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Theoretical Foundations for Archaeological Pedagogy with Digital 3D, Virtual, Augmented, and Mixed Reality Technologies

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Abstract

Archaeology is inherently a visual and spatial discipline and thus we should strive to center student learning within visual and spatial media. Apart from museum work, site visits, and fieldtrips, the traditional tools of the classroom, however, tend to only convey textual or two-dimensional abstractions of primary archaeological data. The latest digital 3D and eXtended Reality (XR) technologies (virtual, augmented, and mixed) hold the potential for engagement with information in ways that more closely represent the true three-dimensional and visual nature of archaeological objects, spaces, and landscapes. This should allow for an embodied mode of interaction that significantly improves understandings of space and visual content. To maximize these benefits, our deployment of these technologies in the classroom should be guided by formal educational theory and research as well as by prior experiments. Here, we introduce theoretical perspectives on visual and spatial learning, as well as other educational theories, relevant to teaching the humanities and the material past. Our goal is to provide a range of theoretical foundations for pedagogical experiments that involve deploying XR teaching in the archaeological classroom.

Introduction

Students of archaeology learn about the human past through the same evidentiary datasets from which we derive our interpretations, namely the results of archaeological fieldwork (Petrosyan et al. 2021). Students are expected to develop the capabilities to construct knowledge beginning only from fragmentary remains of landscapes, architecture, and objects left behind by prior societies. A significant portion of the information contained by these primary material data are obviously visual and spatial, from the colors and shapes of pottery to the topography of a landscape (Figure 1). Therefore, we hypothesize that students will most efficiently gain a more complete understanding of these data if they can interact with them in ways that reflect their original full three-dimensionality and visuality. We also believe students should have embodied experiences of the past to be fully engaged with learning. With improved understanding of primary data, students can spend time on the intellectual tasks associated with deriving meaning about the past. Although direct access to objects, sites, and landscapes would represent the ideal situation for students, taking fieldtrips may not be practical (H. Cobb and Croucher 2014). Traditionally, students learn about archaeological evidence in the classroom through the text, audio, drawings, and photographs conveyed through articles, books, and lectures with slides. Among these, only the imagery conveys significant primary visual content, whereas the remaining visual and almost all spatial data are filtered through various channels of abstraction.

Furthermore, archaeology utilizes a wide variety of data types that may have their own spatial or visual qualities, such as satellite imagery, 3D models, and maps/geographic information systems (GIS).

Figure 1. Excavating and recording data at a field project in Armenia. Photograph courtesy of the Ararat Plain Southeast Archaeological Project (APSAP).

Recent advances in digital 3D and extended reality (XR) technologies hold the potential of enabling more direct engagement between students and primary archaeological data in ways that foreground the visual and spatial aspects of these data (Bekele et al. 2018; Garstki et al. 2019). Removing layers of abstraction should enable students to focus on interpretating data and understanding the past, a concept often referred to as reducing cognitive load. XR covers a spectrum of human-computer interaction for visual and audio stimuli that spans from the real world to the completely enclosed digital worlds of virtual reality (VR; Figure 2). The middle of the spectrum is occupied by augmented reality (AR) and mixed reality (MR) technologies that may use everything from smartphone hardware to head-mounted devices to project computer graphics and sounds to the human eyes and ears within the real world (here, we follow the definitions for each technology by Liang 2021).

Figure 2. Student experiencing virtual reality as part of a university class. Photograph courtesy of Agnes Sung.

Archaeologists have long recognized the potential of XR for many purposes, including teaching (Vlahakis et al. 2001). Yet, the useful, large-scale, sustained application of these technologies in the classroom remains scarce. We see three obstacles to achieving this goal. First are the resource constraints—not only has the equipment itself been costly, but the skills and time required for both creating 3D content and setting up meaningful digital functionality are prohibitive. Elmqaddem (2019) presents an optimistic view that recent advances can now better enable XR deployment for education. Second, VR applications in education have often been solo experiences that lack social interactions with teachers and other students, even though learning is often recognized as a social activity. When combined with the first obstacle, we recognize that XR has been difficult to scale up to a classroom context that can involve a group of students. Yet technological progress now enables a teacher and multiple students to interact in virtual worlds together, using avatars in VR (Cobb and Nieminen 2023). More interestingly, we see the potential for MR to facilitate collaborative learning since everyone would be able to see each other and the spatially aware computer graphics simultaneously. Third, we lack theoretical foundations for predicting and verifying successful teaching with XR in the archaeological classroom. For example, Parong and Mayer (2021) unexpectedly found that students were more engaged in history learning through the lower immersive environment of a video slideshow rather than in a highly interactive VR environment. By conducting additional, similar experiments and interpreting them within a clear educational theory context, we believe that XR holds great potential for learning. Therefore, in this article, we attempt to address this third point by laying the groundwork for the theoretical framing of XR deployment in the archaeological classroom.

Figure 3. A virtual reality group tour of an ancient site in Spatial.io. Screen capture by author.

