Virtual Archaeology Review, **15**(30): 21-34, 2024
https://doi.org/10.4995/var.2024.19806

Received: May 30, 2023
Accepted: October 1, 2023

THINKING THROUGH THE TOOL: COLLABORATIVE ARCHAEOLOGICAL BODYWORK IN IMMERSIVE VIRTUAL REALITY

PENSAR A TRAVÉS DE LA HERRAMIENTA: TRABAJO CORPORAL ARQUEOLÓGICO COLABORATIVO EN REALIDAD VIRTUAL INMERSIVA

Giles Spence Morrow*, Steven A. Wernke

Department of Anthropology, Vanderbilt University, PMB 356050, 2031 Vanderbilt Place, Nashville, Tennessee 37235-6050, USA.
giles.spence.morrow@vanderbilt.edu; s.wernke@vanderbilt.edu

Highlights:

- Immersive virtual reality extends embodied archaeological interpretation beyond the field setting, raising important prospects for knowledge production via repeated visits to primary contexts.
- Increasing accessibility of collaborative virtual reality platforms opens new opportunities to engage with archaeological contexts and digital assets of excavated artifacts.
- Examples of collaborative virtual reality interactions within two Peruvian archaeological sites demonstrate that embodied experience holds valuable potential in knowledge generation.

Abstract:

Thanks to currently available very high-resolution three-dimensional (3D) models via photogrammetric techniques as a primary method of archaeological documentation, constructing immersive, high-fidelity simulacra is imminently possible. This paper considers how the scale at which the human body interacts with immersive digital models is especially important for understanding the affordances and ergonomics of past things and places. The implications of this isometry between archaeological objects of analysis and emerging capabilities to interact with them through digital surrogates in the present are manifold. By enabling interaction with objects and contexts in immersive virtual space, such observational experiences create in silico engagements that are repeatable, distributable, and collaborative. In particular, it is the collaborative capacity of this technology that this paper explores using online immersive virtual reality (iVR). Collaborative online iVR is used in this research as a key instrument for enhancing understanding and reinterpreting the digital records of two archaeological sites under excavation in Peru. The case studies analyzed show a variety of cultural, geographic, and temporal contexts in the Andean region, which illustrates the broad potential of iVR for archaeological hermeneutics. Through iVR frameworks, the authors engage with embodied reconsiderations of Catholic ritual spaces within a planned colonial town in the southern Peruvian highlands and the pre-Columbian site of Huaca Colorada on the north coast. Synchronous scalar experiences that privilege the affordances of architectural space within digital models create opportunities for embodied experience and collaborative dialogue. A fundamental argument is the capacity to digitally inhabit these places and manipulate materials holds subtle as well as profound epistemological and hermeneutic implications for archaeological knowledge construction.

Keywords: virtual reality; interpretation; embodiment; photogrammetry; Andean archaeology; cultural heritage; 3D documentation

Resumen:

Con la llegada de modelos tridimensionales (3D) de muy alta resolución, a través de técnicas fotogramétricas como método principal de documentación arqueológica, la construcción de simulacros inmersivos de alta fidelidad está inminentemente al alcance. Este documento considera cómo la escala a la que el cuerpo humano interactúa con los modelos digitales inmersivos es especialmente importante para comprender las posibilidades y la ergonomía de las cosas y los lugares del pasado. Tanto las implicaciones de esta isometría entre los objetos arqueológicos de análisis, como las capacidades emergentes de interactuar con ellos son múltiples en el presente a través de sustitutos digitales. Al permitir la interacción con objetos y contextos en un espacio virtual inmersivo, tales experiencias de observación crean compromisos *in silico* que son repetibles, distribuibles y colaborativos. En particular, es la capacidad colaborativa de esta tecnología la que se explora en este documento, a través del uso de la realidad virtual inmersiva (iVR) en línea. En este trabajo se usa la iVR en línea colaborativa como un instrumento clave para mejorar la comprensión y reinterpretar los registros digitales de dos sitios arqueológicos bajo excavación en Perú. Se presentan estudios de caso de dos contextos culturales, geográficos y temporales distintos, ambos en la región andina, para ilustrar el amplio potencial de iVR en la hermenéutica arqueológica. A través de los marcos iVR, se crea un compromiso con las reconsideraciones encarnadas de los espacios rituales católicos; estos se ubican dentro de una ciudad colonial planificada en las tierras altas del sur de

*Corresponding author: Giles Spence Morrow, giles.spence.morrow@vanderbilt.edu

Perú y el sitio precolombino de Huaca Colorada, en la costa norte. Las experiencias escalares sincrónicas, que privilegian las posibilidades del espacio arquitectónico dentro de los modelos digitales, crean oportunidades para la experiencia encarnada y el diálogo colaborativo. Se argumenta que la capacidad de habitar digitalmente estos lugares y manipular materiales tiene implicaciones epistemológicas y hermenéuticas sutiles, así como profundas, para la construcción del conocimiento arqueológico.

Palabras clave: realidad virtual; interpretación; encarnación; fotogrametría; arqueología andina; patrimonio cultural; documentación 3D

1. Introduction

Immersive Virtual Reality (iVR) enables interaction with digital surrogates of archaeological materials and spaces on multiple scales. Inspection of artifacts, examination of excavation strata, exploration of buildings, built environments, and landscapes is now imminently possible through iVR frameworks. These digital interactions recruit distinct human perceptual and cognitive systems compared to 2D and non-immersive 3D graphic representations. iVR engages binocular depth perception and sensorimotor systems by enabling physiological engagement with the entities represented, as the body of the participant occupies the same perceptual space as the phenomena of interest. In so doing, iVR enables proprioception in the interpretive process, as the body itself becomes a vehicle of observation and knowledge production. Notably, the sensorimotor and proprioceptive aspects of iVR operate independently of scalar engagement. Even in fields of study in which the objects of observation are of a radically different scale from human experience —for example, protein crystallography— novel forms of knowledge and expertise emerge uniquely through corporeal interaction with intricate digital representations. In this field, Myers (2008) refers to the expertise that emerges from sustained bodywork and proprioception in relation to digital models of protein molecules as “molecular embodiments” (Myers, 2008; Cassidy, Šefčík, Raghav, Chang, & Durrant, 2020). The enriched cognitive effects of iVR are also attested by its demonstrated advantages in diverse applications in learning outcomes (Alfaro, Rivera, Luna-Urquizo, & Fialho, 2019), training (Burin, Liu, Yamaya, & Kawashima, 2020; Frederiksen et al., 2020; Parong & Mayer, 2018; Varela-Aldás, Palacios-Navarro, Amariglio, & García-Magariño, 2020), and rehabilitation (Aida, Chau, & Dunn, 2018; Appel et al., 2020; Bauer & Andringa, 2020; Carnevale et al. 2023; De Luca et al., 2022; Ou et al., 2020; Sayma, Tuijt, Cooper, & Walters, 2020).

