Open Archaeology 2018; 4: 114–122 DE GRUYTER

Original Study

Stuart Eve*

Losing our Senses, an Exploration of 3D Object Scanning

https://doi.org/10.1515/opar-2018-0007
Received May 8, 2017; accepted November 13, 2017

Abstract: 3D scanning and photogrammetry of archaeological objects are now becoming commonplace. Virtual 3D scans are in many cases replacing the drawn record and are leading to objects being more easily accessed, shared and analysed. However, the wholesale production of 3D virtual replicas of artefacts is not always supported by adequate information regarding the multi-sensory nature of artefacts. The visual and geometric aspects are well represented, but the sounds and smells of the artefacts are lost. This paper explores the possible consequences of this and provides some indications of how we may remedy the situation, before our 3D archives become senseless.

Keywords: artefact analysis, photogrammetry, augmented reality, archaeology, 3D scanning

1 Introduction

A simple search for archaeology on the SketchFab online 3D model repository brings back thousands of results for archaeological artefacts. There are currently a large number of campaigns to scan and digitise archaeological and historical artefacts and share them with the world. These range from ongoing excavations (Doneus et al., 2011); institutional collections (Patel, White, Walczak, & Sayd, 2003) and crowd-sourcing initiatives (Bonacchi et al., 2014). Photogrammetry techniques and increasing use of 3D scanners mean that virtual replicas are now extremely low-cost and fast to produce, even for non-experts (Kersten & Lindstaedt, 2012).

By collecting data in this way we are allowing these objects to be shared around the world at millimetre accuracy, with the original colours, patina and toolmarks. We can annotate them with contextual information, light them in ways that would be impossible in real life and even 3D print a copy to put on our desks. Where previously we would have to buy a replica of an object in the museum or site gift shop, we can now take the 3D scan, send it to a 3D printer and have a perfectly scaled replica within a day. Specialists can use the digital replicas for study (Milner et al., 2016; Molloy & Milić, 2018), and as the data is digital hundreds of models can be fed into statistical algorithms to quickly compare and contrast construction or use-wear patterns (Bevan et al., 2014). They can even be used to create powerful political messages, and in some cases have been claimed to 'preserve the past', such as the controversial reconstruction of the triumphal arch from Palmyra (Wahbeh, Nebiker, & Fangi, 2016).

The production of 3D objects by museums and other archaeological projects mean they are becoming widely shared and available to others for further study. The MicroPasts project is a good example of this

Article note: This article is a part of Topical Issue on Exploring Advances in the Use of 3D Models of Objects in Archaeological Research edited by Barry Molloy.

***Corresponding author: Stuart Eve,** L - P : Archaeology 91 Brick Lane, London, E1 6QL, UK, E-mail: stuarteve@lparchaeology.com

(Bonacchi et al., 2014), utilising the power of the crowd to mask out various photographs of artefacts, enabling a smoother and more accurate transition to final 3D model. The industrialisation of the process has worked for the creation of hundreds of models, all of which are now available (currently) for free on the Sketchfab website ("The British Museum on Sketchfab," n.d.).

But what are we losing by creating these digital proxies? Photogrammetry or 3D laser scanning are extremely well placed to reproduce the *visual* fidelity, size and shape of the object, but what are we missing out on? What is lost when we concentrate on the visual? What happens if our current digital tools force us down a path of only being able to capture the visual aspects of an object? We have been here before in archaeology: the obsession with the visual has had long-lasting impacts on the field of landscape archaeology (J. Thomas, 2008), the ocularcentrism of the emergence of GIS analysis of the landscape is still struggled against (Eve, 2012; Gillings, 2012; Llobera, 2007; Rennell, 2009), and, despite a number of both theoretical and practical suggestions, the tendency is still to concentrate on what things looked like rather than how they were felt, experienced and used.

Therein lies the problem with the 3D replica of an object. The results are confined to a screen, to be endlessly spun around, zoomed in and out of and coldly analysed. You cannot smell the incense bottle, or hear the sounds of the musical instrument or feel the heft of the flint axe. Even if it is 3D printed, the plastic replica rarely has the right weight and almost certainly does not reflect light in the same way or have the ringing sound of finely-cast metal when tapped on a table. We are performing what has been called a sensory "self-amputation" (Chrysanthi, Murrieta Flores, & Papadopoulos, 2012, p. 11). In part building on Gartski's recent call to "not simply subsume the next piece of innovative media available to us, but actively engage with how it can be used in the present and future" (2017, p. 745), this paper discusses some ways in which we might reconnect with the multi-sensory nature of 3D digital objects, to couple them with their other sensory aspects and to remember that by privileging the visual over the other senses we are losing the vital essence of the object itself. This paper will open up this area for debate and suggest some steps that we may be able to take to move toward a production of a much-needed methodology for reclaiming our senses in a digital age.

