Jeffrey P. Emanuel
http://dx.doi.org/10.15496/publikation-43202

From Physical to Digital, From Interactive to Immersive: Archaeological Uses of 3D, AR, VR, and More

Jeffrey P. Emanuel
Associate Director of
Academic Technology
CHS Fellow in Aegean
Archaeology and Prehistory
Harvard University
jemanuel@fas.harvard.edu

Abstract

The combination of improved methods and tools, widespread adoption, and continuously-falling barriers to entry has prompted the claim that we are currently living in a 'golden age of digital archaeology'. This paper provides a background discussion of the use and evolution of digital methods and tools in archaeology, as well as a summary of the conference session "From Physical to Digital, from Interactive to Immersive: Uses of Three–Dimensional Representation, Mixed Reality, and More in the Sharing and Exploration of Archaeological Data," held at the CAA 2017 conference in Atlanta.

Keywords: 3D, virtual reality, augmented reality, simulations, field archaeology, digital archaeology

Introduction: Representing a Three–Dimensional Reality

In the October 29, 1989 edition of Bill Watterson's brilliant comic strip 'Calvin and Hobbes,' Calvin approaches his father on the front porch and asks, "Dad, how come old photographs are always black and white? Didn't they have color film back then?" "Sure they did," replies Calvin's father. "In fact, those old photographs are in color. It's just the world was black and white then." He continues in this vein, declaring that, "The world didn't turn color until sometime in the 1930s, and it was pretty grainy color for a while, too." Calvin, perhaps sensing a flaw in his father's explanation, asks why old paintings are in color now, but old photos remain in black and white. His father responds that, while the artists' paintings "turned colors like everything else in the '30s," the photographs were "color pictures of black and white," and therefore remain accurate representations of the formerly colorless world. As he frequently does after these conversations, a confused Calvin retreats to the company of his stuffed tiger Hobbes and declares that "the world is a complicated place, Hobbes" (Watterson 1989).

One could be forgiven if, upon looking back through the vast majority of archaeological publications from the dawn of the modern discipline to the present, they thought the phenomenon being described by Calvin's father in the strip mentioned above was similarly applicable to this field. The exception is that, instead of just having been in black and white, the world seems also to have been–until very, very recently–in just two dimensions, as well. As Gareth Beale and Paul Reilly recently noted:

> "While the archaeological record is now primarily digital, its sections, plans, drawings and photographs are facsimiles of the analogue technologies that preceded them. This retention of analogue conventions is increasingly out of step with the general prevalence and diversity of digital technologies as mediators of professional and private life. It is also challenged by 21st-century advances towards technologies that allow for complex engage-

> ments with and representations of physical matter and facilitate the interplay between digital and material worlds" [Beale and Reilly 2017].

2D photographs, line drawings, and even the codex–based publication format of archaeological research and scholarship all (whether consciously or not) to reinforce the idea of a 'flat' past, and all pull us away from a fact that should be simple to recognize, but that we have all too often seemed to forget: the world did not exist in two dimensions, but in three (Sanders 2014: 30; cf. Emmitt et al. 2017; Richards–Rissetto 2017: 16–17; Roosevelt et al. 2015).

The advent of digital methods in archaeology in the later years of the 20th century CE began to push against this traditional manner of presenting and publishing archaeological data (e.g., Beale and Reilly 2017; Huggett 2017; Reilly 1989: 579). Innovations in digital recording have caused the amount of data collected during modern archaeological excavations to dwarf that collected only a few years before – let alone in the excavations of the previous century (Bevan 2015; Cooper and Green 2017; Rabinowitz et al. 2008). The thoughtful integration of digital methods into the process, from excavation to publication, can assist in more complete recording and, just as importantly, meaningful presentation and dissemination of these data. It is also important that data from prior excavations and campaign seasons, which may have been recorded in different formats and following different methodologies, be integrated into the overall (digital) picture.

What has been called the 'golden age of digital archaeology' (Lasaponara and Masini 2016; cf. Grosman 2016) has been furthered by the development of 3D modeling, and Augmented Reality (AR) and Virtual Reality (VR) experiences. These techniques have opened up a new horizon in excavation, data interrogation, and publication–one in which the 3D reality need not be reduced to a 2D facsimile for analysis and dissemination. These are not altogether new approaches, of course; virtual reconstructions of archaeological data were being undertaken in the 1980s (Fletcher and Spicer 1988), while by the turn of the millennium AR was being experimented with at cultural heritage sites like Olympia in Greece–although, in that pre–smartphone 'dark age,' the user had to carry an onerous amount of equipment–a bicycle helmet mounted with a digital compass and webcam, with the latter tethered to a laptop in a backpack, where the user also carried a Differential GPS (DGPS) receiver to correct for inaccuracy in GPS data, a battery good for one hour's use, a power distribution module, and wireless local network (WLAN) hardware (Vlahakis et al. 2002: 57; Figure 1).

Massive Data—With a Purpose?