In the case of archaeological analysis and interpretation, we suspect that the scale at which the human body interacts with the environment is especially important for understanding the affordances and ergonomics of past things and places (Chemero, 2003; Eve, 2014, 2017; Gibson, 1977; Gibson,1979; Gillings, 2009; Gillings, 2012; Heft,1989; Llobera, 1996; Stoffregen, 2000, Stoffregen, 2003; Wernke, Kohut, & Traslaviña, 2017). There are multiple implications for how our understanding of archaeological objects may be affected by emerging capabilities to interact with them through collaborative iVR venues. Primarily, iVR enables interaction with objects and contexts in a shared immersive virtual space between multiple participants, extending important investigative modes of embodied consultation, debate, and consensus building. Secondly, iVR interactions with high-fidelity 3D archaeological contexts enable embodied observational experiences that are similar to the primary process of observation and data construction during fieldwork. Finally, such engagements are repeatable and distributable, inviting remote access to stable digital surrogates of excavation contexts. As excavation is a destructive process precluding recurrent in situ observations, the capability to create high-fidelity 3D models of excavation contexts and to repeatedly interact with them in ways that are phenomenologically congruent with the experience of primary observation “at the trowel’s edge” holds transformative potential (Díaz-Guardamino & Morgan, 2019; Perry, Taylor, Matsumoto, & Uleberg, 2018). We believe these aspects hold subtle but profound epistemological, hermeneutic, and ethical implications for archaeological knowledge construction. Further, we believe the underlying technologies to produce iVR have now matured to the point that they need not be the exclusive preserve of technical specialists, nor require expensive, specialized equipment. In fact, high-fidelity iVR environments and assets can now be produced with equipment that is more cost-effective than traditional land survey instrumentation. Affordable consumer-grade digital cameras (even cell phone cameras), tablets, and other portable sensors can produce high resolution iVR models. Yet iVR largely remains in the category of a rather exotic or novelty add-on for most archaeological research, employed by large, long-term projects with multiple specialists (Richards-Rissetto and Landau, 2019; Morgan, 2022). We contend that now even small-scale projects can readily incorporate iVR asset production, management, and display into their workflows. In this paper, we focus specifically on the implications of iVR for the construction of archaeological knowledge from two excavation contexts. Although this paper utilizes digital methods in the construction of these iVR interactions, our aim is not to offer a technical workflow for the production of the models themselves (a topic covered in detail by several others; e.g. Cassidy, Sim, Robinson, & Gandy, 2019; Kotoula, Robinson, Gandy, & Jolie, 2019; Gushima & Nakajima, 2021; Lang, Hussein, & Kluge, 2023; Lombardo & Lauro, 2022; Rahaman, Champion & Bekele, 2019; Quinio, Boulbes, De Pechpeyrou, & Kotras, 2020). In contrast, we use this opportunity to discuss the nature of an embodied virtual archaeology through iVR in the setting of excavation contexts, and its broader applicability in landscape-scale and portable media-scale research.

2. Archaeological bodywork

In archaeological fieldwork, the human body and its perceptual apparatus are among the most important instruments of observation and interpretation. Though little remarked upon, much of the work of field-based archaeological interpretation originates in corporeal engagement with the ruins of built features through researchers' tactile interactions with contexts, features, and artifacts in situ. But the tactile and physical interaction with archaeological contexts and media is fleeting. The emergent understandings from such engagements thereafter reside in the excavator's memory, and as variably represented in field notes, field forms, photographs, sketches and maps. Thus, after the primary moment of observation in the field, much of the archaeological interpretation involves tacking between one's memories of excavation contexts and various textual, graphic, and quantitative representations. This process at once calls on remembered experience while partially transforming those memories themselves through repeated review of documentation. Archaeology (and anthropology more generally) thus constructs knowledge through a "double hermeneutic": it investigates the co-constitution of people, polity, and things in the past even as archaeological investigation itself is mediated by the same kind of co-constitutive process between researchers and the representational technologies of observation (Giddens, 1987, pp.30; Johnsen & Olsen, 1992; Shanks & Tilley, 1987). The history of archaeological techniques of representation might be characterized as a cumulative effort to improve upon schematic and data-poor representations toward increasingly detailed and data-rich ones.

Within this framing, iVR models of archaeological excavation contexts represent a qualitatively distinct development as they uniquely enable immersive interaction with 3D digital surrogates of features, spaces, and things at environmental scale (Montello, Waller, Hegarty, & Richardson, 2004; Simpson, 2020, pp.105); that is, at the same scale as their original context of creation and use. In this important sense, iVR comes closest to simulating original field engagements with archaeological phenomena. This essential feature of iVR has major implications for our ability to (re)experience the places constructed and used by peoples in the past, and for revisiting those places as new knowledge and frameworks of understanding emerge (Carter, 2017; Huggett, 2015; Perry et al., 2018; Robinson, Rosemont, Gandy, & Cassidy, 2021). The controlled scale of the participant is of key importance to the overall experience of the setting, for example allowing for immediate appreciation of spatial ergonomics of excavation units and stratigraphic profiles and lines of sight between and within modelled contexts. Additionally, the ability to manipulate the scale of reference elements within iVR environments provides enriched investigative and interpretive potential. As will be discussed in our case studies, the use of reduced scale models of the entire modelled setting while standing within the full-scale version provided participants a shared embodied understanding of a particular room within a complex architectural compound.

The veracity of photogrammetric models of archaeological settings is key to this sense of "presence" both in terms of scale and the level of surface detail. Certain thresholds in morphological and textural sampling are needed to achieve such "presence", with texture quality of utmost importance (Pujol & Champion, 2018). Depending on the context, a relatively simple mesh overlaid with a high-resolution texture may suffice to bring the viewer into the presence of the original context. In others, the complexity of the surface morphology may require a higher polygon count mesh to reach the same level of presence.

The presentation of archaeological data through iVR raises several curatorial concerns. How iVR data are maintained and made manifest to the participant within the virtual setting requires careful consideration with regard to information design and management. Traditional interaction with archaeological data through consultation of site monographs, technical reports, and databases includes both narrative and exploratory modes of access requiring logical presentation alongside the ability to query tables, appendices, and original notes. GIS is often central for managing and analyzing the spatial representations and attribute data of excavation projects. A spectrum of complementary workflows and relationships between iVR and these established modalities can be imagined. Simply standing within a high-resolution excavation model alone may provide the participant enrichment of fieldnotes or GIS-based spatial models, tacking back and forth between narrative and other graphic representations. Marked features within a model with hyperlinks to other datasets could further enrich and guide the experience. Recorded narrative guidance by the original excavator can provide a more nuanced appreciation of a research setting. Live collaborative discussion within iVR among colleagues can enable real-time discovery and interpretive insights. Just as an in-person site visit provides an important understanding of excavation from an embodied perspective, we argue that the capacity to guide users in and through an iVR model provides unique interpretive and collaborative opportunities. Without question, the iVR interfaces we discuss in this paper would be ideal venues for quantitative and qualitative data collection in the realm of user experience studies, however, this is beyond the scope and focus of the current study of the interpretive potential of iVR within full-scale archaeological models.

3. Interpretation at the point of the cursor

During active archaeological excavation, interpretation is emergent as excavators progressively uncover contexts. Understandings evolve and are revised as relationships between constituent elements (features, artifact distributions, etc.) may be grasped within a larger whole as an excavation unfolds (Hodder, 1999). Project directors are often more limited in their tactile engagement with excavation matrices and features in the field, as they rely on excavator observations while maintaining a panoramic view across individual excavation operations. Subsequent to initial observations during excavation, interpretations evolve through the interaction of the memory of the excavator, aided by notes, maps, images, video, and so on, without ever coming into contact with the (now destroyed) primary contexts themselves.

Traditional stratigraphic recording relies on interpretation of the interface between materials excavated and the remaining in-situ walls. In this way, our interpretations are based upon material that is in effect, not part of the excavation, but rather their presence in plans, profiles, sketches, tables, and notes (see Opgenhaffen, 2021). Stacked photogrammetric models of superimposed excavation layers can be appreciated on the screen, but the ability to stand within and peer through strata provides an embodied experience of stratigraphy that we argue can transform post-field archaeological interpretive processes.

With the advent of iVR models of excavation contexts, interpretations can be further refined and revised through repeated immersive revisitation of a digital surrogate of a context (Dell'Unto & Landeschi, 2022; Derudas & Berggren, 2021; Reinhard, 2019; Reinhard & Zaia, 2023). Comparison of strata are usually based on changes in elevation or relative superposition rather than embodied experience of multiple phases at the same moment. With a 3D model of each surface available in iVR, virtual cuts through strata can be made at any angle, enabling scrutiny of stratigraphic relationships that would be otherwise impossible to observe.

With the emergence of very high-resolution 3D textured models—usually via photogrammetric methods, but also through various scanning techniques—as a primary method of archaeological field documentation (Magnani, Douglass, Schroder, Reeves, & Braun, 2020; Sapirstein & Murray, 2017; Roosevelt, Cobb, Moss, Olson, & Ünlüsoy, 2015), the construction of high-fidelity iVR environments is now within reach. The advent of cloud-based processing of photogrammetric data through a growing number of commercial and open-source photogrammetric software suites (RealityCapture, Pix4D, DroneDeploy, Autodesk ReCap, 3DF Zephyr, VisualSFM, MicMac, OpenMVG, Meshroom) has also facilitated access to sufficient computational resources required to produce them.