As archaeologists, we have limited ability to impact the first challenge involving the technological constraints. These also influence the second challenge of having shared learning experiences in XR, though we can experiment more with existing functionality within these tools. On the other hand, the third challenge should provide an area for further research and experimentation that is specific to archaeology, and therefore we as archaeologists can potentially contribute to enhancing the ways XR learning is theorized and deployed. In general, our investigation and deployment of XR in the classroom should be more firmly grounded in existing educational research and theory. In this article, therefore, we examine a wide range of ideas and theories that can serve as a foundation for our research about teaching, particularly concepts specific to spatial and visual learning, but also those related to engagement, embodied learning, and experiential learning. In the following sections, we detail how educational researchers have been discussing these topics and applying them to pedagogical work in other fields. We also briefly touch on general topics in archaeological education as well as the prior use of digital 3D teaching in archaeological classrooms. Finally, we look at a few case study examples of teaching with XR from a variety of other fields to discover useful deployment examples. Resource-rich fields like architecture, engineering, and medicine all deal with various spatial and visual topics and their examples, therefore, should provide useful insights. By combining education theories and examples from prior experiments, we can further determine how best to design and measure successful teaching. This paper provides theoretical foundations for future researchers to adapt and build experiments with XR that can specifically apply to the archaeological classroom.

Foundations of Archaeological and XR Learning

The literature on educational theory provides a rich body of ideas about how students learn. A subset of these ideas should specifically be useful for understanding the intersection of learning about archaeology and learning with XR technologies. Therefore, to establish the theoretical foundations of such learning, we here review a variety of existing pedagogical concepts that we view as most relevant. We propose that the visual and spatial dimensions of learning have additional importance in our field, so we first explore theoretical approaches in the educational literature to better frame our understanding of these concepts. We next examine various other learning theories that may help guide the successful deployment of XR in teaching, including the concepts of embodied learning theory, experiential learning, and student engagement. Our intention is to introduce these topics to an archaeological audience. These foundations in educational theory should help support future XR teaching experiments in archaeology.

Visual Learning

In her overview of visual interpretation, Rose (2001:1) points out that “what we see is as important, if not more so, than what we hear or read.” An online glossary defines visual learning as “a mode of learning where students rely on graphic aids to remember and learn material” (Tophatmonocle Corp. 2024; https://tophat.com/glossary/v/visual-learning/). We should always question how humans can remember the characteristics of what we see, such as the colors, patterns, and shapes of objects. This is, of course, central to the archaeologist’s work in comparing styles of artifacts. But we also study the views afforded by landscapes, the layouts of architectural units, or even the colors of soils in excavation contexts. How can we remember and analyze these visual details? One system, called VARK (Visual, Aural, Read/Write, and Kinesthetic), was developed by Fleming and Mills (1992) to account for different learning behaviors, especially between visual and read-write learners. Following from the VARK model, Othman and Amiruddin (2010) characterize visual learners as those that can learn through description but prefer to learn through visual representations such as demonstrations, charts, graphs, mind-maps, and infographics. Naturally, visual learners also express themselves better through illustrations such as charts and drawings. In contrast, aural learners are predisposed to listening and engaging in classroom discussions to clarify their understanding. XR systems mainly stimulate the visual sense, so we see visual learning as an integral part to XR learning. Yet, systems like VR may lack some of the visual fidelity present in real objects. For example, do the objects shine in the virtual light as realistically as in real light?

In a study of undergraduate science students, Arneson and Offerdahl (2018) propose a system to help guide the enhancement of visual learning skills. They recognize that visual literacy is central to scientific communication, so they developed the Visual Blooming Tool (VBT) to systematically assess the students' visual literacy and articulation of observations in line with course learning objectives. This system is ultimately based on Bloom's taxonomy of learning that sees learning as a hierarchy with the simpler tasks of knowledge acquisition and comprehension at the bottom and more intellectually complex tasks such as evaluation and synthesis at the top (Bloom et al. 1956). Arneson and Offerdahl (2018) ran an experiment with students in science courses where the exam questions were classified on their VBT scale, both by the teacher and by the students. Their results highlight the importance of students having multiple opportunities to practice visual learning that are in line with the goals of each course. To provide a comprehensive visual learning experience, course assessments should target visual skillsets at each cognitive level of their Bloom-based scale. They point out that "Novice learners tend to focus on the surface features of representations and, as a result, may find it difficult to extract meaningful trends or more complex encoded messages" (Arneson and Offerdahl 2018:7). Thus, we need to consider all the levels of complexity in learning that are possible in order to improve visual understanding.

Spatial Learning

Given the centrality of spatial information in archaeology, we here examine educational literature to understand how spatial learning has been conceptualized and how people learn best about space. Several studies try to define spatial thinking, often by dividing this concept into various components. For example, Uttal and others (2013:353) identify spatial visualization and orientation as two of the most discussed spatial skills in the literature. Visualization involves a person being able to "see" space in their mind and move objects around in this imagined space. Orientation augments this by enabling a person to imagine observing the space from various perspectives. An archaeologist-in-training needs to be able to reconstruct spaces and landscapes in their mind, and "visit" them from multiple angles and in various configurations. Uttal and colleagues (2013) further divide spatial thinking into intrinsic versus extrinsic and static versus dynamic. In their system, intrinsic means being able to think about the configuration of an individual object, which can either be conceived as stationary (static) or imagined moving and rotating (dynamic). Extrinsic involves cognition about the spatial relationships among objects, which may be viewed statically as an established map or may be viewed from multiple dynamic perspectives. Archaeologists often think both about the intrinsic shape and patterns of objects while also considering their extrinsic spatial relationships to each other, and we must consider the objects and spaces themselves statically or imagine their dynamic use, modification, and transport.