The further development of digital approaches and tools, from the advent to smartphones in the late 2000s to the more recent (and rapidly–increasing) accessibility of powerful computers and 3D gaming engines like Unity, has fueled a seemingly logarithmic increase in access to, and the use of, these methods in cultural heritage fields writ large. This has spurred further advancement in the use of digital methods for archaeology, as well as more attempts to integrate digital methods and tools into data recording (e.g. Austin 2014; Ellis 2016; Uildriks 2016). However, simply gathering voluminous amounts of data for their own sake is of limited use. Instead, as Adam Rabinowitz and colleagues noted nearly a decade ago, as the exponential growth of data–gathering was under way, digital tools "make it much easier for archaeologists to interpret the results of their own work, and second–perhaps more importantly–they allow future researchers to use more data more effectively to ask new and equally interesting questions of their own" (Rabinowitz et al. 2008: 17). In other words, instead of taking what we might call the 'Sir Edmund Hillary approach' to data collection–gathering massive quantities because they are there, and because we can–there should be both a structure and a method to the madness. This might involve looking at these data in new ways, or answering (or conceiving!) new research questions, but there needs to be some purpose to it.

In the case of Augmented and Virtual Reality, one purpose is the utility they present for the presentation and exploration of archaeological datasets, primarily because of the inherently three–dimensional nature of GIS points and associated finds, and the possible shapes, models, and textures they connote (Emanuel, Morse & Hollis 2016: 8). Thus, the interaction and immersion provided by the combination

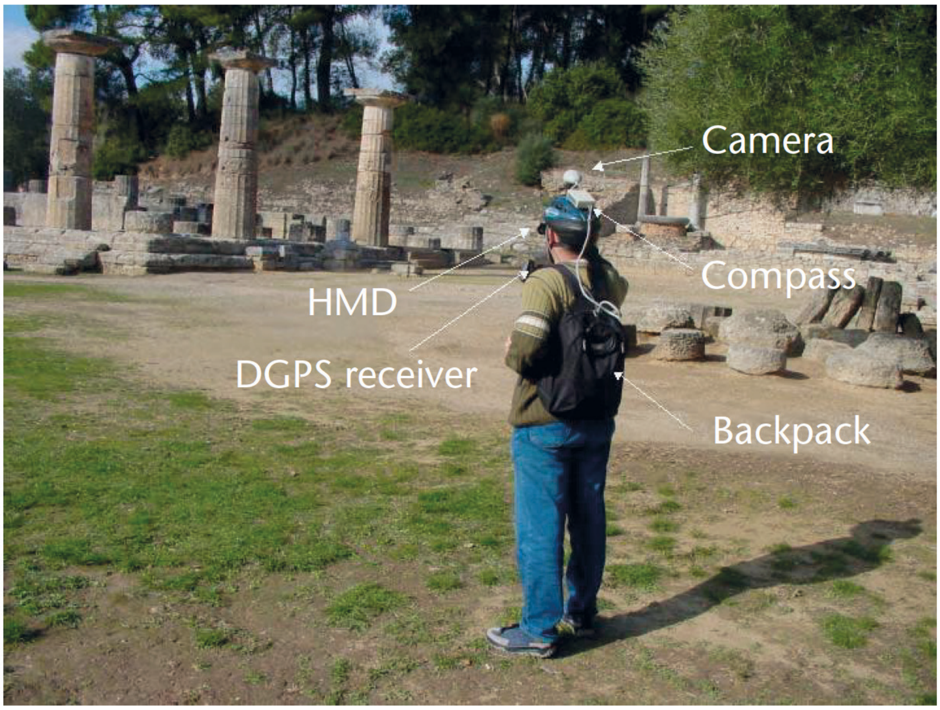

Figure 1. An early user of Augmented Reality touring the site of Olympia (after Vhlakis et al. 2002).

of 3D modeling, VR, and AR can enable two key improvements in the cultural heritage world in general, and archaeology in particular:

- Enhanced exhibition and display, which can include the digital supplements to publications and exhibits, physical reconstruction and replication, and virtual simulation of sites and artifacts, including those that no longer physically exist; and

- The close examination of live datasets, which can run the gamut from database queries to the 3D rendering of archaeological data in situ for the purpose of discovery, analysis, and information sharing.

Even recently, a common critique of 3D, AR, and VR work in archaeology has been that these approaches were "mostly aimed at enriching the tourist experience and have not yet been used to explore past experience or approach archaeological research questions" (Eve 2012: 594). While virtual exhibition is more publicly–visible and widespread, the interrogation of data sets and the development of new research questions and answers is perhaps of greater importance to the field itself. More importantly, it is the latter that will play the strongest role in influencing the future of digital methods in archaeology, as this is a field that will only continue to press forward with these time–and resource–intensive methods if there is a research–based return. Fortunately, positive results continue to be reported–to such a point, in fact, that in 2014 François Djindjian told the 42nd annual Computer Applications and Quantitative Methods in Archaeology meeting that "the very rapid development of 3D archaeology ... may possibly revolutionise field archaeology as well as all data processing that takes place following excavations and surveys" (Djindjian 2015: 4; cf. Grosman et al. 2014; Parker and Eldridge 2015: 115).

But Really ... What Do We Do With All These Data?

Communicating archaeological data in a way that can simultaneously enhance public access *and* facilitate the development of new research questions is a tricky proposition. Digital publications that include 3D–modeled objects and assemblages are an example of an interactive approach to the problem, as are published geospatial datasets and 3D–printed objects. This may be taken a step further with immersion, as AR, VR, and Mixed Reality (MR) allow for the creation of truly immersive experiences around the reconstruction, visualization, and presentation of data. I should note here the importance of noting the fact that these 'reconstructions', whether in 3D, AR, or VR, are not reconstructions at all (nor are they truly *recreations*); rather they are *simulations* of the past (Forte 2011: 8; cf. Vurpillot 2016). This term, then, will be used henceforth in this paper to refer to such virtual objects (where possible, I shall endeavor to clearly delineate between object simulations –the noun version of this term–and active simulations, or the verbal form).

