions at a moment in time, as well as educating both young people and adults, there seems little question that Virtual Heritage and visualization platforms have great value. Behind these systems, however, come vast meshes, model files, animations, and multimedia presentations. The challenge quickly becomes how to store, manage, and share such large repositories and platforms and make them useful beyond their initial needs. The *Flaminia* project is a clear example of how 3D contents and data can be transformed, optimized and re-used to allow the preservation of the information in the long term. This project was developed by a consolidated multi-disciplinary laboratory, the Virtual Heritage Lab (ITABC – CNR), which embraced the re-use of the data and the migration of the original application from the previous platform (Virtools) to the new one (Unity 3D). However, the migration of data and the development of platforms that exploit the most innovative technologies and software can be difficult to accomplish, due to the lack of resources or a loss of interest in the continuation of the project by its stakeholders. To give an example from the Italian context, in a recent study aimed at presenting a recently funded transnational network of virtual museums (V-Must project; www.vmust.net), Sofia Pescarin (2013) showed that in the years 1998 to 2008 there was a substantial increase in the number of Virtual Museums in Italy, which was not accompanied by strategies for maintaining, accessing and re-using these museums datasets. Thus, in a sample of 40 virtual museums, only 50% are still accessible. The main reasons behind the lack of specific strategies for maintaining the visualization platforms relate to the dichotomy between platform designers and developers and platform maintainers. The latter are usually people with insufficient technical expertise, which, when combined with the lack of economic resources, makes it difficult to set a long-term plan for these 3D systems. For this reason, even though the ADS 3D viewer is at an initial stage and its longevity cannot be assessed, we believe that this project potentially represents a good example of long-term infrastructure for the following reasons:

1) The code used for the development of the platform is open and reusable for future implementations;
2) The integration of the viewer within the ADS repository increases the possibilities of its durability;

3) The designers and developers of the infrastructure will be also responsible for its maintenance.

As we envisage ongoing research in to the use of 3D visualization systems in archaeology and heritage studies, we wish to stress the importance of evaluating these systems. This paper has described several methods of evaluation as well as proposing novel methods of assessment that take into account cognitive aspects of human–object interaction in the virtual world. While most of the evaluations done to date have focused on summative assessments of the platforms, we believe that an efficient protocol for the design and development of 3D visualization systems should incorporate formative, mid-term and summative evaluations. These should accommodate cognitive aspects of human–object interaction (e.g. perception, sense of presence, embodiment, etc.), usability, and how these platforms can contribute to learning processes as well as collaborative research.

Table 3. See file: table 3

References

Aldenderfer, M. 2010 'Seeing and Knowing: On the Convergence of Archaeological Simulation and Visualization' in A. Costopoulos and M. W. Lake (eds) *Simulating Change. Archaeology into the Twenty-First Century,* Salt Lake City: Foundations of Archaeological Inquiry. The University of Utah Press. 53–68.

Antinucci, F. 2007 'The Virtual Museum', *Archeologia e Calcolatori* **1**, 79–86.

Arnold, C.J., Huggett, J.W., Reilly, P. and Springham, C. 1989 'A Case Study in the Application of Computer Graphics', CAA 17, B.A.R. International Series 548, Oxford: Archaeopress. 147–155.

Borra, D., Forte, M., Pietroni, E. and Rufa, C. 2006 'Virtual Reality and Virtual Heritage: the Scrovegni Chapel's Project', The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. **XXXIV**, Part 5/W12.

Camporesi, C. and Kallmann, M. 2013 'A framework for immersive VR and full-body avatar interaction', Proc IEEE Virtual Reality (VR) **79** (80), 18–20.

Christou, C., Angus, C., Loscos, C., Dettori, A. and Roussou, M. 2006 'A Versatile Large-Scale Multimodal VR System for Cultural Heritage Visualization', in Proc ACM VRST '06 Symposium on Virtual Reality Software and Technology, Limassol, Cyprus. 133–40.

Clark, A. 2003 *Natural-born cyborgs: Why minds and technologies are made to merge*, Oxford: Oxford University Press.

Cole, M. 1985 'The zone of proximal development: where culture and cognition create each other' in J. V. Wertsch (ed.), *Culture, Communication, and Cognition: Vygotskyan Perspectives*, Cambridge: Cambridge University Press. 146–61.

Dant, T. 1999 *Material culture in the social world: values, activities, lifestyles*, Buckingham-Philadelphia: Open University Press.