Linn and Petersen (1985) divide spatial thinking into three categories: spatial perception, mental rotation, and spatial visualization. Spatial perception centers people by indicating that they can imagine the relationships among objects in space relative to their own bodies and is thus similar to spatial orientation mentioned above. During mental rotation, a person imagines rotating a pair of objects relative to each other to compare them. Once again, though, spatial visualization is the most interesting characteristic of spatial cognition since Linn and Petersen identify visualization with “those spatial ability tasks that involve complicated, multistep manipulations of spatially presented information” (1985:1484). For the purposes of moving through space, Löwen and others (2019:149) categorize spatial knowledge into landmarks, routes, and survey, where survey means an understanding of the entire environment. For movement, a person should be able to visualize an environment, either using landmarks or from a birds-eye perspective, and then orient themselves in the environment to move along different routes.

Building on these definitions of spatial cognition, other studies have attempted to improve the training of spatial knowledge acquisition. Cobb, Rogers, and colleagues (2019) used active, online mapping of historical travelers’ accounts to help immerse students in the narrative descriptions of landscapes that were traversed with premodern transportation technologies. The students combined a close reading of the texts with discovery of historic toponyms and environmental features. In this way, the students developed abilities to visualize the extrinsic relationships between static objects in the ancient landscape, while also learning to orient themselves to multiple perspectives of these landscapes. Löwen and others (2019) attempted to improve people’s wayfinding abilities by highlighting landmarks and other features on maps. The emphasis on structural features of the landscape and landmarks did enhance people’s ability to visualize the space and orient themselves within it. This helped people not only to follow a route but also to gain a high-level understanding of the structure of the environment, which they call survey spatial knowledge. Miola and others (2021) examined the importance of people’s belief in their own spatial abilities as a contributor to success in spatial learning, and they enhanced this belief through positive feedback. Uttal and others (2013) performed a meta-analysis about spatial learning and determined that many studies have shown that spatial cognition and knowledge can be improved through training. They even recognized that video gaming had similar impacts on increasing spatial ability as those from formal coursework (Uttal et al. 2013:368). When it comes to the use of XR, we suggest that the technology enables the user to directly engage with the skills of spatial visualization and orientation. The user can actually experience space and objects from many different perspectives, thus simulating the mind's spatial visualization as the user moves objects around in the virtual space. Similarly, XR can help simulate spatial orientation as the user moves through the space to view the virtual world and objects from many different perspectives. The question then arises as to whether this type of simulation can improve spatial cognition or just makes the user a passive recipient of information. After leaving the XR, will the user be able to both remember the spatial layout and imaginatively manipulate it further, or can they only remember snapshots of the space from the angles they saw in the virtual world? These are the types of guiding questions that can support important future research experiments into XR teaching in archaeology.

Embodied and Experiential Learning

In addition to visual and spatial learning, several other education theories can help us frame the role of XR in improving archaeological learning. We all learn through the interaction of our bodies with the surrounding world. Archaeology in particular emphasizes not only our own learning about the past but also the embodied experiences of people in the past with their own environments. The theory of embodied learning grows out of the field of embodied cognition, which describes "how our body and our environment are related to cognitive processes" (Skulmowski and Rey 2018:1). Embodied learning theory proposes that learning should involve experiences that engage the student's sensory-motor and cognitive faculties. Theories of embodied cognition, in turn, have been influenced by research into perception. Barsalou (1999) proposes that, as we perceive and interact with the world through our senses and motion, these perceptions share neural systems with—and thus are directly integrated with—higher-level thought processes such as language and memory. Thought is not abstract-symbolic but based directly on inferences from actions and the sensory (visual, auditory, vestibular, tactile, proprioceptive, olfactory, etc.) properties of experience—which, in turn, combine to support higher-level conceptual thought. He also suggests these experiences are "simulated" in the brain when we think about things after the fact, which has interesting implications for XR. The linking of perception and cognition foregrounds the role of the body in thinking (embodied cognition) and has been supported by neuroscience research (Kiefer and Trumpp 2012). Kiefer and Trumpp (2012), therefore, suggest that embodied learning will provide a richer learning experience than abstract interaction with learning materials. They provide the example of a student learning about a musical instrument: the bassoon. Embodied learning indicates that a student will maintain richer knowledge about a bassoon far better if they hold, hear, and see the instrument rather than if the teacher reads a verbal description of this object. Learning grounded in perception and action should therefore form an important component in learning theory and embodied learning works because it foregrounds the role of sensory-motor interactions with the world. Skulmowski and Rey (2018) developed a taxonomy for embodied learning that measures in meaningful ways how engaged the body is in the learning activity. They also discuss how XR can be used to facilitate bodily tasks in learning. We propose that by engaging multiple senses and allowing for bodily motion, XR can indeed be a good tool for enabling embodied learning in archaeology.