VR offers a venue for digital fabrication that allows the creator total control over the 'reality' being presented. Because of this, it more fully supports experimentation with multiple definitions of 'authenticity' (Morcillo, Schaaf & Schneider 2017), or what Stuart Eve calls "possible pasts" (2012: 583). AR also supports notional fabrication, but has its own advantages, allowing users to immerse themselves not in a virtual world, but in the real world, at the physical site itself (or at a reasonable facsimile; Esclapes et al. 2013), "while visually receiving additional computer–generated or modelled information to support the task at hand" (Schnabel et al. 2007: 4). In other words, AR *enriches* the real world by adding location-based virtual components (Pierdicca et al. 2016). "The ability to move through the landscape offers us a number of different ways to cognitively involve ourselves with the environment" (Eve 2012: 592), thus giving AR an added dimension that further adds to its value for research and for the communication of cultural heritage alike.

One particular area in which AR can add value is its ability to provide archaeologists with a reconstructed picture of non–extant data. Archaeological excavation is, both axiomatically and by definition, an irreversibly destructive act. As Paul Reilly (1989: 569) once wrote, "It is an unfortunate irony that in order to reveal what lies below, the archaeological excavator must remove, and thereby destroy, what lies above. The anthropologist Sir Edmund Leach once observed that in an anthropological context, this would be rather like interviewing members from the society under study and then shooting them!". Virtual reconstruction of that which was necessarily destroyed by excavation is one method of addressing this necessary evil. While not a novel idea (e.g. Vote et al. 2002, who presented a more rudimentary approach to this a decade and a half ago), it is becoming both more feasible and more useful as visualization technologies and access to them improve (Roosevelt et al. 2015; see also below).

Ongoing improvements continues to be needed, of course, if the 3D–VR–AR approach is to become a more universally–viable method of cataloging and representing both excavations (and excavation data) and cultural heritage sites. Research efforts at institutions around the globe are pushing forward in that direction, studying and sharing approaches to things like:

1. Reconstructing excavation layers and point–find data, as mentioned immediately above (e.g., Emanuel, Morse & Hollis 2016: 8–14; Vote et al. 2002);

2. Virtual simulation, for both documentary and investigative purposes (inter alia Bernard et al. 2017; Eve 2012: 587; Liritzis et al. 2016; Manzetti 2016; Ramallos Asensio et al. 2013; Younes et al. 2017);

3. Applying GIS and landscape studies not just to geographic data, but as the basis for semiotic analysis of interactions between humans and their environment (Eve 2012; Llobera 2012; Richards-Rissetto 2017; cf. Morgan 2016)

4. 3D digitization, including high–volume workflows (Santos et al. 2017) and preservation of at–risk cultural heritage (e.g. Lecari 2016);

5. Rendering static and dynamic images from 3D scans (e.g., Counts, Averett & Garstki 2016; Galeazzi 2016; Gilboa et al. 2013; Koutsoudis et al. 2014

6. Experimenting with different methods and technical approaches to AR, VR, and data management (e.g., Chevrier et al. 2010; Balletti et al. 2015; Jiminez Fernandez–Palacios et al. 2015; Meyer, Grussenmeyer & Perrin 2007; Meyer et al. 2008);

7. Creating an interactive, immersive experience driven by avatars (e.g., Abate, Acampo-

ra & Ricciardi 2011); called 'teleimmersive archaeology' by Forte, Kurillo & Matlock (2010); and

8. Extending photogrammetry and 3D rendering for AR experiences to more complex environments, such as virtual cities (e.g., Guidi, Frischer & Lucenti 2007; Portales, Lerma & Navarro 2009).

A significant number of the publications in these areas are case–study based, presenting the technologies and workflows utilised in those cases either as one way to approach the problem, or as suitable for universal adoption (*inter multis aliis*, Altshuler and Mannack 2014; Averett, Gordon & Counts 2016; Bruno et al. 2010; Dell'Unto et al. 2016; Forte 2014; Galeazzi 2016; Jiminez Fernandez–Palacios et al. 2015; Manzetti 2016; Meyer et al. 2007; Remondino and Campana 2014). However, more widely-shared approaches remain elusive, and methods-and-tools standardization of almost any sort remains a near-impossible proposition. Ultimately, until access to funding and tools becomes more universal, and until enough institutions adopt specific methods and tool–sets to provide them with momentum in the (digital) cultural heritage marketplace, work in this space will continue to be defined, at least in part, by a form of the "not–invented–here syndrome: the conviction that 'you and I will collaborate just fine if you adopt my system and abandon yours'" (Waters 2013: 14).[1]

Experimentation with the general practices of 3D modeling, AR, and VR, on the other hand, continues to make great strides, even if the methods and workflows employed remain disparate. This is true from land to sea, where these technologies are also being used to provide better contextual understanding of shipwrecks and submerged cultural heritage sites (Costa, Beltrame & Guerra 2015). One particular example, VISAS (VIrtual and augmented exploitation of Submerged Archaeological Sites), utilises immersive VR for land–based audiences, allowing them "to live a virtual experience inside the reconstructed 3D model of the underwater archaeological site," and AR for divers who visit the site, "allowing them to have a virtual guide that provides specific information about the artifacts and the area they are visiting" (Bruno et al. 2016: 270). This is a more complex undertaking than AR experiences at land–based sites because, ironically, terrestrial tourism is in many ways a two–dimensional experience. The third dimension appears on the instrument on which the AR application is being run (smartphone, tablet, etc.), but, with allowance made for undulations in terrain, movement around the site is on the X and Y axes. In a diving environment, on the other hand, depth is also a factor, providing a Z axis that has to be accounted for in the AR experience.

