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Original Study

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# Modelling Physical and Digital Replication: Bridging the Gap Between Experimentation and Experience

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**Abstract:** The replication of objects lies at the heart of material culture research in archaeology. In particular, replication plays a key role in a number of core activities in our discipline including teaching, research, and public engagement. Despite its being fundamental to the archaeological process, however, replication comes across as an under-theorised field of artefact research. The problem is compounded by the recent development of digital technologies, which add a new layer of challenges as well as opportunities to the long-established practice of making and using physical copies of objects. The paper discusses a number of issues with artefact replication including aims, design, and methodology, from the standpoint of two research projects currently coordinated by the authors: the Bronze Age Combat project, which explores prehistoric fighting techniques through field experiments and wear analysis (Dolfini); and the NU Digital Heritage project, which centres upon the digital capture and modelling of Roman material culture from Hadrian's Wall (Collins). Both projects have actively created replicas in physical or digital media, and direct comparison of the two projects provide a number of useful lessons regarding the role, uses, and limits of artefact replication in archaeology.

Bronze Age Combat project: http://research.ncl.ac.uk/cias/research/bronzeagecombat/
NU Digital Heritage project: http://research.ncl.ac.uk/cias/research/nudigitalheritage/

**Keywords:** Object replication, experimental archaeology, experience, digital technologies, Bronze Age, Roman

## 1 Introduction

Archaeological objects are normally replicated in the context of experimental archaeology. According to Mathieu:

> Experimental archaeology is a sub-field of archaeological research which employs a number of different methods, techniques, analyses, and approaches within the context of a *controllable* imitative experiment to *replicate past phenomena* (from objects to systems) in order to *generate and test hypotheses* to provide or enhance *analogies for archaeological interpretation.*
>
> (Mathieu, 2002, p. 1; emphasis in the original text)

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This definition has three important implications for our understanding of the context in which archaeological objects are replicated. Firstly, objects are manufactured and used as part of a goal-oriented scientific enquiry, in which the formulation of a research hypothesis precedes experimentation in the laboratory or the field. Secondly, the methodology employed for the construction and testing of the objects must be laid out explicitly. In particular, it must ensure control of a number of significant variables and, at least ideally, it must be repeatable by other researchers interested in validating the experimental results independently. Lastly, the process of object replication and experimentation must be tied to archaeological realities through reference to past phenomena, be they single objects or complex behaviours. The overarching aim of the exercise is to provide or enhance analogies for interpretation of the past. Here lies, according to Mathieu, the real value of experimental archaeology, which offers a context for critically appraising the role of analogy in social enquiries (see also Bell, 2015; Outram, 2008; Mathieu & Mayer, 2002).

Archaeological objects, however, may also be replicated for purposes and within contexts that cannot be construed as research, or with methods and procedures which are dramatically at variance with those of science. The former includes a diverse array of activities such as teaching, public engagement, the enhancement of exhibitions and museum displays, medical therapy, and arts performances (Chatterjee, 2008; Hansen, 2008; Spence & Gallace, 2008). These 'non-research' contexts may utilise modern materials and processes (including 3D printing) for the construction of physical replicas, but may also involve the computer generation of 2D and 3D digital replicas solely intended for virtual environments. The use of modern materials or digital technology in the production of such replicas has a number of advantages, including lower costs and reduced risk of damage to irreplaceable archaeological material. The disadvantage, however, is that such replicas often do not convey the full sensory or experiential aspect that can be attained while handling genuine archaeological material, or carefully researched and produced 'authentic' physical replicas.

Research and non-research contexts are frequently seen as irreconcilable environments, which are separated by an unbridgeable gulf, or are at best ordered by a rigid hierarchy of value (Outram, 2008; Reynolds, 1999). According to this reading, the higher rung in the value ladder would be occupied by experimentation as a legitimate scientific endeavour. Within this realm, objects are made and tested based on tightly controlled methods in order to generate or validate clearly formulated hypotheses concerning past materials, processes, and behaviours. The lower rung, on the other hand, would be crowded by a penumbra of hazily defined re-enactment activities, educational demonstrations, and leisurely experiences, which seem to lack any unifying marker. They are normally grouped under the somewhat belittling term of 'experiences'. Conventional wisdom has it that the two contexts are best kept separated, for the latter risk contaminating the noble quest of the former with their colourful but fundamentally flawed enterprises (see in particular Reynolds, 1999, p. 159 for a disparaging view of re-construction, re-enactment, and other 're-prefixed' activities in archaeology).