2 An Archaeology with the Senses

Yannis Hamilakis, in his *Eleven Theses on the Archaeology of the Senses*, points out, "…that our enemy is not vision *per se*; it is, rather, the de-corporealization of vision, [and] its divorce from all other sensory modalities" (Hamilakis, 2013, p. 412). He proposes that rather than attempting to produce accurate representations in our objects of past senses we evoke the "…materiality, contingency, and (multi)temporality, not as mimetic exercises or reconstructions but as explorations of the range of sensorial possibilities and affordances" (Hamilakis, 2013, pp. 412–413). This would suggest that the exact recreation of the smell or sound or feel of an artefact is not entirely necessary – indeed we should focus on archaeology *with* the senses rather than archaeology *of* the senses (Hamilakis, 2013, p. 416). It is simply not possible to engage sensorially with archaeological artefacts in exactly the same way as the people who first created them, their bodies, senses, life experiences, memories and minds were sufficiently different for the experience to be unrecognisable to us (as an example see Morley, 2014 for an exploration of the different reactions to the smells of ancient Rome). However, much as modern landscape phenomenologists walk the ground in the hope of using their bodies as proxies for past experiences, we can and should attempt to do the same for our interaction with artefacts (Skeates, 2010). Through combining archaeologically informed contextual information with the opportunities provided by a shared sensing body, it is possible to formulate new ideas about past experiences of material culture and place (Day, 2013, p. 6). The use of the entire body as a sensory organ allows us to move beyond the five classic Aristotelian senses, and explore other intermediate senses such as kinaesthesia (awareness of the position and movements of parts of your body), proprioception (awareness of parts of your body in relation to the world), thermoception (awareness of temperature), the so-called somatic senses (see Paterson, 2011, pp. 266–267 for an exploration of this). How can we take Hamilakis' lead and begin to perform an archaeology *with* the senses and engage with the artefacts in a sensorially

meaningful way? We somehow need to find a way to convert the visceral, embodied experience of an object to a digital record, to allow it to be shared and experienced by others (Chrysanthi et al., 2012). First we need to understand how we currently record and share artefactual information and how we might begin to access, share and experience the multi-sensory nature of the objects, especially if they are fragile or are stored in a remote location.

3 We Have a Lot to Gain, but What Do We Lose?

The purpose of archaeological illustration is to create "a single two dimensional (2D) image that (ideally) communicates clearly to the viewer important attributes of the entire artifact, free of distortion and with relational accuracy, while remaining true to the measured, analytical conventions of the illustrative process" (Carlson, 2014, p. 270). These important attributes are generally stylistic, mechanical, patterning, use-wear and form (Adkins & Adkins, 1989). They are not a true reflection of the multi-sensory elements of the object. For example, the tactile nature of rough pottery can be implied by stippling, and the smooth surface of a flint object can be shown by open space and shadowing. However, neither a drawing nor a computer-created 3D model can actually convey accurately to the viewer how that object feels to pick up and touch; the weight in the hand, or the feeling as it is grasped, turned over and used. 3D renderings of musical instruments cannot accurately convey what that instrument would sound like if played, and a drawing of a leather saddle does not smell like the original or creak when you sit on it. 2D and 3D representation are vital parts of the archaeological record, but I argue that they do not go far enough and by relying on them as our form of 'preservation by record' (Hinton, 2013), we are potentially losing a vast amount of further multi-sensory information about the objects.

The current model is well suited to representing the visual aspects of the artefacts but that is where the multi-sensory experience ends. This problem is two-fold:

1. How do we access or create the multi-sensory nature of the artefacts once they are excavated? They are likely in a fragile condition and often need careful conservation before they can even be looked at, picked up, or smelt, let alone played or drunk from.
2. Even if it is possible to experience the multi-sensory nature of the artefact, how do we then preserve and share that experience so that other researchers can have a similar experience without actually visiting the museum or artefact store?