Still further development is necessary to move from using virtual simulation to engage the public, to using these methods to interrogate data for the purpose of generating – and answering–archaeological research questions (cf. Eve 2012: 594). Further, though the ongoing development of virtual building and site simulations is useful and engaging, particularly for the public, "these models are too often the end product of a process in which archaeologists have relatively limited engagement" (Morgan 2009). Maria Manzetti (2016: 36), writing more recently, concurred with this assessment, and argued for a clear methodology for verifying hypothetical scenarios of 3D architectural simulations: "With the diffusion of virtual archaeology, many projects in the field of cultural heritage attempt to virtually reconstruct historical buildings of different types," she wrote. "Unfortunately, some of these [3D] reconstructions still have as principal aim to impress the external users, while the correct interpretation of the buildings modeled is much more important in the domain of archaeological research."

CAA 2017: From Physical to Digital, from Interactive to Immersive

Concerns about imbalanced (though improving) access and the lack of generally–accepted standards for tools, methods, and workflows having been noted, it appears that the state of the field in 2017 can be

1 A relevant example of this is the Unity gaming engine, which has proven to be a low–entry–barrier method for developing software that can be published across AR, VR, and web–based platforms. A potential model for interoperability is the International Image Interoperability Framework (IIIF), a hundred–institution consortium using shared APIs, rather than proprietary software and workflows, to share digital visual material (http://iiif.io; Snydman, Sanderson & Cramer 2015; Emanuel 2018a).

described as both *emergent* and *alive with discovery*, as the adoption curve of digital methods in general–and 3D, AR, and VR in particular–continues to surge. Evidence of this can be seen in the papers presented in the CAA 2017 session *From Physical to Digital, from Interactive to Immersive: Uses of Three–Dimensional Representation, Mixed Reality, and More in the Sharing and Exploration of Archaeological Data*. Themes of this session included example approaches and workflows for data gathering and processing, experimentation with standards for photogrammetry and 3D modeling, geographic analysis, virtual reconstructions of excavation layers, assemblages, and fixtures, and virtual simulations of original constructions.

A noteworthy presentation on the topic of virtual simulations was given by Daniel Löwenborg of Uppsala University, Sweden ("Augmented History – A Virtual 'Window to the Past'). This paper focused on a detailed, interactive 3D simulation of Old Uppsala (Gamla) in the mid–6th century CE, complete with buildings, graves, and animated characters to provide a more complete look not just at architecture, but at life in the Old City. Animated characters were exchanged for avatars (cf. Morgan 2009 and Forte et al. 2010, cited above) in a virtual simulation of the Sanctuary of Hercules at Deneuvre in Eastern France ("Making Virtual Reality Real: What Can We Learn by Bringing Together Virtual Reality and Visual Attention Analysis?"). Damien Vurpillot presented on the utilization of avatars to create interactive scenarios within the sanctuary, and the tracking and quantitative measuring of these users' movement through the landscape – a study conducted in hopes that the trends seen here could serve as a starting point for the development of virtual reality as a research tool. Visitor movement through a site was likewise addressed by Bonna Wescoat and Arya Basu, from Emory University ("On the Dynamics of Interactive Exploration over Animation as Methods of Experiential Simulation in the Sanctuary of the Great Gods on Samothrace"), who utilised 3D modeling of the site of the Great Gods at Samothrace to provide an immersive experience in the physical environment, and to focus on the movements and sensory perceptions of pilgrims visiting the site at the time of its use, including how the nexus of terrain, buildings, and movement heightened the experience of initiation into this cult.

Experimentation with high–quality photogrammetry continues to be a key topic in discussions of 3D modelling, VR, and AR. Ivan Rudov of Siberian Federal University, Krasnoyarsk ("Combined method of 3D model of archaeological objects optimisation for a mobile app") offered the session the results of his own workflow experimentation for static and real–time mobile visualization of photogrammetric models, which provided realistic models with high texture resolution. High–resolution photogrammetry that requires few enough computational resources to properly render in a live mobile environment has become increasingly useful to practitioners and those seeking to interrogate the raw data with the wider adoption of attempts to virtually reconstruction of *excavation levels* themselves (cf. Vote et al 2002: 42). As addressed above, archaeological excavation remains destructive act that is physically irreversible. However, if data are properly gathered throughout the excavation process, such destruction may be reversible in *digital* form.