## 2 Mind the Gap: Bridging Experiment and Experience

In this paper, we want to challenge this long-held hierarchy of value by presenting a framework for the replication and usage of archaeological objects in a diverse suite of activities ranging from research to recreation. Our framework is grounded in a heterodox application of the concept of the *chaîne opératoire*, which draws from Geneste's (1989) theorising it as a methodological procedure for unlocking the spatial and temporal elements of ancient technologies and production sequences (see also Audouze, 1999; Bar-Yosef & Van Peer, 2009; Schlanger, 1990, 2005 for discussion). On a broader level, our model also reflects the cyclic, iterative process intrinsic to the scientific method, in which observation, hypothesis formulation, hypothesis testing, and the development of general theories are inextricably tied together, and in turn lead to new questions and hypotheses (Gauch, 2003). Therefore, we have constructed our framework as a circular self-feeding flowchart, whose steps are defined by the specific aims and characteristics of the activity being conducted. As is explained below, such a flowchart better reflects the interdigitating nature of the processes surrounding artefact replication and analysis than more traditional, linear diagrams, which have a set beginning and a set end. Contrary to a linear process, we co-locate the beginning and the end of the reconstruction process as being in a constant (and often precariously balanced) state of tension. This mirrors the tension between hypothesis generation and hypothesis testing implicit in Mathieu's definition, as well as in any scientific enquiry (see above). Perhaps more importantly, our approach intends to provide the theoretical and methodological basis for a much-needed rapprochement between experiment and experience, thus addressing what many, including ourselves, increasingly perceive as a false dichotomy (Cunningham et al., 2008; Doonan, 2013; Hansen, 2008; Millson, 2010).

In line with this approach, we have constructed our flowchart in the shape of a wheel, in which the hub stands for the question driving the replication and utilisation process (Fig. 1). For research pursuits, this will be the question or problem driving the enquiry, while for other activities it will be whatever question, aim or need compels archaeologists and craft practitioners to replicate past objects. This could be, for instance, the need to provide museum visitors with a handling medium, which replaces valuable or fragile original artefacts (Spence & Gallace, 2008). The spokes indicate the research activity that connects the central question with a discrete step, inclusive of the required methods. The multiplicity of spokes and steps recognise the diversity of research activities and methods encompassed within a project. These steps, indicated along the outer rim of the wheel, are not predetermined, for they are defined by the nature of the activity being undertaken. We maintain that all activities, be they research-oriented or otherwise, must always entail a research element, which critically ties together conceptualisation and realisation. Not only do we argue that this must be central to any meaningful endeavour concerned with the construction and utilisation of replica objects; we also insist that each major step in the process must involve a certain amount of research, whose exact nature and extent must be defined by the archaeologist or craftsperson based on the aim of their project.