Dawson P., Levy R., Lyons, N. **2011.** 'Breaking the fourth wall': 3D virtual worlds as tools for knowledge repatriation in archaeology**.** *Journal of Social Archaeology* 11(3): 387–402

Dell'Unto, N., Di Ioia, M., Galeazzi, F., Moro, A., Pietroni, E., Vassallo, V. and Vico, L. 2007 'The reconstruction of the archaeological landscape through virtual reality applications: a discussion about methodology', in F. Remondino and S. El-Hakim (eds), *3D – ARCH 2007: Virtual Reconstruction and Visualization of Complex Architectures, 12–13 July 2007, ETH Zurich, Switzerland.* http://www.isprs.org/proceedings/ XXXVI/5-W47/pdf/dellunto_etal.pdf

Di Blas, N., Gobbo, E., and Paolini, P. 2005 '3D worlds and cultural heritage: realism vs. virtual presence', in D. Bearman and J. Trant (eds.), Museums and the Web 2005: Proceedings, Toronto: Archives and Museum Informatics, published March 31, 2005 at http://www.archimuse.com/mw2005/papers/diBlas/diBlas.html

Di Giuseppantonio Di Franco, P., Matthews, J. L. and Matlock, T. 2016 ‘Framing the past: How virtual experience affects bodily description of artefacts’, *J Cultural Heritage* **17**, 179–87.

Di Giuseppantonio Di Franco, P., Camporesi, C., Galeazzi, F. and Kallmann, M. 2015 ‘3D Printing and Immersive Visualization for Improved Perception of Ancient Artefacts, *Presence: Teleoperators and Virtual Environments. Special Issue on Living Virtual Heritage (MIT Press)* **24**(3), 243–64.

Di Giuseppantonio Di Franco, P., and Galeazzi, F. 2013 ‘Western Han Dynasty Mural Tombs: from the Use of Integrated Technologies to the Cybermap’ in F. Contreras, M. Farjas and F. J. Melero (eds), *CAA 2010 Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*. Oxford, UK: BAR International Series 2494. 345–52.

Doneus, M., Verhoeven, G., Fera, M., Briese, C., Kucera, M., Neubauer, W., 2011 ‘From deposit to point cloud. A study of low-cost computer vision approaches for the straightforward documentation of archaeological excavation’ in *XXIII International CIPA Symposium on Geomatics* 6, 81–88.

Draper, J. V., Kaber, D. B. and Usher, J. M. 1998 ‘Telepresence’, *Human Factors* **40**(3), 354–75.

Emberling, . 2008 ‘Archaeologists and the Military in Iraq, 2003-2008: Compromise or Contribution?’, *Archaeologies: Journal of the World Archaeological Congress* **4** (3), 445-459.

Featherstone, Mike. 1990. Perspectives on Consumer Culture. Sociology 24(1): 5-22.

Fernie, K. and Richards, J. (eds) 2003 *Creating and Using Virtual Reality. A Guide for the Arts and Humanities*, Oxford: Oxbow Books.

Forte, M. 2014 ‘3D Archaeology. New Perspectives and Challenges. The Example of Çatalhöyük’, *Near Eastern Archaeology* **2**, 1–29. DOI: 10.13140/2.1.3285.0568

Forte, M. (ed.) 2008 *La villa di Livia, un percorso di ricerca di archeologia virtuale*, Roma: Erma di Bretschneider.

Forte, M., Dell'Unto, N., Di Giuseppantonio Di Franco, P., Galeazzi, F., Liuzza, C. and Pescarin, S. 2010 'The Virtual Museum of the Western Han Dynasty: 3D Documentation and Interpretation' in S. Campana, M. Forte and C. Liuzza (eds), *Space, Time, Place, Proceedings of the 3rd International Conference on Remote Sensing in Archaeology (Tiruchirappalli, Tamil Nadu, India, August 17–21),* Oxford, UK: BAR S2118. 195–99.

Forte, M. and Kurillo, G. 2010 'Cyberarchaeology: Experimenting with teleimmersive archaeology', in *Proceedings of 2010 16th International Conference on Virtual Systems and Multimedia (VSMM),* IEEE. 155–62. DOI: 10.1109/VSMM.2010.5665989

Forte, M., Pescarin, S., and Pujol, L. 2006 'VR applications, new devices and museums: visitors' feedback and learning. A preliminary report', in *The e-volution of information technology in cultural heritage. Where hi-tech touches the past: risks and challenges for the 21st century. Proceedings of the 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, Vast2006*. Full Papers Volume. Nicosia, Cyprus: Eurographics. 64–9.

Forte, M. and Siliotti, A. (eds). 1997 *Virtual Archaeology. Re-creating Ancient Worlds*, New York: Harry N. Abrams.