Two papers in particular addressed the representation of excavation phases in 3D, AR, etc. Luke Hollis of Archimedes Digital ("MorgantinaVR: Cityscale Handheld AR and CrossPlatform VR for Visualizing Georeferenced Datasets") reported on the modeling of excavation strata the Contra Agnese Project from Morgantina, Sicily, where they continue to develop the ability to virtually browse day–by–day recreations of trench models and 3D renderings of the datasets associated with CAP's museum (cultural heritage) and geospatial teams. Similarly, Bryan Burns and Jordan Tynes of Wellesley College ("Excavation Progress and Artifact Manipulations in a Virtual Environment"), created 3D models in the Unity game engine to record and reconstruct excavations of early Mycenaean tombs at the site of Eleon in Boeotia (Central Greece). Imagery gathered by drones was converted into photogrammetric models, which could be utilised to track daily progress and to allow for analysis at various points throughout the excavation. They also coupled virtual models with interpretive tools to enable users to interact with finds from the site. A slightly different tack on research and data interrogation was taken by a team from HTW Berlin, represented by Sebastian Plesch, whose presentation provided an overview of a collection of packages designed to support the exploration and examination of 3D archaeological assets in interactive Virtual Environments ("VR:TA – A Virtual Reality Toolset for Archaeologists"). Using the Temple of the Storm God at Aleppo (Kohlmeyer 2009) as an example, Plesch highlighted two particularly useful VR:TA packages: the measurement tool, which can create detailed measurements of 3D assets at multiple scales, and the sky tool, which can allow researchers to adjust the virtual night sky so that the correct constellations and planets appear for the date being presented in the reconstruction.

The open discussion portion of the session provided energetic conversation about tools, workflows, and other approaches to incorporating computer applications and digital methods into field archaeology in particular, and cultural heritage in general. Among the most generative topics was that of connection and collaboration: how contacts can be made, and bridges built, across the appropriate specialties, both within and across institutions. The value of Digital Humanities centers and other on-campus organizations as matchmakers or clearinghouses for collaborative projects was raised, although not all centers operate in this way, and many institutions lack them altogether. The importance of collaborative effort across a range of fields (along with the value of CAA's interdisciplinary membership) was exemplified during the discussion of virtual simulations, as a structural engineer in attendance was able to speak to the value of having an expert in that field as part of the team to consult on the real–life efficacy of virtual designs, much as Manzetti (2016, noted above) rightly called for archaeologists to be involved in the same due to their own expertise. The discussion concluded with general agreement about the importance of building those bridges, and reaching out to those in computer science, engineering, and other relevant academic specialties who can add needed expertise in their field to archaeological and cultural heritage projects.

Conclusion

Archaeology as a discipline is very much in the throes of methodological change: digital methods are becoming more prevalent, tools for data gathering and synthesis are becoming more widespread and interoperable, and the financial and technical barriers to engaging in digitization, and in digital reconstruction and simulation, continue to recede. We may indeed be in the midst of a 'golden age of digital archaeology,' as Rosa Lasaponara and Nicola Masini (2016) described the current period; however, there remains much more to be done, lest the so-called 'digital archaeology' of the present emulate the 'virtual archaeology' of the 1980s, and fail to live up to its remarkable potential to change the way we do business altogether. Modern digital tools and techniques offer far more potential than their 'virtual' predecessors: while the latter was used to describe "the way in which technology could be harnessed in order to achieve new ways of documenting, interpreting and annotating primary archaeological materials and processes," we have now grown into a technological world that "allow[s] for complex engagements with and representations of physical matter and facilitate the interplay between digital and material worlds" (Beale and Reilly 2017: 1).

Much as those who first set sail in the Age of Exploration did not know what lay ahead, and could only learn it by venturing out themselves, we cannot yet know what (or how many) new research questions will arise as the result of three-dimensional site representation. Nor can we yet know what new understandings may be gained from virtual simulations of sites the world over. We can, however, be certain that such discoveries will, at some point, require a shift in thinking about the past itself. For too long, our study of archaeology and of history have been mired in a two-dimensional past. The tools and methods for gathering, analyzing, and communicating voluminous quantities of archaeological data are available and in use; however, while Virtual Reality, Augmented Reality, simulated reconstructions, avatar-based interaction, and more promise a combination of entertainment, interactivity, and illumination, the most basic advantage of the modern digital age is its promise of finally providing the past with what it has needed all along in order to be properly represented, studied, and understood: its long-missing Third Dimension.

References

Abate, A F, Acampora, G and Ricciardi, S 2011 An interactive virtual guide for the AR based visit of archaeological sites. *Journal of Visual Languages & Computing*, 22: 415–425.

Altshuler, B F S and Mannack, T 2014 Shedding New Light on Ancient Objects. *Arion: A Journal of Humanities and the Classics*, 22(1): 53-74.

Averett, E W, Gordon, J M and Counts, D B 2016 *Mobilizing the Past for a Digital Future: The Potential of Digital Archaeology*. Grand Forks: The Digital Press @ The University of North Dakota.

Austin, A 2014 Mobilizing Archaeologists: Increasing the Quantity and Quality of Data Collected in the Field with Mobile Technology. *Advances in Archaeological Practice*, 2(1): 13–23.

Balletti, C, Guerra, F, Scocca, V and Gottardi, C 2015 3D Integrated Methodologies for the Documentation and the Virtual Reconstruction of an Archaeological Site. In: *3D Virtual Reconstruction and Visualization of Complex Architectures, Avila, Spain, 25–27 February 2015*, 215–222. Available at https://www.academia.edu/29879574/3D_Integrated_Methodologies_for_the_Documentation_and_the_Virtual_Reconstruction_of_an_Archaeological_Site [Last accessed 28 July 2017]

Beale, G and Reilly, P 2017 After Virtual Archaeology: Rethinking Archaeological Approaches to the Adoption of Digital Technology. *Internet Archaeology*, 44.