4 Creating the Sensual

Experimental archaeology goes some way to approaching the first part of the problem (see other articles in this issue: Molloy & Milić, 2018; Dolfini & Collins, 2018; Morris et al., 2018). The re-creation of the artefacts using technology and materials that were available to the original makers can perhaps help us to explore the other sensual aspects of the artefacts. Experimental archaeology employs clear methods for hypothesis-testing, predictive modelling and for validating possible methods of production (Eren et al., 2016). But it also embraces what Thomas called 'the flintknapper's fundamental conceit' (D. Thomas, 1986, p. 623), that is, making things for the sake of making things, and through the very act of making, creating new knowledge (Mathieu, 2002). By re-creating the artefacts themselves from the original materials we can come quite close to how the artefact would have looked, felt and smelt (Coles, 2014) when in use (or at least when first made). However, recreating artefacts using experimental archaeology techniques takes considerable amounts of time and can also be prohibitively expensive in terms of materials or the skill level needed (Kennedy, 2014). For example, the famous gold encrusted dagger found at Bush Barrow in Wiltshire is estimated to have taken over 2,500 hours to properly construct – something that is clearly unfeasible for an experiment (Keys, 2014). While some objects, such as pottery or flint tools, can be (and were in antiquity) mass-produced, finer objects such as jewellery or textile may not be quite as simple to produce and distribute.

An exciting alternative is 3D printing. 3D printing is currently in its infancy: the materials that can be used are limited (mainly plastic derivatives and in some cases reconstituted wood or metal). 3D printing has been shown to be highly effective in conveying the size and shape of objects and also (if properly created) the weight and 'heft' of an object (Di Franco, Camporesi, Galeazzi, & Kallmann, 2015; Means, 2015). The technology is moving forward at a terrific rate, and is becoming cheaper and more ubiquitous (Jiang, Kleer, & Piller, 2017; Karin, 2011). The creation of a 3D printed object, however, can currently only go so far in terms of recreating the sensual aspects of the original artefact. It is rare to find 3D printed objects that smell like the original and while flexible materials are available to be printed with, the technology is not yet far enough advanced to produce convincing organic replicas, although Neumüller et al. (2014), in their discussion of best practices for 3D printing in cultural heritage, believe it is only a matter of time before this becomes the case.

However, to completely replicate the object from a 3D digital record we first need to record the multi-sensory aspects themselves. And therein lies the heart of the problem. The visual aspects of artefacts are usually quite easy to record: we can draw and/or photograph them, we can accurately measure their weight (although even this is controversial – see VanPool & Leonard, 2011) and we can give a written description. Archaeologists are responsible human beings, we record everything we can in as full a way as is possible. But some aspects are just extremely hard to record. For example, although we use the Munsell colour chart to record a colour of an earth or a clay, even this is a subjective interpretation of the colour that may vary from person to person (Gerharz, Lantermann, & Spennemann, 1988). How do you even *record* a smell, never mind *recreate* it? We can describe how things feel, soft, hard, smooth, rough, etc., but the written description is never sufficient. The difficulty of describing and recording the other senses is likely to be one of the reasons that we as archaeologists rarely record them. The ocularcentrism of recording in archaeology as discussed by Thomas and others (Day, 2013, pp. 4–5; Rennell, 2009, pp. 37–49; J. Thomas, 2008), may be because we do not have the tools or skill-set to accurately record anything but the visual. Much as sommeliers learn to use their nose and tastebuds to recognise and appreciate fine wines, archaeologists must become re-sensualised – we can only appreciate and record the aspects of the other senses if we are aware of them. Should we be teaching our students to smell and hear as well as draw and take photographs?