Frischer, B., Niccolucci, F., Ryan, N. and Barceló, J. 2002 'From CVR to CVRO: The Past, Present, and Future of Cultural Virtual Reality' in F. Niccolucci (ed.), *Proceedings of VAST 2000,* Oxford: BAR International Series 834. 7–18.

Galeazzi, F., Callieri, M., Dellepiane, M., Charno, M., Scopigno, R. and Richards, J. (in review). 'Web-based Visualization for 3D Data in Archaeology: the ADS 3D Viewer', *J Archaeological Science: Reports*.

Galeazzi, F. 2015 ‘Towards the Definition of Best 3D Practices in Archaeology: Assessing 3D Documentation Techniques for Intra-site Data Recording’, *J Cultural Heritage* **17**, 159–69. DOI:10.1016/j.culher.2015.07.005

Galeazzi, F., Di Giuseppantonio Di Franco, P., and Matthews, J. L. 2015 ‘Comparing 2D Pictures with 3D Replicas for the Digital Preservation and Analysis of Tangible Heritage’, *Museum Management and Curatorship* **30** (5), 462–83.

Galeazzi, F., Di Giuseppantonio Di Franco, P. and Dell’Unto, N. 2010 ‘3D Cybermaps of Western Han Mural Tombs’, in M. Forte (ed.) *Cyber-Archaeology*, Oxford, UK: BAR International Series 2177. 97–108.

Gaugne, R., Gouranton, V., Dumont, G., Chauffaut, A. and Arnaldi, B. 2014. ‘Immersia, an open immersive infrastructure: doing archaeology in virtual reality’, *Archeologia e Calcolatori* **5**, 180–9.

Hutchins, E. 2005 ‘Material anchors for conceptual blends’, *J Pragmatics* **37** (10), 1555–77.

Kenderdine, S., Forte, M., and Camporesi, C. 2012 ‘Rhizome of Western Han: an Omnispatial Theatre for Archaeology’ in Z. Mingquan, I. Romanowska, Z. Wu, P. Xu and P. Verhagen (eds), *Revive the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 39th International Conference, Beijing, April 12–16*, Amsterdam: Pallas Publications. 141–58.

Kenderdine, S., Shaw, J. and Kocsis, A. 2009 ‘Dramaturgies of PLACE: Evaluation, Embodiment andPerformance in PLACE-Hampi’ in *Proceedings of the International Conference on Advances in Computer Entertainment Technology,* Athens: ACM. 249–56.

Kenderdine, S. and Hart, T. 2011 ‘Cultural Data Sculpting: Omni-spatial Visualization for Large Scale Heterogeneous Datasets’, in J. Trant and D. Bearman (eds.), *Museums and the Web 2011: Proceedings, Toronto: Archives and Museum Informatics*, published March 31, 2011 at http://www.museumsandtheweb.com/mw2011/programs/cultural_data_sculpting_omni_spatial_interac.html

Kintigh, K. W., Altschul, J. H., Kinzig, A. P., Limp, W. F., Michener, W. K., Sabloff, J. A., Hackett, E. J., Kohler, T. A., Ludäscher, B. and Lynch, C. A. 2015 'Cultural Dynamics, Deep Time, and Data: Planning Cyberinfrastructure Investments for Archaeology', *Advances in Archaeological Practice* **3**(1), 1–15.

Krauss, R.M. 1998 'Why do we gesture when we speak? Current Directions', *Psychological Science* **7**(2), 54–9.

Kunert, A., Kulik, A., Beck, S., Froehlich B. 2014 'Photoportals: Shared References in Space and Time', in *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing (CSCW '14)*. New York, NY: ACM.1388-1399. DOI=10.1145/2531602.2531727

Ingold, T. 2007 'Materials against materiality', *Archaeological Dialogues* **14**(1), 1–16.

Lakoff, G. and Johnson, M. 1999 *Philosophy in the flesh: the embodied mind and its challenge to Western thought*. Basic Books, New York, NY.

Lakoff, G. and Johnson, M. 1980 *Metaphors we live by*. Chicago: University of Chicago Press.

Latour, B. 1986 'Visualization and cognition. Thinking with eyes and hands' in E. Long and H. Kuklick (eds), *Knowledge and Society. Studies in the Sociology of culture Past and Present*, Greenwich Conn: Jai Press. 1–40.

Latour, B. 1993 *We have never been modern* (Translated by Caterin Porter), London: Prentice Hall, London.

Latour, B. 1997 'Trains of Thoughts: Piaget, Formalism and the Fifth Dimension', *Common Knowledge* **3**(6), 170–91.

Latour, B. 1999 *Pandora's Hope: Essays on the Reality of Science Studies*. Cambridge, Mass.: Harvard University Press.