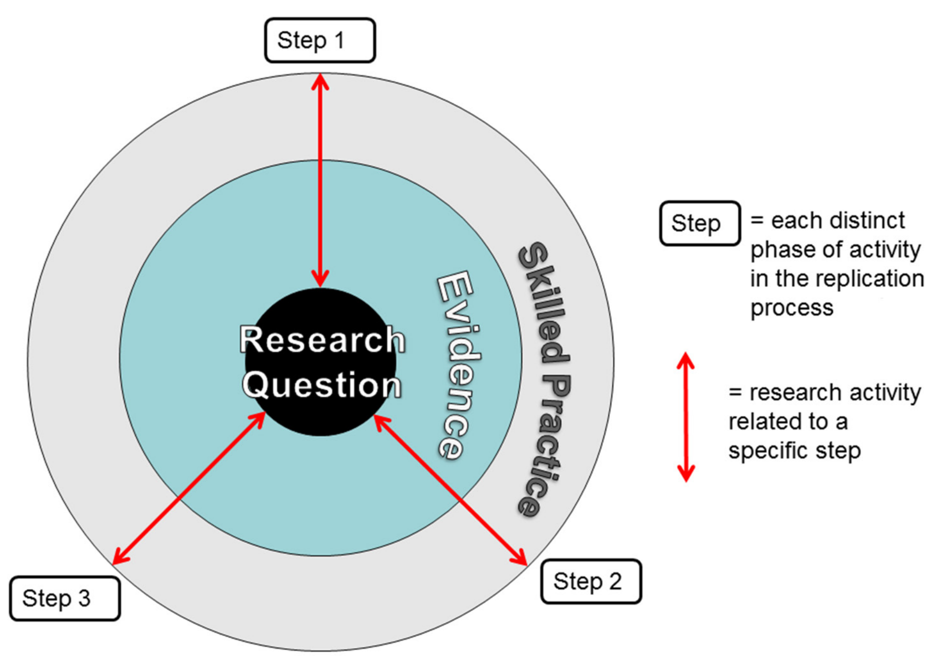


**Figure 1.** A template of our proposed workflow model.

In our wheel, the wedges formed by the spokes between the hub and the outer rim are filled by two superimposed layers that we have identified as the evidential framework and skilled practice within which the replication and utilisation exercise is carried out. The inner layer consists of the physical evidence available in the archaeological and historical record. This is frequently partial. With archaeological material, preservation issues may cause the alteration or decay of significant elements of objects. The investigators must thus fill the missing parts before they can reconstruct the objects meaningfully. In the case of completely decayed objects (e.g. basketry: Hurcombe, 2008, 2014), no physical evidence will be available to guide the reconstruction process, and the investigator must infer the materials, construction technology, and outer look of the object by other means (e.g. via textual or iconographic sources, or ethnographic analogy). Textual and art historical evidence can sometimes provide detailed technical descriptions, though the quality and precision of such evidence is both highly variable and frequently limited in its applicability to replication. Moreover, textual sources may notoriously pose serious interpretative problems, to the point that using them for our reconstructions of past objects and practices can be an extremely subjective and challenging exercise (Molloy, 2008, p. 118).

The outer layer stands for the skilled practice, which is a fundamental component of any replication and utilisation pursuit. Skilled practice is intended here in a broad sense, which on the one hand comprises 'ancient' (i.e. reconstructed) and traditional artisan skills as well as mastery of complex body-centred practices (e.g. the playing of a musical instrument or proficiency in historic martial arts: Molloy, 2008). On the other hand, however, we propose extending the concept of skilled practice as far as to include the analytical, technical, or computing skills needed by the investigator to identify and process appropriate materials, and also to replicate, test, or otherwise use the object (e.g. knowledge of a 3D imaging software or the ability to engineer a testing rig). In this context, we regard as artificial any distinction one may draw between the 'rigorous' testing of replica objects in a laboratory environment and their 'actualistic' (*sensu* Molloy, 2008, p. 119; Outram, 2008, p. 2) experimentation in the field. As others have done before us, we maintain that either approach is valuable in its own right, and it may be necessary to use both jointly to arrive at a meaningful understanding of extinct objects and practices (Crellin et al., in press; Cunningham et al., 2008; Doonan & Dungworth, 2013, pp. 5–6; Outram, 2008). Crucially, our stance allows for the placing of both ancient/traditional and modern technical skills under a unifying theoretical umbrella – something John Coles himself considered desirable while first articulating the principles of experimental archaeology (Coles, 1973, p. 16).

Archaeometallurgy provides a useful example of the complex intertwining of ancient/traditional craft skill and modern scientific knowledge, for one must normally master both before s/he can reconstruct and test ancient metalwork in any meaningful way (Dolfini & Crellin, 2016, p. 81; Heeb, 2014; Heeb & Ottaway, 2014; Kienlin & Ottaway, 1998; see also below). The complexity of the task in hand cannot be underestimated, especially when seeking to understand long-extinct technologies, reconstruct especially intricate operational sequences, or appraise the utilisation of objects that have no parallels in the ethnographic record (e.g. prehistoric halberds: O'Flaherty, 2007; O'Flaherty et al., 2011). In all these cases, multifaceted research strategies are to be put in place in order to unlock each and any step of the reconstruction and utilisation process. Research must thus be conceptualised as a two-way, continuous, and targeted procedure tailored to the specific needs of the task in hand. In our model, this is visually expressed by the wheel spokes running through the two layers to tie together the research question, physical evidence, and skilled practice informing the experimental work.

We shall illustrate this framework by presenting two case studies in the replication of archaeological objects. The first is a research project seeking to reconstruct Late Bronze Age fighting styles by means of controlled combat experiments with replica swords, spears, and shields. The second is a project experimenting in digital capture using Roman stone monuments and artefacts from Hadrian's Wall. We will try to show that the framework proposed in this article has enhanced our understanding of the replication and utilisation process in both projects. We will also argue that its application can help break down disciplinary barriers and bridge the gap between experiment and experience, while at the same time maintaining a useful distinction between meaningful and futile replication exercises.