Although now widely produced, the modes by which 3D data are disseminated remain restricted. Given the large file sizes of the high-resolution models and the proprietary software and expertise often required to engage with these reconstructions, few user-friendly options are available to easily examine the resulting data. Among these, the web-based Sketchfab platform (Sketchfab.com) has taken the lead in the cultural heritage sector as an accessible venue for hosting 3D models of objects and environmental scale contexts (Hess, Colson, & Hindmarch, 2018; Statham, 2019). Sketchfab offers browser-based manipulation of uploaded models, the capacity to download data if given proper permissions, and most importantly, a relatively seamless integration with virtual reality hardware through the WebXR Device API (https://immersiveweb.dev/). As the dominant 3D platform within the cultural heritage sector, Sketchfab is a useful conduit through which data can be accessed and appreciated, however there is relatively little the viewer can do with these data beyond consumption of interpretations via information panels, animations, and embedded audio. This unidirectional interaction with 3D media on screen-based and iVR devices precludes manipulation of orientation, scale (apart from positional scale) or note making, image capture or measurement. Embodied experiences of media within these digital environments are also solitary; users can only observe the set environment or object by themselves. From this perspective, interaction with collections through Sketchfab is museological in nature, as the platform is not designed for fully exploratory immersive interactions, nor for synchronous interaction with other users.

4. Collaborative digital interpretation

Massively multiplayer online role-playing games (MMORPG) have an enduring presence in the iVR medium, ranging from Fortnite and Roblox, through Call of Duty, World of Warcraft, and other titles that allow players to interact within detailed and complex virtual worlds (see Aycock, 2021; Reinhard, 2018; Reinhard, 2019 and see Morgan, 2021 for discussion of "Archaeogaming"). This familiarity of online, disembodied interaction has been recently extended into iVR platforms as optional additional hardware components to popular gaming platforms such as the PlayStation 5. Generally, the bar to entry for such systems is high, requiring considerable initial investment in both high-end gaming desktops and virtual reality systems. Early lower-budget options such as the Oculus Quest 1, Oculus Go, and various phone-based options such as Google Cardboard were widely adopted but quickly abandoned due to the limitations of their processors. In 2020, the introduction of the Meta Quest 2 drastically changed the iVR market, offering a cost-effective and relatively high-performance on-board processor. This movement to standalone iVR processing has opened opportunities yet has recently faltered in adoption. Meta's investment in the creation of a singular commercial Metaverse has been widely criticized, however developments from both Meta (Meta Quest 3, Meta Quest Pro) and Apple (Apple Vision Pro) with an eye on a more inclusive Augmented Reality (AR) and Mixed Reality (MR) offer promising directions forward. Multiple options are readily available within hardware-specific applications, however, require all users to interact with the material in solitary iVR, limiting the broad utility of the resultant data in a collaborative setting (Bekele & Champion, 2019; Champion & Rahaman, 2020; Forte & Kurillo, 2015; Wilkins, 2020; see De Bonis, Nguyen, & Bourdot, 2022 for an excellent review of current literature on user experience). Here we outline some of the collaborative VR platforms that support the import of digital assets that we explored prior to choosing Spatial.io as our preferred venue for archaeological iVR interactions.

SketchBox: https://design.sketchbox3d.com/

Models uploaded to the Sketchbox platform are viewable in an iVR setting, scaled, annotated, and shared, allowing for measurements to be taken within the models, including the capacity to take "photographs" within the scenes to capture specific elements for posterity. This platform allows remote users to interact simultaneously within a given 3D scene as highly simplified avatars. As this platform is geared towards collaborative manipulation of 3D assets for video game development, one of the most useful components of the interface allows users to upload individual models as "scenes" or layers that can be toggled on and off.

MeetinVR: https://www.meetinvr.com/

The MeetinVR platform allows for remote co-working within 3D spaces, however, a subscription is required to upload personal data. This platform is an entirely VR application without a desktop option for non-VR participants.

Mozilla Hubs: https://hubs.mozilla.com/

The Mozilla Hubs platform allows multiple users to import models as navigable spaces for collaborative interaction, including on demand imports from linked Sketchfab accounts. As this platform is open-source software, there is very low barrier to entry. However, the user experience does not lend itself to high resolution models nor does it allow for fluid interaction between participants.

StellarX: https://www.stellarx.ai/

The StellarX platform holds great potential for collaborative interaction across several VR platforms as well as desktop interaction, however it was not ideal for our purposes. Although relatively high-resolution models can be imported, an expensive subscription is required for full development of interactive VR spaces amenable to a classroom setting. As well, the complexity of editing tools within VR setting became a barrier to fluid interaction in our tests.

Meta Horizon Workrooms:

https://forwork.meta.com/horizon-workrooms/

Due to a lack of realism, the initial release of Meta Horizon Workrooms was heavily criticized and suffered from low user uptake. This platform was designed primarily as a hybrid video meeting format, with desktop users joining as video and audio participants with a static view of the proceedings. Although flexible in nature, this platform was not able to support the resolution of our models required for immersive collaboration.

Spatial.io: https://www.spatial.io

Formerly a multi-platform system with interoperability between HTC Vive, Nreal, and Microsoft Hololens systems, this platform currently supports only Meta Quest iVR products. The overwhelming dominance of Meta products in the consumer iVR market limits Spatial.io in some ways. However, the robust web-based desktop and mobile options for interaction creates by far the most user-friendly option available.

Spatial.io, launched in 2019, is a recent entry in the online iVR space. It is designed as a collaborative interface primarily for virtual co-working, meeting, and presentation, and has developed into a premier platform for artistic and cultural exhibitions. As a true open world environment, the flexibility of its interface is key, as participants are able to join a given space in iVR or on a desktop as avatars who can navigate within a 3D virtual audience space. Interaction in Spatial.io through desktop and mobile platforms requires locomotion though mouse and keyboard controls. This allows users to view the scene in either point-of-view or at a distance above the participants through a modifiable perspective that brings a rich, if not fully embodied experience of the subject. Such a "2.5D" experience of a given setting through the plane of their screen is familiar and serves as a starting point prior to full immersion in iVR. Participants engaging with the spaces in this browser-based format can manipulate all objects and media imported into the scene, albeit with less nuance, and only in linear cartesian space and planar rotation.

True immersive interaction for those with the required iVR hardware allows those participants to manipulate objects more naturally and from an embodied first-person perspective. Models in a variety of formats can be imported into the scene by any participant, manipulated, scaled, annotated, and documented through both "photographic" simulacra, or even as video captured from an iVR participant's point of view. Although collaborative immersion is by far the most engaging format by which these models can be experienced, this platform also has the capacity to upload video recordings of guided first-person tours of contexts within the same virtual space, allowing participants to interact within the models while detailed explanation is provided at their own pace.

Unlike many previous stand-alone iVR applications that require download as a single executable file (Carter, 2017; Ellenberger, 2017; González-Tennant, 2010), Spatial.io scenes are built within digital spaces that are made available on external servers to all users invited to a given setting, regardless of the mode of interaction. The spaces created by this form of server-based interaction are venues for real-time interaction. Users can experience these settings as loci for natural interaction and manipulation of assets if permissions to do so are enabled by the creator. All changes made within a space are maintained as they are left by the participants, allowing for continuous and evolving interaction over time through imported media, notes, and in-application "photographic" captures. Versions of the space can be saved at any juncture, and "portals" can be placed within scenes allowing users to travel to other digital spaces. The locational persistence of assets imported into the iVR setting is of vital importance in such an ongoing collaborative workspace as this provides users the opportunity to return to a given session of exploratory interaction.

Below we sketch our workflow for generating and managing assets and environments in Spatial.io. In both case studies, overlapping photographic imagery was used to generate photogrammetric 3D models of each excavation context. The following basic workflow was employed to bring the excavation contexts into Spatial.io:

1) In-field photogrammetric photography was conducted using pole-mounted digital single-lens reflex cameras (DSLR or reflectorless interchangeable lens cameras), with which overlapping vertical shots were taken and supplemented by handheld monopod-mounted obliques, as necessary. Photogrammetry image capture was conducted for each excavation locus (defined as the minimal unit of provenience; any discrete context composed of a distinctive excavation matrix and/or feature element). Spatial control was achieved via ground control point targets which were precisely located relative to Universal Transverse Mercator (UTM) coordinates via total station, or Real-time kinematic (RTK) Global Navigation Satellite Systems (GNSS) receivers.