Latour, B. 2003 ‘The Promises of Constructivism’ in D., Ihde and E. Selinger (eds), *Chasing Technoscience: Matrix for Materiality*, Bloomington & Indianapolis: Indiana University Press. 27–46.

Lave, J. 1988 *Cognition in practice*. Cambridge: Cambridge University Press.

Lederman, S. J. and Klatzky, R. L. 1990 ‘Haptic classification of common objects: Knowledge-driven exploration’, *Cognitive Psychology* **22**, 421–59.

Levy, T., Petrovic, V., Wypych, T., Gidding, A., Knabb, K., Hernandez, D., Smith, N. G., Schlulz, J. P., Savage, S. H., Kuester, F., Ben-Yosef, E., Buitenhuys, C., Barrett, C. J., Najjar, M. and DeFanti, T. 2010 ‘On-site Digital Archaeology 3.0 and Cyber-Archaeology: Into the Future of the Past – New Developments, Delivery and the Creation of a Data Avalanche’, in M. Forte (ed.), *Cyber-Archaeology*, BAR International Series 2177, Oxford: Archaeopress. 135–53.

Losier, L.-M., Pouliot, J., Fortin, M., 2007 ‘3D geometrical modeling of excavation units at the archaeological site of Tell ‘Acharneh (Syria)’, *J Archaeological Science* **34**, 272–288.

MacGregor, G. 1999 ‘Making sense of the past in the present: A sensory analysis of carved stone balls’, *World Archaeology* **31**, 258–71.

Malafouris, L. 2004 ‘The Cognitive Basis of Material Engagement: Where Brain, Body and Culture Conflate’, in E. DeMarrais, C. Gosden, and C. Renfrew (eds.), *Rethinking materiality: the engagement of mind with the material world*, Cambridge, UK: McDonald Institute for Archaeological Research, 53-62.

Martinez-Carrillo, A. L., Ruiz-Rodriguez, A., Mozas-Martinez, F. and Valderrama-Zafra, J.M. 2009 ‘An interactive system for storage, analysis, query and visualization of archaeological pottery’, in B. Frischer, J. W. Crawford, and D. Koller (eds), *Making History Interactive. Computer Application and Quantitative methods in Archaeology (CAA): proceedings of the 37th international conference, Williamsburg, Virginia, USA, March 22-*

26, 2009, 1-6. Online Proceedings: http://www.caa2009.org/articles/Carrillo_ Contribution169.pdf, accessed November 15, 2013.

Microsoft. 2015 ‘Human Interface Guidelines: Kinect for Windows’, on-line document: https://msdn.microsoft.com/en-us/library/jj663791.aspx, accessed March 16, 2016.

Nexus, 2015 Nexus, Multiresolution Visualization. Electronic document, http://vcg.isti.cnr.it/nexus/, accessed October 28, 2015.

Niccolucci, F. and Richards, J.D. 2013 ‘ARIADNE: Advanced Research Infrastructures for Archaeological Dataset Networking in Europe’, *Internat J Humanities and Arts Computing* **7**(1–2), 70–88.

Nisbett, R. 2003 *The Geography of Thought: How Asian and Westerners Think Differently… and Why*, New York: Free Press.

Norman, D. A. 1988 *The Psychology of Everyday Things*. New York: Basic Books.

Olsen, B. 2010 *In Defense of Things: Archaeology and the Ontology of Objects*, Plymouth UK: Rowman & Littlefield Publishers.

Pescarin, S. 2013 'Virtual Museums: from the Italian experience to a transnational network’, *EAC Occasional Paper* 7, 181–91.

Petridis, P., Pletinckx, D., Mania, K., and White, M. 2006 ‘The EPOCH Multimodal Interface for Interacting with Digital Heritage Artefacts’, Lecture Notes in Computer Science 4270, 408–17. DOI 10.1007/11890881_45

Petridis, P., Mania, K., Pletinckx, D., and White, M. 2003 ‘Evaluation of the EPOCH Multimodal User Interface’, in *Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST 06)*. New York, NY: ACM. 116–22.

Pietroni, E., Forlani, M. and Rufa, C. 2015 ‘"Livia's Villa Reloaded" – An Example of Re-use and Update of a Pre-existing Virtual Museum, Following a Novel Approach in Storytelling

Inside Virtual Reality Environments' in G. Guidi, J. C. Torres, R. Scopigno, and H. Graf (eds), *Proceedings of the 2015 Digital Heritage Congress, 28 Sep – 2 Oct 2015, Granada, Spain*, IEEE Computer Society. 499–506.