Experiential learning is related to embodied learning in that it often engages the body. In experiential learning, the learner reconfigures their knowledge through experience (Kolb 2014). Kolb and Kolb (2012:1216) conceptualize this theory with six dimensions: first, experiential learning assesses learning as a process of experience, rather than the outcomes of such experience; second, learning is augmented when a learner's previously held beliefs and ideas are brought forth to be assessed and compared with newer ideas; third, learning is the reconciliation of conflicting ideas as the learner reflects, feels, and thinks; fourth, learning involves the whole learner, synthesizing cognitive, mental, and emotional adaptation; fifth, learning is an outcome of the learner's interaction with their environment; and sixth, learning is a dialectic process of creating knowledge within social and personal contexts. This theoretical model emphasizes the construction of knowledge through experience in the world that involves a cycle of learning through experiencing, reflecting, thinking, and acting (Kolb and Kolb 2012). XR provides a way for a student, as a user, to experience archaeological information and interact with those data in multiple ways. The user can control the environment by walking through it and moving objects, while at the same time having an embodied experience that exercises visual, spatial, auditory, and motor interactions. The teacher can frame experiences through guided tours of a virtual location with groups of students or by building tasks that students need to complete within XR. Kwon (2019:101) found positive results from using VR in experiential learning, showing that "the enhanced vividness and interactivity of VR technologies allow the users to closely recognize virtual experiences as direct experiences," so that "the learning effect is enhanced." Archaeological field schools traditionally provide students with the best experiential learning, but perhaps XR can serve to replicate some aspects of this type of learning (Cobb et al. 2022).

Student Engagement

XR should enable a more direct engagement between the student and the archaeological information and learning. Fredricks and others (2004:60–61) conceptualize engagement as a "multidimensional construct" that fuses "behavior, emotion, and cognition" as they are "dynamically interrelated within the individual," with the aim that students become committed to and invested in their own education. Fredricks and McColskey (2012:764) characterize behavioral engagement as student participation in a variety of social and academic activities and explore how these can lead to good outcomes. Emotional engagement incorporates how students interact and identify with their learning community at a personal level. Cognitive engagement involves students making efforts to understand difficult ideas (Fredricks and McColskey 2012:764). Engagement research, therefore, examines how the student as a human can better connect on multiple levels with their community and learning topic. Numerous studies on applying XR-assisted instruction and learning make attempts to tackle the behavioral, emotional, and cognitive elements that govern a student's performance in the classroom. Nevertheless, student experiences of engagement may not be uniform, as a result of various extraneous variables that affect student motivation from outside the classroom.

Although teachers have very important roles to play in increasing student engagement (Sagayadevan and Jeyaraj 2012), many studies highlight the limitations of traditional lecture- and teacher-centric instructional approaches in supporting engagement (Hamilakis 2004; Hu-Au and Lee 2018; Peuramaki-Brown et al. 2020). Traditional approaches, which involve the passive transmission of knowledge from teacher to student through oral communication and lecture slides, simply do not meet archaeology's wide-ranging demands due to a lack of contextualized absorption of new information among students (Hamilakis 2004; Henson 2017). It is cliché to say that "archaeologists learn everything in the field," yet many archaeology curricula and courses still mandate fieldtrips to sites (H. Cobb and Croucher 2014). However, there may be practical limitations to taking students to visit sites and museums, so many scholars have suggested bringing the fieldtrip into the classroom instead. After all, students who are learning archaeology passively may lose engagement with the subject and question the relevance of attaining archaeological education (Hu-Au and Lee 2018). Williams (2011) highlights the importance of collaborative learning in supporting the cognitive and emotional elements of learning that were later articulated in Fredricks and McColskey's (2012) concept of student engagement. Collaboration improves student internalization of learning material by creating a social context and reducing individual cognitive load, yet collaboration in XR has been somewhat limited by the technology.

Learning Archaeology

Archaeology has its own set of pedagogical research that can help frame the deployment of XR. No topic receives more attention than active fieldwork as a component of archaeological education and, thus, fieldwork studies have been a primary focus of educational research (Abu Alsaud et al. 2021; Cobb et al. 2022; Mehari et al. 2014). Fieldwork, which is a naturally visual and spatial way of learning, provides opportunities for mentoring in the research process. It is often identified as an experiential learning practice that allows for embodied engagement with archaeological knowledge production. If XR experiences could replicate some aspects of fieldwork, they could support students learning about how we move from complex, incomplete data to interpretations about the past. Some studies about fieldwork in archaeological education have also highlighted the learning of practical skills, often with an eye towards students finding jobs and developing in their careers (Aitchison 2004; Handley 2015). Exposure to XR, including the steps of creating 3D models (Figure 4) and engineering immersive functionality, may also provide some level of transferable digital skills (Anderson et al. 2021; Cobb, Sigmier, et al. 2019).