2) Agisoft Metashape Pro v. 2.0.0 was used to generate photogrammetric models of each excavation context in UTM coordinate space at a resolution that best suited the particularities of the excavation at hand.

3) The resulting models were exported in GLTF (Graphics Library Transmission Format) to reduce file size and to compress textures. File size requirements set out by Spatial.io suggest best practices for generating models that are less than 60MB in total size with a maximum of four 2048 x 2048 px textures per file. High-polygon, high-texture models requiring greater memory usage could result in slower load times limited by the processing capacities of the Meta Quest 2 hardware.

4) If required, the resulting models were first manipulated and scaled in Blender v. 3.5.1 when multiple models were required to be combined in static relation to each other prior to importation into a singular virtual scene.

5) Once the models were saved in GLTF format, importation into a Spatial.io scene was accomplished in one of two ways. The first option simply requires the model

file to be dragged and dropped into a browser-based version of a given virtual scene prior to immersive interaction. The second option involved importation from within the immersive VR space through an easily navigated content portal visible within the user menu that is seamlessly connected to cloud-based drives such as Google Drive, Microsoft365, or from a linked Sketchfab account.

6) All digital assets imported into an iVR setting could be variably locked and unlocked, allowing users to control who was given permission to make adjustments. Alternatively, any digital asset could be scaled and set as the “Environment” such that the entire model was used as surface collider to allow participants to “stand” on all horizontal surfaces.

7) Image, video capture and annotation tools were available to both iVR and desktop/mobile users which allowed participants to document particular views, write or dictate notes and observations that persisted within the scene.

8) Various other textual, image or video media (PDF, JPG, MP4) were easily imported as planar 2D objects within the virtual space itself. The capacity to import fully manipulable multi-page PDF documents as a resource while investigating excavation contexts was of considerable value, as will be highlighted in the case studies that follow.

5. Case studies

We explore the implications of the availability of such collaborative iVR platforms through two case studies examining multiple excavation phases of research conducted at the planned colonial town of Mawchu Llacta (Wernke) and Huaca Colorada (Spence Morrow). Excavations of these sites took place between between 2016 and 2022, with each research strategy employing photogrammetric documentation throughout each field season. Previously, the resulting high-resolution 3D models of multiple phases of excavation were used by both projects in the production of orthomosaics and Digital Elevation Models (DEM) within project GIS databases, which were, in turn used for digitizing vector-based graphical representations and registry of attributes such as field notes and other observations. Additionally, manipulable, and annotated 3D models were produced and made available through Sketchfab.com as embedded hyperlinks to allow reader interaction as supplemental material.

In 2016 and 2017 both projects made initial forays into immersive interaction within these models in Virtual Reality using Oculus and HTC Vive head mounted displays running on desktop computers. In both cases the models were experienced at 1:1 scale, and entirely as solitary experiences that could be observed by colleagues as a live point-of-view feed to external monitors. These early iVR experiments underlined the interpretive utility of embodied immersive experiences, however, the limitations of available hardware and the nature of software integrations required considerable initial effort to create relatively simple virtual environments. By 2020, the availability of cost-effective Meta Quest 2 headsets and the highly accessible Spatial.io iVR software platform allowed the authors the most viable venue to revisit models from a fully collaborative perspective.

Below we present two case studies from very different geographic, temporal, and cultural contexts in the Andes to illustrate the breadth of the utility of iVR for extending and enriching the analysis and interpretation of architectural and excavation contexts. To this end, first, we present a case study at the Colonial period site of Mawchu Llacta, followed by a second consideration of the Middle Horizon Period Moche culture site of Huaca Colorada.

5.1. Mawchu Llacta

The town of Mawchu Llacta —originally the *Reducción de Santa Cruz de Tuti* (also known as *El Espinar de Tuti*)— is located in the high reaches of the Colca Valley of southern highland Peru (Caylloma Province, Arequipa Department) at an elevation of 4100 m.a.s.l. (Fig. 1).

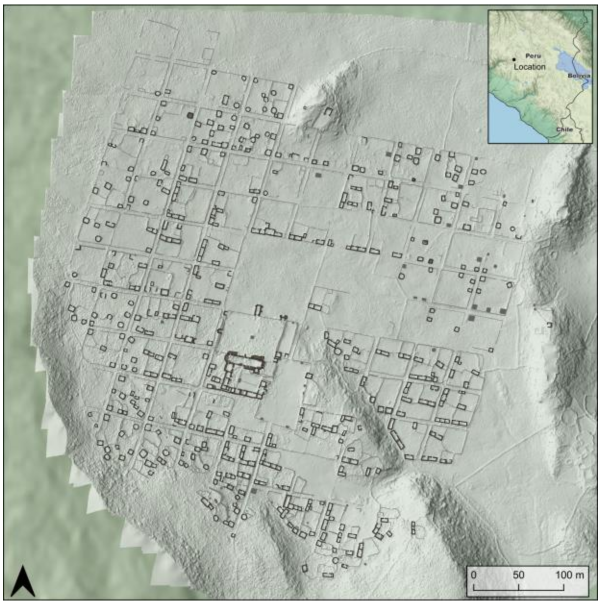

Figure 1: Location map and plan of Mawchu Llacta.

This large, gridded settlement measuring roughly 500 m x 500 m is an unusually well-preserved example of a planned colonial town, built as part of a viceroyalty-wide forced resettlement program instituted in Peru by the Viceroy Francisco de Toledo in the 1570s (Wernke, 2015; Wernke et al., 2017; see also Mumford, 2012 on the history of resettlement during this period). During this mass resettlement program, over 1.4 million Indigenous Andean people were compelled to build over 1000 “*reducción*” (literally: “reduction”) towns built around central plazas, churches, and civic complexes. Traditional homes were razed and new ones were built within these *reducciones.* This audacious *Reducción General de Indios* (General Resettlement of Indians) was motivated by a normative theory of the built environment which posited that the implementation of certain urban forms and spaces would generate proper social order —*policia*— and compliant, Christian indigenous vassals and tributaries (Mumford, 2012; Wernke, 2013). With its unusual state of preservation, combined with a large corpus of related archival documents, Mawchu Llacta affords the opportunity to document and analyze the built environment of a *reducción* in detail (Fig. 2) (see Wernke, 2015; Wernke et al., 2017).

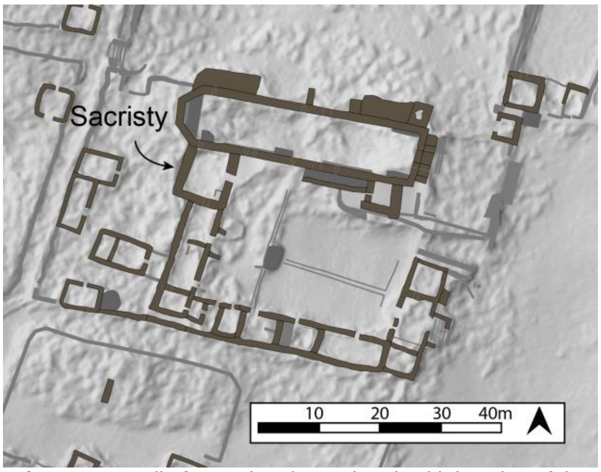

Figure 2: Detail of Mawchu Llacta church with location of the sacristy highlighted.