Pietroni, E. and Rufa, C. 2008 'Il Museo Virtuale alle Terme' in M. Forte, *La Villa di Livia. Un percorso di archeologia virtuale*, Roma: Erma di Bretschneider. 225–34.

Potenziani, M., Callieri, M., Dellepiane, M., Corsini, M., Ponchio, F. and Scopigno, R. 2015 '3DHOP: 3D Heritage Online Presenter', *Computer & Graphics* **52**, 129–141.

Pujol, L. And Champion, E. 2012 'Evaluating Presence in Cultural Heritage Projects', *International Journal of Heritage Studies* **18**(1), 83–102.

Ratey, J. J. 2002 *A user guide to the brain. Perception, attention, and the four theatres of the brain*. New York: Vintage Books.

Reilly, P. 1989 'Data Visualization in Archaeology', *IBM Systems Journal* **28**(4), 569–79.

Reilly, P. 1991 'Towards a virtual archaeology', in Lockyear, K. and Rahtz, S. (eds), *Computer Applications and Quantitative Methods in Archaeology 1990*, BAR International Series 565, Oxford: Tempvs Reparatvm. 133-139.

Reilly, P. and Shennan, S. 1989 'Applying Solid Modeling and Animated Three-Dimensional Graphics to Archaeological Problems', *Technical Report UKSC 209*, Winchester: IBM UK Scientific Centre.

Renaud, A. 2002 'Memory and the Digital World: A Few Philosophical Pointers for New Memory Practices in the Information Era', *Museum International* **54**(3), 8–18.

Simon, K. M., Payne, A. M., Cole, K., Smallwood, C. S., Goodmaster, C., and Limp, F. 2009 'Close-Range 3D Laser Scanning and Virtual Museums: Beyond Wonder Chambers and Cabinets of Curiosity?', in B. Frischer, J. W. Crawford, and D. Koller (eds.), *Making History Interactive. Computer Application and Quantitative methods in Archaeology (CAA): proceedings of the 37th international conference, Williamsburg, Virginia, USA, March 22-26, 2009*, 1-6. Online Proceedings:

http://www.caa2009.org/articles/Simon_Contribution368_a (1).pdf, accessed November 15, 2013.

Sims, D. 1997 'Archaeological models: pretty pictures or research tools?', *IEEE Computer Graphics* **17**(1), 13–15.

Stal C., Van Liefferinge, K., De Reu, J., Docter, R., Dierkens, G., De Maeyer, P., Mortier, S., Nuttens, T., Pieters, T., van den Eijnde, F., van de Put, W., De Wulf, A., 2014 'Integrating geomatics in archaeological research at the site of Thorikos (Greece)', *J Archaeological Science* **45**, 112–125.

Suchman, L. A. 1987 *Plans and situated actions. The problem of human-machine communication*, Cambridge: Cambridge University Press.

Trautner, T., 2015 'Visualizing Archaeological Excavations based on Unity3D' in *Proceedings of CESCG 2015: The 19th Central European Seminar on Computer Graphics*. Electronic document: http://www.vrvis.at/publications/pdfs/PB-VRVis-2015-014.pdf, accessed 15 October 2015.

Varela, F. J., Thompson, E. and Rosch, E. 1991 *The embodied mind: Cognitive science and human experience.* Cambridge MA: MIT press.

Wave, C. 2004 *Information Visualization: Perception for Design*, San Francisco: Elsevier Science & Technology Books.

Weber, J. A., and Malone, E. 2011 'Exporting Virtual Material Culture. Cheap and Easy Methods to Preserve ad Share data', *The SAA Archaeological Record* **11**(1), 15-18.

Wilcock, J.D. 1973 'A General Survey of Computer Applications in Archaeology', CAA 1, Stratford: George Street Press. 17–21.

Wilson, B. G. and Myers, K. M. 2000 'Situated cognition in theoretical and practical context' in D. H. Jonassen and S. M. Land (eds), *Theoretical foundations of learning environments*, Mahwah, NJ: Erlbaum. 57–88.

Wood, J. and Chapman, G., 1992 ‘Three-dimensional Computer Visualization of Historic Buildings – With Particular Reference to Reconstruction Modelling’ in P. Reilly and S.P.Q. Rahtz (eds), *Archaeology and the Information Age: A Global Perspective*, London: HarperCollins. 123–46.

Zubrow, E. B. W. 2010 ‘From Archaeology to I-archaeology: Cyberarchaeology, paradigms, and the end of the twentieth century’ in M. Forte (ed.), *Cyber-Archaeology*, BAR International Series 2177, Oxford: Archaeopress. 1–8.