The sound of an object is slightly easier to record. We have available technology for recording the acoustic properties of spaces and objects: Catriona Cooper has clearly outlined a methodology for recording and analysing the acoustic properties of medieval spaces (Cooper, 2014); and the sub-disciplines of music archaeology (Both, 2009) and acoustic archaeology (Murphy, Shelley, Foteinou, Brereton, & Daffern, 2017; Scarre & Lawson, 2006) have shown that replicas of objects can be made and their sounds accurately recorded. Movements are being made toward the recording of heritage smells, particularly through the work of Cecilia Bembibre who has had some success using headspace solid phase microextraction along with gas chromatography-mass spectrometry (Bembibre & Strlič, 2017). She uses specialised equipment to record the chemical composition of the air above an archaeological artefact – effectively capturing its smell - and then analyses and lists its component parts, meaning it should be able to recreate the smell in the future. But this is still far from being an everyday part of archaeological practice. However, just because something is *difficult* does not mean we should not try to achieve it. Even the act of trying to record the other senses can bring them to the forefront of ones mind and make us think about how we use and interact with objects in a different way. This is reflected through the work of the artist Kate McLean, who conducts 'smellwalks' around different cities and reports that her subjects frequently comment "paying attention to smells made me stop and pay more attention in the environment around me" (McLean, 2017). Further collaborative work between archaeologists and artists may enable us to be more reflexive in our attention to the sensory aspects of our work (see Pearson & Shanks, 2001 for examples of archaeological insights from collaborations with theatre practitioners). The role of memory and storytelling in our sensory engagement should also be considered, something that has been explored in detail by scholars such as Sarah Kenderdine (2015) and also attempted successfully by the CHESS Project (Pujol et al., 2012), with the creation of an application that based on your responses to a survey assigns you to a specific persona on a museum visit – allowing you to follow a personally curated journey around the exhibits.

5 Sharing the Sensual

Let us fast-forward a little and assume that we can in some way record the sounds and smells of artefacts, either by recording the sensual aspects of the originals or by using replica artefacts made from similar materials. How do we then share them with other researchers in a simple and easy way, the same way that we share the visual aspects via the 3D models of Sketchfab? One solution may be to use the emerging technologies of Augmented Reality (AR). Augmented Reality (Schnabel, Wang, Seichter, & Kvan, 2007) along with Virtual Reality (VR) are parts of the wider concept of Mixed Reality (MR): essentially, the melding of the real world with the digital world.

VR sits at one end of the Mixed Reality scale: the entire experience is created within and experienced through a computer interface. Sketchfab has a VR mode, that allows a user with the correct equipment to view and manipulate the virtual artefact whilst wearing VR goggles and using VR controllers. An ambitious project was started in 2009 to create a 'Virtual Cocoon', a VR headset that, when worn, would simulate all of the five senses (Chalmers, Howard, & Moir, 2009), but this product is yet to come on the market, and unfortunately it seems that work on it has stalled – but it nevertheless represents an early attempt to tackle the problem of delivering multi-sensory experiences. When you are within the VR space, you are entirely within the virtual world: the goggles and headphones create a barrier between the body and the real world. This can lead to extremely emotive experiences (Schultheis & Rizzo, 2001), but also has the effect of detaching the user from the real world. Augmented Reality, by contrast, seeks to keep the connection with the real world and utilise the power of the digital to 'insert' digital artefacts into that real world. A mainstream example of this technology is the AR game Pokémon Go, where the user employs their smartphone to 'hunt' cartoon Pokémon creatures. The Pokémons are only visible in the real world by holding up the smartphone and viewing the world through the camera.

AR has been explored in some depth for archaeological applications (Benko, Ishak, & Feiner, 2004; Eve, 2012, 2014), and has enormous potential to become the delivery mechanism for a more multi-sensory experience of virtual artefacts. Currently a simple form of AR is experienced through the use of a see-through Head-Mounted Display (HMD), for instance a smartphone inserted into a pair of goggles such as Google Cardboard (Fabola, Miller, & Fawcett, 2015). Other AR headsets are well into development, such as the Microsoft Hololens or the Magic Leap, and as early as 1998, the AR interface was being hailed as the next generation of computer and mouse technology (Mackay, 1998).

When using the smartphone example, the user is shown the real world mediated through the camera feed of the smartphone. This feed allows a 1:1 interaction with the real world, which can also be augmented with the virtual objects. The position and size of these objects are currently governed by 2D- or 3D printed markers. Sounds are delivered through bone-conducting headphones that allow the virtual sounds to meld with the real world sounds, rather than to entirely obscure them (Eve, 2014, p. 115). The live delivery of smells is currently under development by industry and is currently not readily available at a consumer level; however some experiments have been undertaken (Chalmers et al., 2009; Eve, 2017) that are moving closer to being able to deliver on-demand smell combinations via a worn and mobile device. Tactile interaction can be delivered through gloves (or even body-suits) or a force-feedback apparatus (Ch'ng, 2009, p. 463), but again this is still a burgeoning technology and perhaps by augmenting a 3D-printed object the illusion of touch could be better simulated.