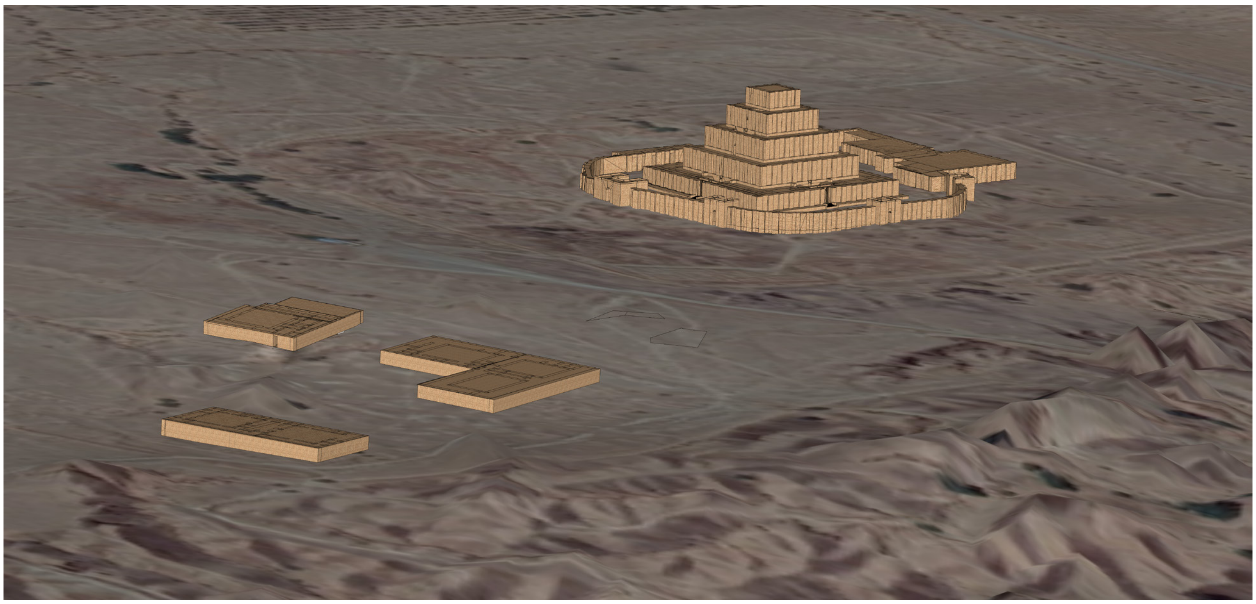

Figure 4. Digital 3D model reconstruction of ancient Chogha Zanbil in Iran. Screen capture by author.

Other research has focused on the place of archaeology within the wider society, and thus the role of public education. After all, as Perry (2019) points out, archaeology has the potential to enchant people. We get emotionally engaged and become attached to the past and, therefore, archaeology has often been the subject of popular cultural products. Henson suggests that we “can give people the knowledge and skills of archaeological practice, and help them to make links between past and present and to see the value and complexity of heritage,” and create “a past in the minds of the present” (2017:44–45). Apostolidou (2020) highlights how material culture can assist in learning history through exploratory processes and critical thinking. Public engagement with excavations and public visits to museums can help inform people’s understanding of how we develop historical narratives. Many recent studies have examined the methods and value of public education, especially when connected to active field projects. Apaydin (2016) evaluated the local outreach undertaken at the Turkish site of Çatalhöyük over many years, emphasizing the need for such programs to measure their own effectiveness. Khatchadourian’s (2020) camp for girls to participate in her field project emphasizes the need for public education to move beyond preservationist goals and to consider, instead, how active engagement in the processes of archaeology can contribute to addressing societal challenges, such as inequality. Arias-Ferrer and Egea-Vivancos (2017) found that engaging secondary school students with object-based learning on archaeological artifacts improved their ability to develop inquires and hypotheses on their own.

Finally, some researchers have focused on teaching archaeology at the university level. While pointing out that “Play is a powerful motivational tool,” Smith and Burke (2007:11) advocate that we should make lectures fun and engaging, particularly for topics in archaeological theory. They suggest teachers seek imaginative teaching exercises that encourage interaction in the classroom, including those supported by technology. Their edited volume provides examples of a variety of strategies for teaching archaeology at the university level in a more interactive fashion: from role-playing and games, to the creative construction of narratives. Clarke (2005) describes how narratives can support archaeological teaching, pointing out certain characteristics of storytelling about the past such as the need for structure, meaning, and a search for “whole-ness” in the process of transforming understanding. She sees narrative as a “constructive process of communicative interaction” that can enhance learning (Clarke 2005:86). Creative use of XR could make classroom learning more interactive, but we can also consider how to embed narrative into XR experiences. Peuramaki-Brown and others (2020:1) advocate for improving the “social/emotional, teaching, and cognitive” presences of students even in a digital environment to build a “‘communities of inquiry’ experience in archaeology.” Henson (2017:55) points out the value of archaeological education in supporting students’ ability to think spatially and in three dimensions. He observes that constructivist theories suggest teachers should help students build their own knowledge in archaeology, while constructing understanding of abstract concepts through the experience of concrete practice. Garstki and others (2019) emphasize the value of group experiences with 3D data from an archaeological site to learn about the archaeological process. However, they point out the limitations in terms of digital equipment availability for university courses as well as the current absence of physical haptic interaction with the spaces and artifacts.

H. Cobb and Croucher aim to address “the undervaluation of pedagogy and pedagogic research in archaeology” (2014:197). They suggest more closely connecting teaching and research since learning is a core part of the production of archaeological knowledge. They advocate for “enmeshing” student learning directly in the theoretical and research processes of archaeological work. As part of his discussion on political aspects of pedagogy, Hamilakis (2004) proposes to transform the classroom into one in which both students and instructors participate in a collaborative inquiry-based environment while enabling students to reflect on and critique their own learning. Through critical reflexive processes, students could have more agency in designing the conditions of their education. Furthermore, Peuramaki-Brown and others (2020) highlight the issues of accessibility and ethics in university-level archaeological education within the Canadian context. Does XR hold the potential for allowing students more control over learning, for example by allowing them to help reconstruct and wander through an archaeological site? In their book, H. Cobb and Croucher (2020) again advocate for turning our attention to archaeological pedagogy and engaging in research in this area. They suggest that archaeologists themselves should engage in finding pedagogical solutions that could contribute to wider discussions in educational research. Colaninno (2019) also advocates for research into our educational practices that are specific to our discipline. Perhaps the recent uptick in research surrounding online learning in archaeology, driven by world events, can help to guide research into archaeological learning with this other digital technology, XR (Baxter 2021; Bernard 2021; Pacifico and Robertson 2021).