Bernard, Y, Barreau, J–B, Bizien–Jaglin, C, Quesnel, L, Langouët, L and Daire, M–Y 2017 3D Model as a Dynamic Compilation of Knowledge: Interim Results on the City of Alet. *Virtual Archaeology Review*, 8(16): 51–60.

Bevan, A 2015 The Data Deluge. *Antiquity*, 89: 1473-1484.

Bruno, F, Bruno, S, De Sensi, G, Luchi, M L, Mancuso, S and Muzzupappa, M 2010 From 3D reconstruction to virtual reality: a complete methodology for digital archaeological exhibition. *Journal of Cultural Heritage*, 11(1): 42–49.

Bruno, F, Lagudi, A, Barbieri, L, Muzzupappa, M, Ritacco, G, Cozza, A, Cozza, M, Peluso, R, Lupia, M and Cario, G 2016 Virtual and Augmented Reality Tools to Improve the Exploitation of Underwater Archaeological Sites by Diver and Non–diver Tourists. In: Ioannides, M, Fink, E, Moropoulou, A, Hagedorn-Saupe, M, Fresa, A, Liestøl, G, Rajcic, V and Grussenmeyer, P (eds.). *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*. Lecture Notes in Computer Science 10058. Cham: Springer International, pp. 269–280.

Chevrier, C, Charbonneau, N, Grussenmeyer, P and Perrin, J–P 2010 Parametric Documenting of Built Heritage: 3D Virtual Reconstruction of Architectural Details. *International Journal of Architectural Computing*, 8(2): 135–150.

Cooper, A and Green, C 2017 Big Questions for Large, Complex Datasets: Approaching time and space using composite object assemblages. *Internet Archaeology*, 45.

Costa, E, Beltrame, C and Guerra, F 2015 Potentialities of 3D Reconstruction in Maritime Archaeology. In: Giligny, F, Djindjian, F, Costa, L, Moscati, P and Robert, S (eds.). *21st Century Archaeology: Concepts, Methods and Tools*. Oxford: Archaeopress, pp. 549–556.

Counts, D B, Averett, E W and Garstki, K 2016 A fragmented past: (Re)constructing antiquity through 3D artefact modelling and customised structured light scanning at Athienou-Malloura, Cyprus. *Antiquity* 90: 206–218.

Dell'Unto, N, Landeschi, G, Touati, A–M L, Dellepiane, M, Callieri, M and Ferdani, D 2016 Experiencing Ancient Buildings from a 3D GIS Perspective: A Case Drawn from the Swedish Pompeii Project. *Journal of Archaeological Method and Theory*, 23: 73–94.

Djindjian, F 2015 Computers and Mathematics in Archaeology: Anatomy of an Ineluctable Success! In: Giligny, F, Djindjian, F, Costa, L, Moscati, P and Robert, S (eds.). *21st Century Archaeology: Concepts, Methods and Tools*. Oxford: Archaeopress, pp. 1–8.

Ellis, S J R 2016 Are we ready for new (digital) ways to record archaeological fieldwork? A case study from Pompeii. In: Averett, E W, Gordon, J M and Counts, D B (eds.). *Mobilizing the Past for a Digital Future: The Potential of Digital Archaeology*. Grand Forks: The Digital Press @ The University of North Dakota, pp. 51–76. Available at https://dc.uwm.edu/arthist_mobilizingthepast/1/ [Last accessed12 July 2017]

Emanuel, J P 2018a Stitching Together Technology for the Digital Humanities with the International Image Interoperability Framework (IIIF). In: Joranson, K and Kear, R (eds.). *Digital Humanities, Libraries, and Partnerships: A Critical Examination of Labor, Networks, and Community*. Oxford: Chandos Elsevier, pp. 125–135. Available at https://scholar.harvard.

edu/emanuel/publications/stitching-together-technology-digital-humanities-international-image [Last accessed 1 November 2018]

Emanuel, J P 2018b It Takes a Village: An Interdisciplinary Approach to Supporting and Facilitating Digital Scholarship Initiatives. Paper presented at the 2018 Digital Initiatives Symposium, University of San Diego. Available at https://scholar.harvard.edu/emanuel/publications/it-takes-village-interdisciplinary-approach-supporting-and-facilitating-digital [Last accessed 1 July 2018]

Emanuel, J P, Morse, C M and Hollis, L 2016 The New Interactive: Reimagining Visual Collections as Immersive Environments. *VRA Bulletin*, 43(2): 1–17. Available at https://scholar.harvard.edu/emanuel/publications/new-interactive-reimagining-visual-collections-immersive-environments [Last accessed 12 July 2017]

Emmitt, J, Sefton, B, Phillips, R, Wendrich, W and Holdaway, S 2017 Reimag(in)ing the Past Adding the Third Dimension to Archaeological Section Drawings. *Advances in Archaeological Practice*, 5(1) 44–53.

Esclapés, J, Tejerina, D, Bolufer, J and Aurelio Esquembre, M 2013 Augmented Reality System for the musealization of archaeological sites. *Virtual Archaeology Review*, 4(9): 42–47.

Eve, S 2012 Augmenting Phenomenology: Using Augmented Reality to Aid Archaeological Phenomenology in the Landscape. *Journal of Archaeological Method and Theory*, 19(4): 582–600.