Intensive site survey and drone-based photogrammetry in 2013 and 2014 were followed by excavations in 2016. Excavations were documented photogrammetrically throughout the process of investigation, resulting in hundreds of locus models from eleven excavation units. Within each excavation area, a sequential stack of excavation models was combined in Blender and exported in a variety of temporal orientations to allow for specific strata to be viewed in the same iVR scene. A subset of these combined models was reprocessed in Agisoft Metashape Pro and exported in the GLTF file format amenable for direct import into the Spatial.io iVR platform. Drone-based photogrammetric models of the entire site were also processed for import into Spatial.io and served as a navigable scalar environment within which the excavation specific models were situated. By incorporating a site-level model within the iVR scene, the experience of intervisibility between structures and their relative location within the local environs clarified the nature of post-abandonment processes. As all of the excavations at Mawchu Llacta took place within spaces enclosed by standing walls of buildings with known general function (for instance, domestic structures, church nave, sacristy, rectory) in different states of preservation, knowledge of the state of the enclosing structures immediately clarified variations in the depths of initial surface overburden (Fig. 3).

Were the models of excavation surfaces presented only as isolated floors, these relationships to standing architecture would not have been as easily apprehended. Instead, the consultation of aerial and ground-based photographs taken from specific angles, and the close reading of site report entries to determine wall heights adjacent to particular areas of excavation would have been required. In comparison to traditional text and image-based interpretation of site records, iVR interaction within such a carefully curated space allowed for a relatively immediate comprehension of taphonomic processes. When these spaces were consulted in collaborative capacity in iVR, the original excavation director (Wernke) guided the observer (Spence Morrow) through a detailed recontextualization of each phase of excavation, highlighting notable excavation loci and the variable preservation of architectural features as a result of depositional processes (Fig. 4).

Figure 3: Authors collaborating in Spatial.io inspecting collapsed overburden of the Mawchu Llacta sacristy.

Figure 4: Collaboration in Spatial.io comparing excavation phases of the Mawchu Llacta sacristy.

Of particular note was a rectangular depression in the floor of the church sacristy, adjacent to the chancel of the church. This stone-lined recessed area measured approximately 2.97 m in overall length and 1.25 m in depth from the wall, a space that was suspected to have served as the foundation for a vestuary, a large bureau in which liturgical vestments are stored in Roman Catholic sacristies. Church inventories from the late 18th and early 19th centuries include narrative descriptions (including dimensions and construction details) of the church, sacristy, and adjoining rectory complex, with detailed listings of sacramental objects and furnishings, including a vestuary. Following the abandonment of the site of Mawchu Llacta in 1843, the contents of the original church were relocated into a newly constructed church located 4km downslope in the modern town of Santa Cruz de Tuti. A survey of furniture in the modern sacristy included a chest of drawers that was long suspected to have once been installed as the vestuary in the Mawchu Llacta sacristy under excavation. To test this hypothesis, a digital twin of the vestuary was created in Blender based on photographs and measurements of the relocated chest. When brought into the iVR scene of the sacristy excavations in Spatial.io, the vestuary proved to fit perfectly within the floor depression (Fig. 5).

Figure 5: Point of view perspective of collaboration in Spatial.io during placing of 3D model of a vestment chest model the Mawchu Llacta sacristy.

Digital relocation of this object to its original intended location provided the authors an opportunity to reassess the assumed orientation of moveable objects in the sacristy space, not in an effort to fully recreate the lived experience of the room, but as proof of concept in the capacity to think through relationships of room orientation in a manner that would be impossible in any other format. This kind of hermeneutic operation could be repeated on many other items in the church inventory, as its contents were transferred from the old church to the new one, and many remain there today.

5.2. Huaca Colorada

The site of Huaca Colorada is located in the Jequetepeque Valley on the North Coast of Perú, dating to the Late Moche Period (ca 650-950AD). Directed by Dr. Edward Swenson of the University of Toronto and Francisco Seoane of the Universidad Nacional de Trujillo between 2009 and 2022, the excavations of Huaca Colorada focused on the sequence of architectural reconstructions of a monumental adobe brick platform structure that served as a ceremonial stage for generations of religious performance (Spence Morrow, 2019; Swenson, 2018). Research at this site clarified that each phase of occupation was punctuated by comprehensive renovation events that encased previous structures in a well-defined and complex stratigraphic sequence of overlaid walls, floors and fill events. Broad horizontal excavations in three sectors expanded over each year of investigation, allowing considerable cumulative stratigraphic relationships to be recorded. Beginning in 2012 all excavations were documented photogrammetrically, creating a considerable database of 3D models of the excavation contexts. The resulting models were used to relate stratigraphy between years by digitally compiling each model in a shared coordinate space. Interactions with these composite spatial models served as powerful interpretive tools in the preparation of site reports and publications. Beginning in 2017, the capacity to virtually revisit the complicated stratigraphy once imported to Sketchfab and viewed through an HTC Vive VR system underlined the utility of this emerging technology as a viable archaeological tool.

Subsequent collaborative explorations of these data in Spatial.io allowed project members to compare the stratigraphic relationships of two contiguous research areas that were excavated in 2016 and 2018 during the planning for continued research in the same sector in 2022 (Fig. 6).

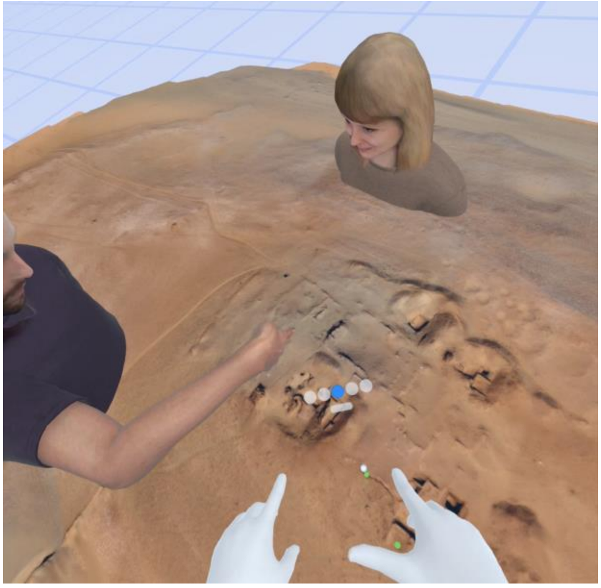

Figure 6: Point of view of collaboration with colleagues in relation to a scale model of Huaca Colorada in Spatial.io.

Embodied interaction within these temporally separated excavations allowed for clarification of the relationship of continuous stratigraphic levels that proved difficult to connect conceptually from site reports alone. Based upon these collaborative interpretive sessions, the location of where new excavation units would be placed in the 2022 campaign were made (Fig.7). During excavations, the capacity to import photogrammetric models into the iVR scene in Spatial.io allowed for continuous comparison of previously excavated units on a daily basis. As Spatial.io requires a stable internet connection to allow interaction with the server-based scene, a review of daily progress was conducted in our field laboratory following photogrammetric processing of daily photograph sets. The capacity to constantly update the iVR scene and share results online throughout the excavation campaign allowed project collaborators in the field in Peru to virtually collaborate with colleagues in Toronto and Nashville in decision-making that directly affected excavation strategy (Fig.8). In concept, it would be entirely possible to use Spatial.io in iVR as a resource during active excavations with suitable internet access. In this particular case, the remote location of the field site limited internet connectivity, and harsh environmental conditions of blowing sand and strong equatorial daylight were not amenable to using the Meta Quest 2 in the field. However, in practice, the excavation team was able to use the mobile version of Spatial.io to consult modelled scenes in first person perspective through AR versions of the contexts as a valuable resource when required. Upcoming hardware developments of field-ready VR / AR headsets would open great opportunities for seamless interaction with such datasets.

Given that photogrammetric models of every context were recorded during the process of excavation, project members were able to immersively consult particular components during the preparation of the subsequent field report for the Peruvian Ministry of Culture following the closure of excavations. This capacity to revisit a fleeting moment in time allowed excavators to revise notes, reinterpret relationships, and seek second opinions from colleagues who were not present on site. The capacity to compare temporally and spatially separated data in a fully embodied fashion fundamentally changes the way that a site is understood. From this perspective, in the future, making such data available in an immersive format could easily become a requirement in archaeological data management and a powerful mode of accountability within the cultural heritage community.

Figure 7: Collaborations between authors in Spatial.io during inspection of multiple phases of excavation at Huaca Colorada.