XR Learning and Teaching for Archaeology

Thus, a wide range of educational theories and ideas can guide and serve as foundations for our deployment of XR in archaeological pedagogy. We see great potential for XR to improve visual and spatial learning in the classroom through embodied interaction with archaeological information that makes learning more experiential and engaging. We hope that the affordable headsets that are increasingly coming onto the market can make XR learning more accessible, particularly since our efforts should be guided by inclusive teaching practices (Heath-Stout and Hannigan 2020; Quave et al. 2020). We see some interesting potential directions to take the research into XR for learning archaeology in the classroom based on some research gaps that we have identified in the educational literature. Williams (2011) highlights the importance of collaborative learning and group work, but this type of research should also be expanded to examine how instructors and multiple students can learn together in XR (Cobb and Nieminen 2023). We also identify the use of MR for learning as a particularly important research gap. MR can help support group learning because students would see the real world and each other at the same time they are interacting with a full

Figure 5. Student using the Microsoft HoloLens 2 MR headset to visit an archaeological site. Photograph courtesy of Phoebe Fong Tsz Ching.

3D environment (Figure 5). Skulmowski and Rey's (2018) review of embodied learning cites the potential of using MR for providing a digitally applied visual-spatial learning experience. The foundational educational ideas and theories reviewed here establish the context for seeking examples of the application of XR for visual and spatial learning. We next examine prior 3D learning experiments within the field of archaeology and then we briefly review some attempts at spatial-visual learning with XR in other academic fields.

Examples of Immersive and 3D Learning in Archaeology

While discussing the advantages of the 3D recording of archaeological data during fieldwork, Knabb and others note that "two-dimensional maps and photos reflect scale but never fully embody" sites and landscapes (2014:228). They recognize the heuristic potential of 3D archaeological data to allow the revisitation of sites and excavations—both remotely and continuously—for the purpose of reviewing and reinterpreting these data. Their project used a Cave Automated Virtual Environment (CAVE) to enable people to visit their site in southern Jordan, Khirbat en-Nahas, through a 3D immersive experience. Around the same time, Forte (2014) also used a CAVE to introduce stratigraphic concepts to students with data from the Çatalhöyük site. With various stages of an excavation recorded in 3D through photogrammetry, students were able to experience the excavation process in a type of virtual dig. By visiting together as small groups of 5 students, they could also learn through discussing and comparing their understandings of the data. CAVE technology is resource intensive and is designed for a single user, but newer VR headsets offer more accessibility. Thus, Cobb and Nieminen (2023) used VR to take students from a university course on remote group tours of reconstructed archaeological sites in Mesopotamia.

Garstki and others (2019) also used an environment similar to a partial CAVE to host 3D experiences for students in groups. In their setup, the screens were mostly on one wall, with small side extensions, which enabled more of a 3D-cinema-type experience with up to 40 students. Their experiment focused on an introductory anthropology course designed to teach archaeological excavation methods. Students viewing the virtual environment were shown variations in soil colors, architecture, or artifact assemblages and asked to "reevaluate excavation strategies as the excavation proceeds" (Garstki et al. 2019:53). Their large-scale immersive environment allowed many students to engage with the same material collaboratively, though only one user could control movement within the CAVE system. They also noted that all such XR experiences do not engage the learner's haptic senses, which are considered crucial in archaeological fieldwork (Garstki et al. 2019).

Ellenberger (2017) experimented with VR environments for teaching 8- to 12-year-olds about archaeological artifacts, building on the work of Di Franco and others (2016) in using screen-based 3D visualizations to teach about objects. Other experiments with using XR to teach archaeology have mostly been conducted outside of the classroom, usually in the context of public education or tourism. Falconer and others (2020) found that tourists exploring a VR reconstruction of an ancient site had a greater sense of place if they felt that the virtual site was highly believable. Liu and others (2021) used a VR game to teach museum visitors about archaeology, finding that this enhanced their engagement with learning. In fact, “serious games” in VR have been found to enhance learning in many ways since users become active participants in their own learning (Checa and Bustillo 2020). Our interests here are more focused on the formal classroom teaching of archaeology with immersive 3D environments, but these applications in public education can be informative.

Beyond these more immersive experiences, other teachers have been generally experimenting with using 3D models in archaeological pedagogy. Derudas and Berggren (2021) advocate for 3D education to foster deep learning, student engagement, and reflexive thinking about the material past. In their study, two successive cohorts of first-year archaeology students participated in two separate seasons of archaeological excavation work at Södra Sallerup in 2019 and 2020. Both cohorts conducted a week-long excavation of real Bronze–Iron Age deposits, in an area with straightforward stratigraphy and plentiful artifacts. The students created 3D models of the pre- and post-excavation states of the whole trench as well as some models of artifacts in situ. Students appeared to have no problem navigating the custom 3D modeling software. They also found it useful to visualize the excavation process by combining models that were spatially adjacent but recorded at different times. François and others (2021) describe how 3D reconstructions and VR can be closely embedded into the research process about past spaces that no longer exist.