Fletcher, M and Spicer, D 1988 Clonehenge: An experiment with gridded and non–gridded survey data. In: Rahtz, S P Q (ed.). *Computer and Quantitative Methods in Archaeology 2*. Oxford: Archaeopress, pp. 309–325.

Forte, M 2011 Cyber–Archaeology: Notes on the simulation of the past. *Virtual Archaeology Review*, 2(4): 7–18.

Forte, M 2014 3D Archaeology: New Perspectives and Challenges – The Example of Çatalhöyük. *Journal of Eastern Mediterranean Archaeology and Heritage Studies*, 2(1): 1–29.

Forte, M, Kurillo, G and Matlock, T 2010 Teleimmersive Archaeology: Simulation and Cognitive Impact. In: Ioannides, M, Fellner, D, Georgopoulos, A and Hadjimitsis, D (eds.). *Digital Heritage: Proceedings of the Third International Euro-Mediterranean Conference, EuroMed 2010, Lemessos, Cyprus, November 8-13, 2010*. Heidelberg: Springer, pp. 422–431.

Galeazzi, F 2016 Towards the definition of best 3D practices in archaeology: Assessing 3D documentation techniques for intra-site data recording. *Journal of Cultural Heritage*, 17: 159–169.

Gilboa, A, Tal, A, Shimshoni, I and Kolomenkin, M 2013 Computer–based, automatic recording and illustration of complex archaeological artifacts. *Journal of Archaeological Science*, 40: 1329–1339.

Guidi, G, Frischer, B, and Lucenti, I 2007 *Rome Reborn – Virtualizing the Ancient imperial Rome*. Workshop on 3D Virtual Reconstruction and Visualization of Complex Architectures. Available at https://www.researchgate.net/publication/228632513_Rome_Reborn_-_Virtualizing_the_ancient_imperial_Rome [Last accessed 10 July 2017].

Grosman, L 2016 Reaching the Point of No Return: The Computational Revolution in Archaeology. *Annual Review of Anthropology*, 45: 129–145.

Grosman, L, Karasik, A, Harush, O and Smilansky, U 2014 Archaeology in Three Dimensions: Computer–Based Methods in Archaeological Research. *Journal of Eastern Mediterranean Archaeology and Heritage Studies*, 2(1): 48–64.

Huggett, J (2017) The apparatus of digital archaeology. *Internet Archaeology*, 44: Available at https://doi.org/10.11141/ia.44.7

Jiménez Fernández–Palacios, B, Nex, F, Rizzi, A and Remondino, F 2015 ARCube—the Augmented Reality Cube for Archaeology. *Archaeometry*, 57: 250–262.

Koutsoudis, A, Vidmar, B, Ioannakis, G, Arnaoutoglou, F, Pavlidis, G and Chamzas, C 2014 Multi-image 3D reconstruction data evaluation. *Journal of Cultural Heritage*, 15: 73-79.

Kohlmeyer, K 2009 The Temple of the Storm God in Aleppo during the Late Bronze and Early Iron Ages. *Near Eastern Archaeology*, 72: 190–202.

Lasaponara, R and Masini, N 2016 Living in the Golden Age of Digital Archaeology. In: Gervasi, O, Murgante, B, Misra, S, Rocha, A M A C, Torre, C M, Taniar, D, Apduhan, B O, Stankova, E and Wang, S (eds.). *International Conference on Computational Science and Its Applications 2016*. Cham: Springer International, pp. 597–610.

Lecari, N, Shulze, J, Wendrich, W, Porter, B, Burton, M and Levy, T E 2016 3–D Digital Preservation of At–Risk Global Cultural Heritage. *Eurographics Workshop on Graphics and Cultural Heritage*, 2016: 1–4.

Liritzis, I, Pavlidis, G, Vosynakis, S, Koutsoudis, A, Vo-

lonakis, P, Petrochilos, N, Howland, M D, Liss, B and Levy, T E 2016** Delphi4Delphi: First results of the digital archaeology initiative for ancient Delphi, Greece. *Antiquity*, 90: 1–6.

Llobera, M 2012 Life on a pixel: Challenges in the development of digital methods within an "interpretive" landscape archaeology framework. *Journal of Archaeological Method and Theory*, 19: 495-509.

Manzetti, M C 2016 3D visibility analysis as a tool to validate ancient theatre reconstructions: the case of the large Roman theatre of Gortyn. *Virtual Archaeology Reviews* 7(15): 36–43.

Meyer, E, Grussenmeyer, P and Perrin, J–P 2007 Virtual research environment for the management and the visualization of complex archaeological sites. In: Raimondino, F and El–Hakim, S. (eds.). 3D–ARCH 2007: *Virtual Reconstruction and Visualization of Complex Architectures*. Hanover: ISPRS. Available at http://www.isprs.org/proceedings/XXXVI/5–W47/pdf/meyer_etal.pdf [Last accessed 10 July 2017].

Meyer, E, Grussenmeyer, P, Perrin, J–P, Durand, A and Drap, P 2008 A Virtual Research Environment for Archaeological Data Management, Visualization and Documentation. In: Posluschny, A, Lambers, K and Herzog, I (eds.). *Layers of Perception: Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, April 2–6, 2007*. Kolloquien zur Vor– und Frühgeschichte 10. Bonn: Dr. Rudolf Habelt GmbH, 1–6. Available at https://halshs.archives-ouvertes.fr/halshs-0a0280671/document [last accessed 31 July 2017]

Morcillo, J M, Schaaf, F, Schneider, R H and Robertson–von Trotha, C Y 2017 Authenticity through VR–based documentation of cultural heritage: A theoretical approach based on conservation and documentation practices. *Virtual Archaeology Review*, 8(16): 35–43.