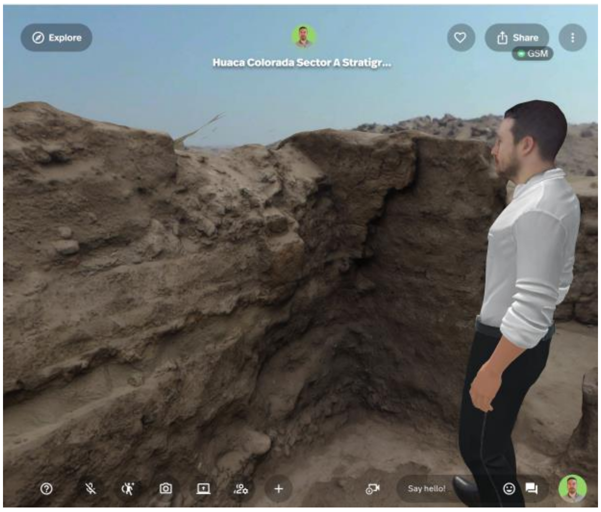

Figure 8: Inspection of Huaca Colorada stratigraphic profile in Spatial.io.

6. Conclusions: collaborative VRchaeology

VR is now a viable interface for archaeological research and holds transformational potential in archaeological interpretation and knowledge production. We are no longer limited to Cartesian representations of archaeological spaces, nor even non-immersive subject-centered ones. We may now discuss subjective experience of archaeological spaces in real time with others, inspect, and re-visit spaces with new knowledge, and investigate stratigraphic and proxemic questions at varied scales —even in ways that are not possible during fieldwork. The rapid evolution of mobile VR has opened opportunities that are only limited by the quality of the software interface used to interact with these media. Powerful desktops connected via cable to bulky headsets are no longer compulsory. Previously, photogrammetric models could be brought into video game engines such as Unreal Engine or Unity, loaded as a single program and experienced alone (Carter, 2017; González-Tennant, 2010). In these systems, projects were run locally, which tended to silo users apart from one another and limited collaborative potential. The recent emergence of web-based multi-user platforms opens new avenues for collaborative interaction in iVR.

Of the options explored, the Spatial.io platform was the most approachable and well-designed venue for synchronous collaboration between participants in fully immersive settings. The user-friendly interface of Spatial.io allows for data to be introduced, inspected and manipulated at various scales in a highly intuitive manner. The experience of virtual archaeological spaces through these platforms allows users to apprehend proxemics and spatial relationships within and across archaeological contexts in an embodied fashion that is qualitatively similar to the primary experience of being present at the site itself. A single session between researchers in such a collaborative space allows for a deeper knowledge of the context than by text alone, opening proprioceptive and experiential aspects of contexts that are not accessible via 2D and 2.5D representational modalities. Full immersion in iVR is by far the most engaging format by which these models can be experienced, however, the flexibility of user interaction via desktop and mobile interfaces provides various configurations of collaboration. Video or audio recordings of guided first-person tours embedded within Spatial.io virtual environments allow participants to collaboratively interact with models, while also watching or listening to such media as supplementary materials. From this perspective, future research directions will focus on the utility of Spatial.io as an interface for virtual class enrichment, and how it may allow for the collection of expanded qualitative data on user experience.

With the emergence of these new potentials and capabilities come new challenges. Increasingly, 3D models are incorporated into project websites and extended digital media as hyperlinks within publications, but all these representations stand outside of the embodied experience of the places and objects in question. If a picture is worth a thousand words, a model may be worth a thousand pictures —that is, if we recognize the value of embodied experience in archaeological interpretation. But is an embodied experience in a virtual archaeological space also somewhat ineffable? We argue that the capacity to discuss and debate the experience of an archaeological space in real time in a high-fidelity iVR simulation opens generative potential for the emergence of inter-subjective understandings that would otherwise not be possible.

In this sense, we agree with Huggett's (2015) critique of the overweening Cartesian mode of representation in archaeology, citing Haraway's "God trick," which "sees everything from nowhere" (Haraway, 2013). Here, the potential is to produce a homologous phenomenal experience to that of being emplaced within the contexts of the past, both the subject past, and the moment of excavation. Moreover, from within a collaborative iVR space, perspective is rendered effable through discussion and made mutable through active scaling of representations from the miniature to the environmental scale. In this way, one very much "sees everything from somewhere". This tacking back and forth through scale and experience is one that truly has no comparable representational modality. Within an iVR space of an archaeological excavation, we are able to collaborate with colleagues separated by great distance while concurrently consulting the same models, maps and GIS data. In essence, through this technology, we return to the fundamental phenomenology of research spaces and the interpretation that occurs within these conditions.

In our opinion, the capacity for iVR in archaeology rise to most of Huggett, Reilly, and Lock's (2018) "Grand Challenges": it is *Fundamental* (addressing theory and practice), *Innovative* (using techniques specifically designed for archaeology), *Revolutionary* (paradigm changing, with new technological competencies and ways of knowing), *Inspiring* (engaging across the sector and beyond), *Measurable* (with intermediate goals to gauge progress and achievement), and most importantly, *Co-operative* (involving more than just an individual researcher or team and crossing national and potentially disciplinary boundaries) (Huggett, Reilly, & Lock, 2018).

Lastly, the production of high-fidelity models attends to the ethical imperative that archaeologists document the perishable and non-renewable heritage that we destroy in the act of excavation itself. Though no substitute for conserving the original in situ, we argue that there are no compelling reasons not to undertake photogrammetric documentation of every archaeological excavation context given its low barrier to entry and relatively simple technical requirements, especially for the photogrammetric data collection phase. It is only through such measures (or via more costly methods, such as terrestrial laser scanning) that high-fidelity simulacra of sufficient resolution for producing the ghostly "presence" of archaeological things and contexts can be rendered.

Far from curiosities or novelties, digital twins and iVR present unique affordances for working through the double hermeneutic of archaeological reasoning, and therefore should figure centrally in archaeological field methods and post-field analytics and interpretation.

Acknowledgments

The authors would like to acknowledge Prof. Robert Bodenheimer (Vanderbilt University School of Engineering) and Dr. Ole Molvig (Vanderbilt University Department of History) for guidance in the state of Virtual Reality technologies, Dr. Lindi Masur (McMaster University Department of Anthropology and Dr. Stephen Berquist (Sewanee University of the South, Department of Global Studies), in their assistance in testing our collaborative interfaces in Spatial.io.

This work was supported by a Vanderbilt University Chancellor's Faculty Fellowship (P.I. Steven A. Wernke); Vanderbilt University Data Science Institute Postdoctoral Fellowship (Giles Spence Morrow 2019-2022); Social Science and Humanities Research Council Insight Grant (P.I. Edward Swenson). Computational infrastructure was provided by the Vanderbilt University Spatial Analysis Research Laboratory.

References

Aida, J., Chau, B., & Dunn, J. (2018). Immersive virtual reality in traumatic brain injury rehabilitation: a literature review. *NeuroRehabilitation*, *42*(4), 441-448. https://doi.org/10.3233/NRE.172361

Alfaro, L., Rivera, C., Luna-Urquizo, J., & Fialho, F. (2019). Virtual reality full immersion techniques for enhancing workers performance, 20 years later: a review and a reformulation. *International Journal of Advanced Computer Science and Applications*, *10*(10), 500-510. https://doi.org/10.14569/IJACSA.2019.0101066

Appel, L., Appel, E., Bogler, O., Wiseman, M., Cohen, L., Ein, N., Abrams, H. B., & Campos, J. L. (2020). Older adults with cognitive and/or physical impairments can benefit from immersive virtual reality experiences: a feasibility study. *Frontiers in Medicine*, *6*, 329, 1-13. https://doi.org/10.3389/fmed.2019.00329

Aycock, J. (2021). The coming tsunami of digital artefacts. *Antiquity*, *95*(384), 1584-1589. https://doi.org/10.15184/aqy.2021.84

Bauer, A. C. M., & Andringa, G. (2020). The potential of immersive virtual reality for cognitive training in elderly. *Gerontology*, *66*(6), 614-623. https://doi.org/10.1159/000509830