Using these technologies, a possible workflow for experiencing a multi-sensory 3D virtual copy of a real artefact could be as follows. As already discussed, the visual aspects of the artefact are easily represented by a 3D model created from 3D scanning or photogrammetry. This 3D model can then be programmed with the weight information and the proper physics of its 'heft' can be calculated. At this point decisions would need to be made about the appropriate material and colour for the object. Using AR would enable other real world objects to interact with the virtual object. For example, if the virtual object is a drum then it should interact when a real drumstick hits it (Lobo, 2015); or a virtual bronze spearhead should be programmed to fall and settle in the correct way when it is dropped onto a real table. This is where the results from experimental archaeology may become vital. The experimental model could be used to calibrate the physics of the spearhead as it falls or flies through the air. This calibration information should

form part of the metadata about the 3D model in the repository. In addition, the sound that the spearhead makes when it hits a wooden table or a metal table or thuds into an organic body could also be recorded and stored alongside the virtual model. If the smell of the original or the experimental replica have been captured, then they can also be stored as metadata alongside the model. There is currently no standard for this data, but a record of the volatile organic compounds (VOC) could be used (Bembibre & Strlič, 2017, p. 4). As much information about the surface and 'feel' of the object as possible should also be recorded and stored, perhaps by using the standards laid out by the industrial sector (Sharma, 1999, pp. 426–428).

When the AR interface is used, the object itself is augmented into the real world at the correct scale: that is, the spearhead is the correct size in the hand, something very hard to judge from the normal presentation of 3D models within a wholly virtual environment (such as the Sketchfab interface). Once the augmented model is created it can be interacted with in the same way as a 'real' object. It can be moved, turned, held and if dropped, hit or even blown; the stored sounds can be augmented alongside the 3D model, allowing a closer and more natural interaction with the object itself. Depending on the smell technology used, a reproduction of the smell can be released as the object is moved closer or further away from the user's nose.

6 Towards a Practical Approach to Digital Sensory Archaeology

However, the workflow and vision as I have outlined it is currently unfeasible for the majority of archaeologists and museums. It involves a high investment in knowledge acquisition (learning the tools and technologies); a deep knowledge of experimental archaeological techniques (if replicas are too made as proxies for the sensory aspects of the originals); further development of sensory capture techniques (such as smell capture); and the computing resources and infrastructure to store and share the sensory digital objects. The production of a full multi-sensory archival record of either newly excavated of current archival artefacts is currently out of reach for commercial archaeological units and most museums.

Throughout this paper I have outlined some initial ways that the sensory nature of objects can be recorded and I propose an Augmented Reality interface as an appropriate way to experience those virtual representations. However, there is a long journey to be undertaken before the vision becomes a reality. Standards will need to be written to govern the sharing and production of the multi-sensory information; policies will need to be devised outlining which artefacts or types of artefacts the multi-sensory approach is appropriate for (presumably not every pot sherd will warrant the effort); current and emerging technologies (such as mobile phones or mixed reality devices) will need to be mastered; prototypes will need to be produced and tested; and a multi-disciplinary approach will need to be undertaken including sensory scientists, computing experts, archaeologists and end-users.

The main aim of this paper was to bring the multi-sensory nature of the artefacts to the fore. 3D scanning is increasingly being seen as a quick and easy way of preserving artefacts and archaeological objects, the controversy over the 3D-printed Palmyra arch is testament to this. The danger of relying on the current technologies for creating 3D representations of the artefacts is that they almost solely concentrate on recording the visual aspects. The tactile, olfactory, acoustic and even gustatory properties are entirely forgotten and removed from the 3D record. Recording these extra sensory aspects is hard, which is part of the reason why it is not done – but there is a deeper societal issue here too: modern Western culture has become obsessively visual, perhaps due to the technological developments of the 20th century which have led to humanity being able to *see itself more*. But because it is difficult does not mean that it should not be attempted. Technology is relentlessly driving the advancement of archaeological method and the ubiquity of certain technologies (such as photogrammetry and 3D scanners) has vastly increased the volume of 3D representations of both sites and artefacts. This is of course a good thing in many ways, but not if it means that other aspects of the archaeological record are being ignored because they are too hard to capture. We must not be guilty of blindly following the latest technological advance, without thinking through the ways in which we work to produce knowledge.