## 3 Bronze Age Combat: The Physical Replication of Objects

The Bronze Age Combat project was launched in 2013 in order to explore fighting styles and techniques in late 2nd millennium BC Europe. It seeks to investigate uses of Bronze Age swords, shields and spears based on a combination of wear analysis and tests with replica weapons. The aim of the project is to understand how prehistoric bronze weapons were used, in what kind of combat situations, and with what weapon strikes and bodily engagements. One of its main objectives was to explore the possibility of linking distinctive combat marks (identified by wear analysis of archaeological and experimental objects: Dolfini & Crellin, 2016) with specific uses of the weapons including strikes, blocks (or 'parries' in swordplay jargon), stabs, and throws. Due to its multidisciplinary nature, the project has engaged specialists in Bronze Age studies (Marion Uckelmann, Durham), wear analysis (Rachel Crellin, Leicester, and PhD candidate Raphael Hermann, Newcastle), and metallurgical analysis (Quanyu Wang, British Museum), coordinated by one of the authors (Andrea Dolfini, Newcastle). It has also enjoyed invaluable inputs from craft practitioners, historic fighters, and other researchers (Crellin et al., in press; Hermann et al., in press).

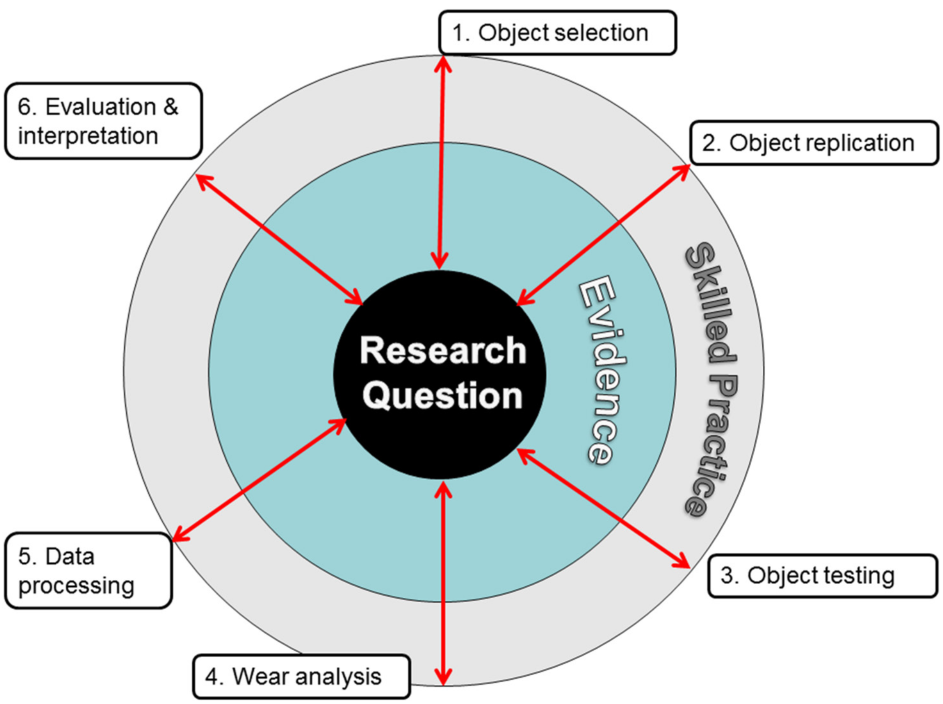


**Figure 2.** Our model, as utilised by the Bronze Age Combat project.

The project comprised the following major steps: (1) object selection; (2) object replication; (3) object testing; (4) wear analysis of experimental and archaeological weapons; (5) data processing and interpretation; and (6) evaluation of the experimental data against the archaeological record (Fig. 2). In line with the scope of the article, only the first two steps will be discussed here, i.e. object selection and object replication. The discussion will centre on swords as they presented us with a particularly challenging set of problems.