Each of these studies focuses on the spatial and visual characteristics of archaeological excavations. This spans from the shape of excavated contexts and layers to the models of the individual artifacts. In many examples, the goal seems to be for students to be able to navigate within a trench that was already dug, and thus to revisit the excavation. This helps students to see the process and not just some 2D interpretations of results like architectural plans. In this way, it is likely the students are able to achieve better visualization and orientation of these archaeological spaces in their imaginations. It seems that these prior studies have focused less on embodied learning, since the target objects viewed by the users were often projected on walls and then animated, rather than the users being truly immersed within the environment. From an experiential standpoint, they also are balancing passive intake of visual information with active engagement through the students being able to control and even modify the 3D data. Furthermore, these studies often involve group analysis of excavation methods and interpretations, enabled by both instructor-student interactions and peer-to-peer discussions.

Teaching with XR in Other Academic Disciplines

Here we briefly review several research experiments in non-archaeological fields that have attempted to improve teaching using XR techniques. The goal is often to enhance student motivation and performance, and this is usually directly tested by the researchers through an educational study. These studies can serve as models for archaeologists.

Tang and others (2020) used the Microsoft HoloLens headset in an MR teaching experiment for mechanical engineering students to learn about the design of an aircraft engine. The students could manipulate the engine; they could move it around, pull out components to understand their geometry, and activate the engine to work as a simulation. In addition to placing this virtual model on their real desk, the student could also read the physical paper manual at the same time as they interacted with the model. In their experiment, 72 students were divided equally into control and experimental groups. The control group learned about the engine with only traditional 2D learning materials like books and lecture slides. Then all the students were tested on creativity in problem-solving, model visualization and geometric analysis. Post-test results after using the HoloLens showed that the experimental group received higher marks than the control group on all assessment components. This mechanical engineering topic highlights the spatial and embodied learning potential of MR. The students who learned with the virtual model could better visualize the spatial, and thus mechanical, relationships among the parts of the engine. Since MR supports gestures with the user's own hands, the embodied interaction the students had with the virtual engine also helped them to remember how the parts fit together.

Jitmahantakul and Chenrai (2019) used VR to teach high school students about Earth's long-term geological processes. They recognized the deficiencies of learning from traditional paper maps and cross-section photographs since "most geological phenomena require spatial visualization and object visualization abilities," concepts generally central to spatial learning (Jitmahantakul and Chenrai 2019:577–578). As with archaeology, geological fieldtrips have been central to the full learning experience in geology. In addition to enabling virtual fieldtrips that could visit multiple distant places in rapid succession, the technology can also simulate dangerous geological situations—think of the hazards of earthquakes or volcanic eruptions. Thus, in this study the authors selected dozens of locations of geological interest across Thailand that the students would virtually visit. They then went to each location and recorded a 360-degree photograph using Google tools. Such photographs provide a high-quality view in all directions to the users of VR and can be annotated with further information, but they do not enable the user to move around the environment to investigate the landscape from different angles. In this way they better support visual learning than the orientation aspect of spatial learning and, therefore, the experiences are likely less embodied. In the study, 93 high school students used these VR experiences as part of their geological learning, guided by teachers who told students what to look for and answered questions. The authors then evaluated the pre- and post-test results of their learning and determined that grades had improved.

Birt and others (2018) emphasize the importance of hands-on, experiential learning in the medical and health sciences fields. Computer simulation helps medical students to practice the techniques they may one day need to apply to real humans. In the first part of their study, a group of students used VR or tablet-AR to study the brain and spinal cord. The sections of the brain were color-coded to assist in learning and a narrator in the virtual space guided the students through the 3D models of these body parts. The students wrote feedback about their learning experiences. The teachers also observed student learning and conducted formal one-on-one interviews. Birt and colleagues (2018) ran a second experiment involving the remote training of medical students in the emergency removal of items blocking the human airway. In this case, the students received 3D printed tools for removing objects from the throat and they wore a head-mounted smartphone AR device. Through the camera of the smartphone, they could see their real hands and the 3D printed tools. Then AR overlaid a virtual head and neck of a manikin into the view, together with visual guides that instructed the students how to use the real tools. This type of AR that combines some real tangible objects in the students' hands with a virtual environment is extremely powerful. Thus, in both experiments, the medical students are learning the visual aspects of the target objects—parts of the human body—and the spatial relations among these parts. In the latter experiment they are also learning how to physically navigate these spaces by actually engaging in fine-motor-skills training with their hands.

Thees and others (2020) investigated the effects of MR on cognitive load for students learning about physics through laboratory exercises. In their study, students ran an experiment where they heated a metal rod at one end and then measured the thermal changes across the length of the rod. Normally, the students would need to collect the data and then analyze them later, but by using the HoloLens the students were able to visualize the results of the experiment in real-time. When looking through the MR device, the students could see a false-color projection virtually overlaid on the rod that showed relative temperature (redder=hotter). The students could also see a line graph of the change in temperature projected in line with and above the actual physical metal rod. Furthermore, multiple students could see the same virtual data in the same place and thus discuss the experiment. The results from a later test that evaluated student knowledge about this physics experiment showed that students trained with MR performed similarly to students who learned in a traditional lab. However, the efficiency of being able to visualize and interact with the data in real-time during the lab led to a much greater reduction in cognitive load among the students who used MR.