There is a very real possibility that the production of virtual 3D representations of objects will advance to such a point that the keeping of the original will no longer be necessary. How long is it until the museums

run out of space and introduce the policy that a 3D virtual representation is enough, and the original can be discarded? Museums have varied discard policies, but as more material is removed from the ground and the physical storage space of museums is reduced, these discard policies are likely to become more aggressive. When we reach this point, we must be entirely sure that our 3D virtual copies are the best that they can possibly be. Currently, we are only recording accurately one of the five Aristotelian sensory aspects of the object, without even beginning to approach the effects the artefacts have on our other somatic senses. Without the addition of information about the smells, sounds, feel and even taste of our artefacts, then our digital record captures only a fifth of the whole object – and our knowledge of the past world is all the poorer for it.

Acknowledgements: Many thanks to Barry Molloy and Marina Milić for inviting me to the Breaking the Mould workshop and to the other participants for an extremely enjoyable and inspiring two days. Thanks also to the two anonymous reviewers and Anna Collar who all made essential suggestions leading to a much improved manuscript.

References

Adkins, L., & Adkins, R. (1989). *Archaeological illustration*. Cambridge ; New York: Cambridge University Press.

Bembibre, C., & Strlič, M. (2017). Smell of heritage: a framework for the identification, analysis and archival of historic odours. *Heritage Science*, *5*(1), 2. https://doi.org/10.1186/s40494-016-0114-1

Benko, H., Ishak, E. W., & Feiner, S. (2004). Collaborative mixed reality visualization of an archaeological excavation. In *ISMAR 2004. Third IEEE and ACM International Symposium on Mixed and Augmented Reality, 2004.* (pp. 132–140). IEEE.

Bevan, A., Li, X., Martinón-Torres, M., Green, S., Xia, Y., Zhao, K., … Rehren, T. (2014). Computer vision, archaeological classification and China's terracotta warriors. *Journal of Archaeological Science*, *49*, 249–254.

Bonacchi, C., Bevan, A., Pett, D., Keinan-Schoonbaert, A., Sparks, R., Wexler, J., & Wilkin, N. (2014). Crowd-sourced Archaeological Research: The MicroPasts Project. *Archaeology International*, *17*(0). https://doi.org/10.5334/ai.1705

Both, A. A. (2009). Music archaeology: some methodological and theoretical considerations. *Yearbook for Traditional Music*, *41*, 1–11.

Carlson, E. S. (2014). Representation and Structure Conflict in the Digital Age Reassessing Archaeological Illustration and the Use of Cubist Techniques in Depicting Images of the Past. *Advances in Archaeological Practice*, *2*(4), 269–284.

Ch'ng, E. (2009). Experiential archaeology: Is virtual time travel possible? *Journal of Cultural Heritage*, *10*(4), 458–470. https://doi.org/10.1016/j.culher.2009.02.001

Chalmers, A., Howard, D., & Moir, C. (2009). Real Virtuality: A Step Change from Virtual Reality. In *Proceedings of the 25th Spring Conference on Computer Graphics* (pp. 9–16). New York, NY, USA: ACM. https://doi.org/10.1145/1980462.1980466

Chrysanthi, A., Murrieta Flores, P., & Papadopoulos, C. (2012). Archaeological computing: towards prosthesis or amputation? Retrieved from https://eprints.soton.ac.uk/209557/

Coles, J. (2014). *Archaeology by experiment* (Vol. 16). Routledge.

Cooper, C. (2014, December). *The exploration of lived experience in medieval buildings through the use of digital technologies* (phd). University of Southampton. Retrieved from https://eprints.soton.ac.uk/377916/

Day, J. (2013). Introduction: Making Senses of the Past. In *Making Senses of the Past: Toward a Sensory Archaeology* (pp. 1–31). SIU Press.

Di Franco, P. D. G., Camporesi, C., Galeazzi, F., & Kallmann, M. (2015). 3D printing and immersive visualization for improved perception of ancient artifacts. *Presence*, *24*(3), 243–264.

Dolfini, A. & Collins, R. (2018). Modelling Physical and Digital Replication: Bridging the Gap Between Experimentation and Experience. *Open Archaeology*, 4(1), 36–49. https://doi.org/10.1515/opar-2018-0002

Doneus, M., Verhoeven, G., Fera, M., Briese, C., Kucera, M., & Neubauer, W. (2011). From deposit to point cloud–a study of low-cost computer vision approaches for the straightforward documentation of archaeological excavations. *Geoinformatics FCE CTU*, *6*, 81–88.