Morgan, C L 2009 (Re)Building Çatalhöyük: Changing Virtual Reality in Archaeology. *Archaeologies*, 5(3): 468–487.

Morgan, C L 2016 Analog to Digital: Transitions in Theory and Practice in Archaeological Photography at Çatalhöyük. *Internet Archaeology*, 42.

Parker, A and Eldridge, M 2015 Archaeology in the Third and Fourth Dimensions: A Case Study of 3D Data Collection and Analysis from Prince Rupert, BC, Canada. In: Giligny, F, Djindjian, F, Costa, L, Moscati, P and Robert, S (eds.). *21st Century Archaeology: Concepts, Methods and Tools. Oxford: Archaeopress, pp. 115–122.*

Pierdicca R 2016 Cyberarchaeology: Improved Way Findings for Archaeological Parks Through Mobile Augmented Reality. In: De Paolis, L and Mongelli A (eds.). *Augmented Reality, Virtual Reality, and Computer Graphics*. Lecture Notes in Computer Science 9769. Cham: Springer International, pp. 172–185.

Portales, C, Lerma, J L and Navarro, S 2009 Augmented Reality and Photogrammetry: A Synergy to Visualize Physical and Virtual City Environments. ISPRS *Journal of Photogrammetry and Remote Sensing*, 65(1): 34–42.

Rabinowitz, A, Sedikova, L, Trelogan, J and Eve, S 2008 New methodologies at an ancient site: digital technology and excavation in the Southern Region of Crimean Chersonesos, 2001–2006. *Archeologia*, 2008(1–2): 1–20.

Ramallos Asensio, S F, Fernández Díaz, A, Flores Gutiérrez, M, Romero Soria Á and Martínez García, J 2013 Virtual reconstruction of the roman villa in La Quintilla (Lorca) based on the existing physical evidence and related scientific comparisons as a reference. *Virtual Archaeology Review*, 4(9): 181–189.

Reilly, P 1989 Data Visualization in Archaeology. *IBM Systems Journal*, 28(4): 569–570.

Remondino, F and Campana, S 2014 *3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and Best Practices*. BAR International Series 2598. Oxford: Archaeopress.

Richards–Rissetto, H 2017 What can GIS + 3D mean for landscape archaeology? *Journal of Archaeological Science*, 84: 10-21.

Roosevelt, C H, Cobb, P, Moss, E, Olson, B R and Ünlüsoy, S 2015 Excavation is Destruction Digitization: Advances in Archaeological Practice. *Journal of Field Archaeology*, 40: 325–346.

Santos, P, Ritz, M, Fuhrmann, C and Fellner, D 2017 3D mass digitization: a milestone for archeological documentation. *Virtual Archaeology Review* 4(8): 1–11.

Schnabel, M A, Wang, X, Seichter, H and Kvan, T 2007 From Virtuality to Reality and Back. In: Poggenpohl, S (ed.). *Proceedings of the International Association of Societies of Design Research 2007 Conference*. Hong Kong: Hong Kong Polytechnic University, pp. 1–15.

Snydman, S, Sanderson, R and Cramer, T. 2015. The International Image Interoperability Framework (IIIF): A community and technology approach for web-based images. In: *Archiving 2015*, Los Angeles, CA, May 19-22. Available at http://purl.stanford.edu/df650pk4327 [Last accessed 30 July 2017]

Uildriks, M 2016 iDig – Recording Archaeology: a review. *Internet Archaeology*, 42. Available at http://intarch.ac.uk/journal/issue42/13/uildriks.html [Last accessed 12 July 2017]

Vlahakis, V, Ioannidis, N, Karigiannis, J, Tsotros, M, Gounaris, M, Stricker, D, Gleue, T, Daehne, P and Almeida, A 2002 Archeoguide: An Augmented Reality Guide for Archaeological Sites. *IEEE Computer Graphics and Applications*, 22: 52–60.

Vote, E, Feliz, D A, Laidlaw, D H and Joukowsky, M S 2002 Discovering Petra: Archaeological Analysis in VR. *IEEE Computer Graphics and Applications*, 22: 38–50.

Vurpillot, D 2016 *Aspectus operis and visual attention: from Vitruvius to Virtual Reality, 2016*. Available at https://www.academia.edu/14903812/Aspectus_operis_and_visual_attention_from_Vitruvius_to_Virtual_Reality [Last accessed 27 July 2017]

Watterson, B 1989, Oct. 29 Calvin and Hobbes Available at http://www.gocomics.com/calvinandhobbes/1989/10/29 [Last accessed 27 July 2017]

Williams, J I and Burke, A A 2016 'You have entered Joppa': 3D Modeling of Jaffa's New Kingdom Egyptian Gate. *Near Eastern Archaeology*, 79(4): 260–270.

Younes, G, Kahil, R, Jallad, M, Asmar, D, Elhajja, I, Turkiyyah, G and Al–Harithy, H 2017 Virtual and augmented reality for rich interaction with cultural heritage sites: A case study from the Roman Theater at Byblos. *Digital Applications in Archaeology and Cultural Heritage*, 5: 1–9.