The Affordances of XR for Learning

Thus far, we have introduced multiple theoretical foundations based in educational research that can support future experimentation with XR learning in the archaeology classroom. Furthermore, we see several potential important affordances of the XR technology that would support different aspects of how students learn spatially and visually. These include learning in groups, automating learning, visiting virtual places, simulating methods, manipulating and reproducing objects, and creating reconstructions. By reviewing these concepts, we hope to help set the agenda for future serious efforts in archaeological teaching with XR.

A tour to a virtual archaeological site can involve guests from anywhere in the world in a combined experience (Figure 6) . Group learning enhances student engagement through connecting them to their learning community in a social environment. Perhaps also, as students discuss what they see and how they move, they will help each other to improve spatial abilities such as visualization and orientation. For in-person immersive group learning, we see potential for spatially aware MR. With MR, everyone can see each other and the room but also see the same virtual objects in the same place. In the experiment of Thees and others (2020), multiple students wearing HoloLens devices could point things out to each other, thus enhancing embodied engagement through physical actions.

Figure 6. Virtual group tour in Spatial.io. Screen capture by author.

Technology also provides an opportunity to automate the learning experience for students, as with the narrated VR tours of Birt and others (2018). This gives students agency to control the pace of learning, to repeat challenging topics, and to receive immediate feedback on their learning. Recent advances in artificial intelligence (AI) will further support individualized learning through automated feedback (Cobb 2023). With MR teaching like that described by Thees and colleagues (2020), instructions can be overlaid directly on the physical teaching materials. Such assistance can also be engaging for the students and increase their interest in carrying out assignments.

Next, an obvious use for XR is the potential to visit many different locations across the Earth, including archaeological sites and landscapes. Interaction with important spaces could partially replicate the emotional and physical learning highlighted by experiential learning theory. These teaching methods enable embodied spatial learning that allows students to find their way around sites or landscapes as they experience the visual impact of different views. Through XR, we could experiment with how ancient peoples would have viewed their landscapes and thus elucidate how they may have given various emotional, political, or religious significances to different landmarks or used landmarks as wayfinding guides in transportation.

XR can also be used for simulating archaeological methods such as excavation. We are constantly thinking about the spatial qualities of excavated data. Through an XR re-excavation, students can greatly improve their spatial abilities to visualize the relationships among the excavated contexts and can orient the contexts as well as interpretive reconstructions relative to each other. XR could train their visual recognition of artifacts or soil color changes. This can reinforce their confidence in being able to make decisions during digging and help them understand if this type of activity will be truly engaging before they commit to joining a field project. Moving to the field itself, one could imagine using MR to assist in excavation training. This could be similar to the teaching done by Thees and others (2020) to display information above the heated rod in the scientific lab. One could imagine presenting information to MR users at the trench concerning what has been excavated during prior days or years, thus assisting with making new excavation decisions.

The ability to interact with objects in XR is important for archaeology, particularly objects that are otherwise hard to access. This is similar to how Birt and others (2018) used XR in medical education to give access to the human brain. We could allow students to manipulate artifacts such as puzzling pottery fragments back together or comparing the shapes of animal bones. The engine simulated in Tang and others' (2020) experiment serves as an example of students improving their spatial abilities to understand how pieces of an object fit together and function. The embodied experience provided during such activities, where the hands are used to manipulate objects in virtual space, would enhance spatial learning. Students will learn to orient objects and think about their intrinsic spatial qualities, including shape. At the same time, the close proximity to potentially many other objects can enhance visual information acquisition on topics such as decoration and color.

Beyond just moving the objects around, we also see the potential for XR to help teach about how ancient artifacts were produced. We imagine virtually replicating the steps of constructing pottery vessels, decorating these vessels, forging metal objects, or knapping stone tools. It is true that a major downside will be the lack of haptic feedback, as the user will not feel the pottery wheel or the pressure exerted on a stone. However, being able to replicate many of the other steps could still help the students learn in an embodied way as they develop fine motor skills for craft production. The example of Birt and others (2018) using AR to train medical students how to free a person's airways is instructive. Perhaps for archaeology, an MR environment could help guide the students to work on real objects, similar to the experiment of Brondi and others (2016) for teaching printmaking. Finally, we see great potential in teaching students through the creation of 3D content that could then be used in XR. This could entail students doing interpretive reconstructions of architecture from sites that require them to consider a variety of evidence including building remains and comparands from other sites. The students will learn the critical processes of evaluating primary evidence, and at the end of the process they can visit these reconstructions in XR.

We predict that in the coming decade archaeologists will greatly increase their experimentation with XR in learning given the increasing availability of this type of technology. Although XR is still finding its footing in terms of useful applications in the classroom and real world, many companies are experimenting with different ways of engaging XR. Immersive environments present new opportunities for embodied and experiential learning where students interact directly with ancient objects, sites, and landscapes. This should provide a more engaging experience for students than traditional lectures and readings. XR experiences should help students understand essential archaeological concepts such as the spatial relationships among contexts at a site and the associations of sites with their surrounding environment. As part of an academic discipline, we archaeologists should further engage in pedagogical studies to determine how best to deploy XR in our classrooms. Our experiments should be securely grounded in educational theory, which is why we present the theoretical foundations outlined in this paper.

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