Eren, M. I., Lycett, S. J., Patten, R. J., Buchanan, B., Pargeter, J., & O'Brien, M. J. (2016). Test, Model, and Method Validation: The Role of Experimental Stone Artifact Replication in Hypothesis-driven Archaeology. *Ethnoarchaeology*, *8*(2), 103–136. https://doi.org/10.1080/19442890.2016.1213972

Eve, S. (2012). Augmenting Phenomenology: Using Augmented Reality to Aid Archaeological Phenomenology in the Landscape. *Journal of Archaeological Method and Theory*, *19*(4), 582–600. https://doi.org/10.1007/s10816-012-9142-7

Eve, S. (2014). *Dead Men's Eyes: Embodied GIS, Mixed Reality and Landscape Archaeology*. BAR British Series 600, 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

Fabola, A., Miller, A., & Fawcett, R. (2015). Exploring the past with Google Cardboard. In *Digital Heritage, 2015* (Vol. 1, pp. 277–284). IEEE.

Garstki, K. (2017). Virtual Representation: the Production of 3D Digital Artifacts. *Journal of Archaeological Method and Theory*, *24*(3), 726–750. https://doi.org/10.1007/s10816-016-9285-z

Gerharz, R. R., Lantermann, R., & Spennemann, D. R. (1988). Munsell color charts: A necessity for archaeologists? *The Australian Journal of Historical Archaeology*, 88–95.

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

Hamilakis, Y. (2013). Afterword: Eleven Theses on the Archaeology of the Senses. In *Making Senses of the Past: Toward a Sensory Archaeology* (pp. 409–419). SIU Press.

Hinton, P. (2013). The National Planning Policy Framework and Archaeology: A Response – How did the Profession come to this? *Papers from the Institute of Archaeology*, *22*(0). https://doi.org/10.5334/pia.392

Jiang, R., Kleer, R., & Piller, F. T. (2017). Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technological Forecasting and Social Change*, *117*, 84–97.

Karin, J. (2011, July 4). The Future of 3D Printing. Retrieved May 8, 2017, from http://thefutureofthings.com/4664-the-future-of-3d-printing/

Kenderdine, S. (2015). Embodiment, Entanglement, and Immersion in Digital Cultural Heritage. In *A New Companion to Digital Humanities* (pp. 22–41). John Wiley & Sons, Ltd. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/9781118680605.ch2/pdf

Kennedy, M. (2014, September 18). Stonehenge: children revealed to be the metal workers of prehistoric Britain. *The Guardian*. Retrieved from https://www.theguardian.com/uk-news/2014/sep/18/stonehenge-gold-workers-metal-children-eyesight

Kersten, T., & Lindstaedt, M. (2012). Image-based low-cost systems for automatic 3D recording and modelling of archaeological finds and objects. *Progress in Cultural Heritage Preservation*, 1–10.

Keys, D. (2014, September 17). Was Stonehenge's prehistoric bling all down to child labour? Retrieved October 2, 2017, from http://www.independent.co.uk/news/science/archaeology/stonehenges-most-intricate-archaeological-finds-were-probably-made-by-children-9738993.html

Llobera, M. (2007). Reconstructing visual landscapes. *World Archaeology*, *39*(1), 51. https://doi.org/10.1080/00438240601136496

Lobo, N. (2015). V-Drum : An Augmented Reality Drum Kit. *International Journal of Advanced Research in Computer and Communication Engineering*, *4*(10), 295–299.

Mackay, W. E. (1998). Augmented reality: linking real and virtual worlds: a new paradigm for interacting with computers. In *Proceedings of the working conference on Advanced visual interfaces* (pp. 13–21). ACM.

Mathieu, J. (Ed.). (2002). Introduction. In *Experimental archaeology, replicating past objects, behaviors and processes* (Vol. 1035, pp. 1–11). Oxford: BAR International Series.

McLean, K. (2017, April 27). "Paying attention to smells made me stop and pay more attention in the environment around me" #smellwalk for @NYC_DOT arts @RCACommResearch [microblog]. Retrieved May 5, 2017, from https://twitter.com/katemclean/status/857556675317948416

Means, B. K. (2015). Promoting a More Interactive Public Archaeology: Archaeological Visualization and Reflexivity through Virtual Artifact Curation. *Advances in Archaeological Practice*, *3*(3), 235–248. https://doi.org/10.7183/2326-3768.3.3.235

Milner, N., Bamforth, M., Beale, G., Carty, J., Chatzipanagis, K., Croft, S. C. K., … Knight, B. (2016). A Unique Engraved Shale Pendant from the Site of Star Carr: the oldest Mesolithic art in Britain. *Internet Archaeology*.