Bekele, M. K., & Champion, E. (2019). A comparison of immersive realities and interaction methods: Cultural learning in virtual heritage. *Frontiers in Robotics and Artificial Intelligence*, *6*(91), 1-14. https://doi.org/10.3389/frobt.2019.00091

Burin, D., Liu, Y., Yamaya, N., & Kawashima, R. (2020). Virtual training leads to physical, cognitive, and neural benefits in healthy adults. *Neuroimage*, *222*, 117297. https://doi.org/10.1016/j.neuroimage.2020.117297

Carnevale, A., Mannocchi, I., Sassi, M. S. H., Carli, M., De Luca, G., Longo, U. G., Denaro, V., & Schena, E. (2022). Virtual reality for shoulder rehabilitation: Accuracy evaluation of oculus quest 2. *Sensors*, *22*(15), 5511. https://doi.org/10.3390/s22155511

Carter, W. M. (2017). *Virtual Archaeology, Virtual Longhouses and "envisioning the unseen" within the archaeological record* (Doctoral dissertation, The University of Western Ontario). Retrieved from https://www.proquest.com/dissertations-theses/virtual-archaeology-longhouses-envisioning-unseen/docview/2714866407/se-2

Cassidy, B., Sim, G., Robinson, D. W., & Gandy, D. (2019). A virtual reality platform for analyzing remote archaeological sites. *Interacting with Computers*, *31*(2), 167-176. https://doi.org/10.1093/iwc/iwz011

Cassidy, K. C., Šefčík, J., Raghav, Y., Chang, A., & Durrant, J. D. (2020). ProteinVR: Web-based molecular visualization in virtual reality. *PLoS Computational Biology*, *16*(3), e1007747. https://doi.org/10.1371/journal.pcbi.1007747

Champion, E., & Rahaman, H. (2020). Survey of 3D digital heritage repositories and platforms. *Virtual Archaeology Review*, *11*(23), 1-15. https://doi.org/10.4995/var.2020.13226

Chemero, A. (2003). An outline of a theory of affordances. *Ecological Psychology*, *15*(2), 181-195. https://doi.org/10.1207/S15326969ECO1502_5

Dell'Unto, N., & Landeschi, G. (2022). *Archaeological 3D GIS* (pp. 176). London: Taylor & Francis. https://doi.org/10.4324/9781003034131

De Bonis, M., Nguyen, H., & Bourdot, P. (2022, October). A Literature Review of User Studies in Extended Reality Applications for Archaeology. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 92-101). Singapore: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/ISMAR55827.2022.00023

De Luca, R., Bonanno, M., Rifici, C., Pollicino, P., Caminiti, A., Morone, G., & Calabrò, R. S. (2022). Does non-immersive virtual reality improve attention processes in severe traumatic brain injury? Encouraging data from a pilot study. *Brain Sciences*, *12*(9), 1211. https://doi.org/10.3390/brainsci12091211

Derudas, P., & Berggren, Å. (2021). Expanding field-archaeology education: The integration of 3D technology into archaeological training. *Open Archaeology*, *7*(1), 556-573. https://doi.org/10.1515/opar-2020-0146

Díaz-Guardamino, M., & Morgan, C. (2019). Human, transhuman, posthuman digital archaeologies: an introduction. *European Journal of Archaeology*, *22*(3), 320-323. https://doi.org/10.1017/eaa.2019.26

Ellenberger, K. (2017). Virtual and augmented reality in public archaeology teaching. *Advances in Archaeological Practice*, *5*(3), 305-309. https://doi.org/10.1017/aap.2017.20

Eve, S. (2014). Dead Men's Eyes: embodied GIS, mixed reality and landscape archaeology. BAR Br. Ser. 600. Oxford: UK: Archaeopress.

Eve, S. (2017). The Embodied GIS. Using Mixed Reality to explore multi-sensory archaeological landscapes. *Internet Archaeology*, *44*. https://doi.org/10.11141/ia.44.3

Forte, M., & Kurillo, G. (2015). Teleimmersive archaeology. *Archeomatica*, *6*(5). https://doi.org/10.48258/arc.v6i5.1665

Frederiksen, J. G., Sørensen, S. M. D., Konge, L., Svendsen, M. B. S., Nobel-Jørgensen, M., Bjerrum, F., & Andersen, S. A. W. (2020). Cognitive load and performance in immersive virtual reality versus conventional virtual reality simulation training of laparoscopic surgery: a randomized trial. *Surgical Endoscopy*, *34*, 1244-1252. https://doi.org/10.1007/s00464-019-06887-8

Gibson, J. J. (1977). The theory of affordances. In R. E. Shaw & J. Bransford (Eds.), *Perceiving, Acting, and Knowing: Toward and Ecological Psychology.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception.* Boston: Houghton Mifflin.

Giddens, A. (1987). *Social Theory and Modern Sociology*. Cambridge: Polity Press.

Gillings, M. (2009). Visual affordance, landscape, and the megaliths of Alderney. *Oxford Journal of Archaeology*, *28*(4), 335-356. https://doi.org/10.1111/j.1468-0092.2009.00332.x

Gillings, M. (2012). Landscape phenomenology, GIS and the role of affordance. *Journal of Archaeological Method and Theory*, *19*, 601-611. https://doi.org/10.1007/s10816-012-9137-4

González-Tennant, E. (2010). Virtual archaeology and digital storytelling: A report from Rosewood, Florida. *African Diaspora Archaeology Newsletter*, *13*(3), 1. https://scholarworks.umass.edu/adan/vol13/iss3/1

Gushima, K., & Nakajima, T. (2021). Virtual fieldwork: Designing augmented reality applications using virtual reality worlds. In *International Conference on Human-Computer Interaction* (pp. 417-430). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-77599-5_29

Haraway, D. (2013). Situated Knowledges: The science question in Feminism and the privilege of partial perspective. In *Women, Science, and Technology* (pp. 455-472). London: Routledge.

Heft, H. (1989). Affordances and the Body: an intentional analysis of Gibson's ecological approach to visual perception. *Journal for the Theory of Social Behaviour, 19*(1), 1–30. https://doi.org/10.1111/j.1468-5914.1989.tb00133.x

Hess, M., Colson, A., & Hindmarch, J. (2018). Capacity building and knowledge exchange of digital technologies in cultural heritage institutions. *Museum International*, *70*(1-2), 48-61. https://doi.org/10.1111/muse.12192

Hodder, I. (1999). *The archaeological process: an introduction*. Oxford: Blackwell.

Huggett, J. (2015). A Manifesto for an Introspective Digital Archaeology. *Open Archaeology*, *1*(1), 86-95. https://doi.org/10.1515/opar-2015-0002

Huggett, J., Reilly, P., and Lock, G. (2018) Whither digital archaeological knowledge? The challenge of unstable futures. *Journal of Computer Applications in Archaeology*, 1 (1), 42-54. https://doi.org/10.5334/jcaa.7.

Johnsen, H., & Olsen, B. (1992). Hermeneutics and Archaeology: on the philosophy of contextual archaeology. *American Antiquity, 57*(3), 419-436. https://doi.org/10.2307/280931

Kotoula, E., Robinson, D., Gandy, D., & Jolie, E. (2019). Computational photography, 3-D modelling, and online publication of basketry for Cache Cave, California. *Advances in Archaeological Practice, 7*(4), 366-381. https://doi.org/10.1017/aap.2019.23

Lang, M., Hussein, R., & Kluge, P. (2023). The 3D Digital Documentation of Shaft K24 in Saqqara. In Lucarelli, R., Roberson, J. A., & Vinson, S. (Eds.), *Ancient Egypt, New Technology: The Present and Future of Computer Visualization, Virtual Reality and Other Digital Humanities in Egyptology* (pp. 186-212). Leiden: Brill. https://doi.org/10.1163/9789004501294_009

Llobera, M. (1996). Exploring the topography of mind: GIS, social space and archaeology. *Antiquity, 70*(269), 612-622. https://doi.org/10.1017/S0003598X00083745

Lombardo, V., & Lauro, V. (2022, July). Prototype of virtual reality and CAVE installation for transdisciplinary archeology. In *2022 12th International Congress on Advanced Applied Informatics (IIAI-AAI)* (pp. 581-586). Singapore: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IIAIAAI55812.2022.00116.