Molloy, B. & Milić, M. (2018). Wonderful Things? A Consideration of 3D Modelling of Objects in Material Culture Research. *Open Archaeology*, 4(1), 97–113. https://doi.org/10.1515/opar-2018-0006

Morley, N. (2014). Urban Smells and Roman Noses. In M. Bradley (Ed.), *Smell and the Ancient Senses* (1 edition, pp. 110–119). London ; New York: Routledge.

Morris, C., Peatfield, A., & O'Neill, B. (2018). 'Figures in 3D': Digital Perspectives on Cretan Bronze Age Figurines. *Open Archaeology*, 4(1), 50–61. https://doi.org/10.1515/opar-2018-0003

Murphy, D., Shelley, S., Foteinou, A., Brereton, J., & Daffern, H. (2017). Acoustic Heritage and Audio Creativity: the Creative Application of Sound in the Representation, Understanding and Experience of Past Environments. *Internet Archaeology*. https://doi.org/10.11141/ia.44.12

Neumüller, M., Reichinger, A., Rist, F., & Kern, C. (2014). 3D Printing for Cultural Heritage: Preservation, Accessibility, Research and Education. In *3D Research Challenges in Cultural Heritage* (pp. 119–134). Springer, Berlin, Heidelberg. Retrieved from https://link.springer.com/chapter/10.1007/978-3-662-44630-0_9

Patel, M., White, M., Walczak, K., & Sayd, P. (2003). Digitisation to presentation: building virtual museum exhibitions. *Vision, Video and Graphics 2003*.

Paterson, M. (2011). More-than visual approaches to architecture. Vision, touch, technique. *Social & Cultural Geography*, *12*(3), 263–281. https://doi.org/10.1080/14649365.2011.564733

Pearson, M., & Shanks, M. (2001). *theatre/archaeology*. London: Routledge.

Pujol, L., Roussou, M., Poulou, S., Balet, O., Vayanou, M., & Ioannidis, Y. (2012). Personalizing interactive digital storytelling in archaeological museums: the CHESS project. In *40th annual conference of computer applications and quantitative methods in archaeology. Amsterdam University Press*. Retrieved from http://www.chessexperience.eu/phocadownload/papers/caa2012_paper_final.pdf

Rennell, R. (2009). *Exploring places and landscapes of everyday experience in the Outer Hebridean Iron Age: a study of theory, method and application in experiential landscape archaeology* (Doctoral). UCL (University College London). Retrieved from http://discovery.ucl.ac.uk/1348202/

Scarre, C., & Lawson, G. (Eds.). (2006). *Archaeoacoustics*. Cambridge: McDonald Institute for Archaeological Research.

Schnabel, M. A., Wang, X., Seichter, H., & Kvan, T. (2007). From Virtuality to Reality and Back. In *Proceedings of the IASDR 2007 Conference*. The Hong Kong Polytechnic University.

Schultheis, M. T., & Rizzo, A. A. (2001). The application of virtual reality technology in rehabilitation. *Rehabilitation Psychology*, *46*(3), 296.

Sharma, P. C. (1999). *A Textbook of Production Engineering*. S. Chand.

Skeates, R. (2010). *An archaeology of the senses: Prehistoric Malta*. Oxford: Oxford University Press.

The British Museum on Sketchfab. (n.d.). Retrieved May 8, 2017, from https://sketchfab.com/britishmuseum

Thomas, D. (1986). Points on Points - a Reply to Flenniken and Raymond. *American Antiquity*, *51*(3), 619–627. https://doi.org/10.2307/281758

Thomas, J. (2008). On the ocularcentrism of archaeology. In V. Jorge & J. Thomas (Eds.), *Archaeology And The Politics Of Vision In A Post-Modern Context* (new, pp. 1–12). Cambridge Scholars Publishing.

VanPool, T. L., & Leonard, R. D. (2011). *Quantitative Analysis in Archaeology*. John Wiley & Sons.

Wahbeh, W., Nebiker, S., & Fangi, G. (2016). Combining Public Domain and Professional Panoramic Imagery for the Accurate and Dense 3D Reconstruction of the Destroyed Bel Temple in Palmyra. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sci*ences, 3(5).