Magnani, M., Douglass, M., Schroder, W., Reeves, J., & Braun, D. (2020). The digital revolution to come: photogrammetry in archaeological practice. *American Antiquity, 85*(4), 737-760. https://doi.org/10.1017/aaq.2020.59

Montello, D. R., Waller, D., Hegarty, M., & Richardson, A. E. (2004). Spatial memory of real environments, virtual environments, and maps. In G. L. Allen, (Ed.), *Human Spatial Memory* (pp. 271-306). London: Lawrence Erlbaum Associates.

Morgan, C. (2021). An archaeology of digital things: social, political, polemical. *Antiquity, 95*(384), 1590-1593. https://doi.org/10.15184/aqy.2021.125

Morgan, C. (2022). Current digital archaeology. *Annual Review of Anthropology*, *51*, 213-231. https://doi.org/10.1146/annurev-anthro-041320-114101

Mumford, J. R. (2012). *Vertical Empire: The General Resettlement of Indians in the Colonial Andes*. Durham and London: Duke University Press.

Myers, N. (2008). Molecular embodiments and the body-work of modelling in protein crystallography. *Social Studies of Science*, *38*(2), 163-199. https://doi.org/10.1177/0306312707082969

Opgenhaffen, L. (2021). Visualizing archaeologists: a reflexive history of visualization practice in archaeology. *Open Archaeology*, *7*(1), 353-377. https://doi.org/10.1515/opar-2020-0138

Ou, Y. K., Wang, Y. L., Chang, H. C., Yen, S. Y., Zheng, Y. H., & Lee, B. O. (2020). Development of virtual reality rehabilitation games for children with attention-deficit hyperactivity disorder. *Journal of Ambient Intelligence and Humanized Computing*, *11*, 5713-5720. https://doi.org/10.1007/s12652-020-01945-9

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology*, *110*(6), 785-797. https://doi.org/10.1037/edu0000241

Perry, S., Taylor, J. S., Matsumoto, M., & Uleberg, E. (2018). Theorizing the digital: A call to action for the archaeological community. In *Oceans of data: Proceedings of the 44th conference on computer applications and quantitative methods in archaeology* (pp. 11-22). Oxford: Archaeopress. http://digital.casalini.it/9781784917319

Pujol, L., & Champion, E. (2012). Evaluating presence in cultural heritage projects. *International Journal of Heritage Studies*, *18*(1), 83-102. https://doi.org/10.1080/13527258.2011.577796

Quinio, B., Boulbes, N., De Pechpeyrou, P., & Kotras, B. (2020). Use cases of virtual reality to visualize a database: how useful is VR for archaeology researchers?. In *Proceedings of the 2nd International Conference on Digital Tools & Uses Congress* (pp. 1-8). https://doi.org/10.1145/3423603.3424001

Rahaman, H., Champion, E., & Bekele, M. (2019). From photo to 3D to mixed reality: A complete workflow for cultural heritage visualisation and experience. *Digital Applications in Archaeology and Cultural Heritage*, *13*, e00102. https://doi.org/10.1016/j.daach.2019.e00102

Reinhard, A. D. (2018). *Archaeogaming: An Introduction to Archaeology in and of Video Games*. New York: Berghahn Books.

Reinhard, A. D. (2019). *Archaeology of digital environments: tools, methods, and approaches* (Doctoral dissertation, University of York). Retrieved from https://etheses.whiterose.ac.uk/26499/

Reinhard, A., & Zaia, S. (2023). Photogrammetry and GIS in Human-Occupied Digital Landscapes. *Advances in Archaeological Practice, 11*(2), 198-210. http://doi.org/10.5334/jcaa.30

Richards-Rissetto, H., & Landau, K., (2019). Digitally-Mediated Practices of Geospatial Archaeological Data: Transformation, Integration, & Interpretation. *Journal of Computer Applications in Archaeology,* 2(1), 120–135. http://doi.org/10.5334/jcaa.30

Robinson, D., Rosemont, C., Gandy, D., & Cassidy, B. (2021). When the virtual becomes actual: Indigenous ontologies within immersive reality environments. In Ó. M. Abadía, & M. Porr, (Eds.), *Ontologies of Rock Art: Images, Relational Approaches and Indigenous Knowledges* (pp. 412-430). London: Routledge.

Roosevelt, C. H., Cobb, P., Moss, E., Olson, B. R., & Ünlüsoy, S. (2015). Excavation is destruction digitization: advances in archaeological practice. *Journal of Field Archaeology*, *40*(3), 325-346. https://doi.org/10.1179/2042458215Y.0000000004

Sapirstein, P., & Murray, S. (2017). Establishing best practices for photogrammetric recording during archaeological fieldwork. *Journal of Field Archaeology*, *42*(4), 337-350. https://doi.org/10.1080/00934690.2017.1338513

Sayma, M., Tuijt, R., Cooper, C., & Walters, K. (2020). Are we there yet? Immersive virtual reality to improve cognitive function in dementia and mild cognitive impairment. *The Gerontologist*, *60*(7), 502-512. https://doi.org/10.1093/geront/gnz132

Shanks, M., and Tilley, C. (1992). *Re-Constructing Archaeology: Theory and Practice.* London: Routledge.

Simpson, M. (2020). *Scale and space: Representations in immersive virtual reality* (Doctoral dissertation, The Pennsylvania State University). Retrieved from https://www.proquest.com/dissertations-theses/scale-space-representations-immersive-virtual/docview/2572606674/se-2

Spence Morrow, G. (2019) *Scaling the Huaca: Constructing space, time, and identity at the late Moche ceremonial centre of Huaca Colorada, Jequetepeque Valley, Peru* (Doctoral Thesis, University of Toronto, Canada). https://www.proquest.com/dissertations-theses/scaling-huaca-constructing-space-time-identity-at/docview/2324854715

Statham, N. (2019). Scientific rigour of online platforms for 3D visualization of heritage. *Virtual Archaeology Review*, *10*(20), 1-16. https://doi.org/10.4995/var.2019.9715

Stoffregen, T. A. (2000). Affordances and events. *Ecological Psychology*, *12*(1), 1-28. https://doi.org/10.1207/S15326969ECO1201_1

Stoffregen, T. A. (2003). Affordances as properties of the animal-environment system. *Ecological Psychology*, *15*(2), 115-134. https://doi.org/10.1207/s15326969eco1502_2

Swenson, E. R. (2018). Assembling the Moche: the power of temporary gatherings on the North Coast of Peru. *World Archaeology*, *50*(1), 62-85. https://doi.org/10.1080/00438243.2018.1474132

Varela-Aldás, J., Palacios-Navarro, G., Amariglio, R., & García-Magariño, I. (2020). Head-mounted display-based application for cognitive training. *Sensors*, *20*(22), 6552, 1-22. https://doi.org/10.3390/s20226552

Wernke, S. A. (2013). *Negotiated Settlements: Andean Communities and Landscapes under Inka and Spanish Colonialism.* Gainsville: University Press of Florida. https://doi.org/10.5744/florida/9780813042497.001.0001

Wernke, S. A. (2015). Building Tension. Dilemmas of the Built Environment through Inca and Spanish Rule. In M. Barnes, I. de Castro, J. Flores Espinoza, D. Kurella, K. Noack (Eds.), *Tribus Sonderband / Special Edition: Perspectives on the Inca, International Symposium at Linden-Museum Stuttgart in Cooperation with Universität Bonn, Abteilung für Altamerikanistik from March 3rd to March 5th, 2014* (pp. 226-251). Stuttgart: Linden-Museum Stuttgart, Staatliches Museum für Völkerkunde.

Wernke, S. A., Kohut, L. E., & Traslaviña, A. (2017). A GIS of affordances: movement and visibility at a planned colonial town in highland Peru. *Journal of Archaeological Science*, *84*, 22-39. https://doi.org/10.1016/j.jas.2017.06.004

Wilkins, B. (2020). Designing a Collaborative Peer-to-peer System for Archaeology: The DigVentures Platform. *Journal of Computer Applications in Archaeology*, *3*(1), 33-50. https://doi.org/10.5334/jcaa.34