### 3.1 Object Selection

Selecting the weapons to be cast, finished, and tested involved a multi-stranded approach to the archaeological and metallurgical evidence. Within Bronze Age studies, a great deal of scholarship has been devoted to swords. This, however, has largely concentrated on issues of typological classification, best exemplified by the *Prähistorische Bronzefunde* series. These reference volumes provide specialists with an invaluable tool for researching the chronology and find context of prehistoric swords on a broad European scale, but do not give them any inkling as to their past uses as actual instruments of violence (Crellin et al., in press; Sørensen, 2015). Therefore, the first decision that our team had to make was to determine which of the many types of prehistoric swords known from the archaeological record we wanted to reconstruct. Chronology and geography provided a modicum of guidance, for we had previously agreed to focus on the Late Bronze Age (c. 1200–800 BC), the period of European prehistory that yielded the most copper-alloy swords, and Britain, as this would have facilitated the wear analysis of museum specimens. We also thought it useful to select a variety of sword types displaying significant differences in their shapes and sizes, as this would enable us to test the combat capabilities of different weapons, as well as their limitations.


**Figure 3.** The four replica swords used for the Bronze Age Combat project; A: Type Wilburton; B: Type Ewart Park; C: Type Carp's Tongue; D: Kemenczei's Type S Vollgriffschwert (Image: R. J. Crellin).

Based on these criteria, we selected three swords classified by Burgess and Colquhoun's (1988) within their Wilburton, Ewart Park, and Carp's Tongue types respectively (Fig. 3). Wilburton type swords mark the first stage of the British Late Bronze Age (Wilburton Phase, c. 1150–975 BC); they are found all over Britain with a special concentration in the south-east. Ewart Park swords are found in great numbers throughout the British Isles and are dated to the later part of the Late Bronze Age (Ewart Park Phase, c. 925–800 BC). Carp's Tongue swords are mostly found in areas of Atlantic Europe, particularly in Brittany and southeast England; they are generally dated to the later part of the Late Bronze Age (Ha B2/B3 and Bronze Final III, c. 950–800 BC). For our fourth sword, we thought it informative to have a broader and sturdier blade to test, and one with a different balance point, although this meant adding to the sample a relatively uncommon continental sword type, which is poorly represented in British museum collections. Our choice fell on a *Vollgriffschwert* (cast-hilt sword) belonging to Kemenczei's type S; these swords are mostly found in Hungary and are dated to the Ha A1 period, c. 1200–1000 BC (Kemenczei, 1991, p. 47).

## 3.2 Object Replication

Replicating these objects involved in-depth research into the manufacturing technology, alloy composition, and post-casting treatment of Bronze Age swords. The last two factors were judged to be of particular consequence. It is certainly the case that, even within a self-contained area and period, prehistoric swords show a wide variety of alloy compositions and post-casting treatments depending on factors ranging from technical constraints to culturally informed technological choices (Allen et al., 1968; Northover, 1988). Moreover, it has been proved experimentally that chemical composition, microstructure, and edge hardness can all influence the mechanical properties of the weapons by producing during the tests quantitatively (though not qualitatively) different wear marks (Soriano-Llopis & Gutiérrez-Sáez, 2009). This compelled us to have all swords cast and finished in exactly the same way, for doing otherwise would have introduced into our tests a number of variables we could not account for.

At this point, however, a deep gulf still separated our intellectual understanding of all the technical parameters involved in sword making from their actual translation into physical objects. Skilled practice and dexterity had to come to the fore at this stage of the project if we were to arrive at accurate, faithful replicas of technologically advanced bronze swords. We therefore joined forces with Neil Burridge (www.bronze-age-craft.com), a bronzesmith with decades-long experience in casting prehistoric tools and weapons to high technical standards. He proceeded to cast our swords using a 12% copper-tin alloy, polish the cast blanks, and then work-harden and razor-sharpen their cutting edges using smithing techniques partly of his own design. Finally, he expertly carved the hilt plates and pommels out of oak wood and riveted them onto three swords (the fourth has a cast hilt and pommel). As an important control point in the process, we carried out metallography and hardness testing on the replica swords in order to understand if, and to what extent, the mechanical properties of their edges deviated from those of their prehistoric counterparts.

## 3.3 Discussion

Two broad questions stem from our selection and replication work. Firstly, what is the degree of concordance that is practically achievable between original and replica objects? And how much of that is actually desirable? In our project, we had to make several decisions concerning how to channel the multifarious archaeological and metallurgical evidence into the four replica swords we intended to make and test. These minimally included sword shape, alloy composition, method/amount of edge hardening, method/degree of sharpening, and the wood species to be used for the hilt plates and pommels. It is important to stress that Neil Burridge was actively involved in all stages of the planning and decision-making process as all these choices entailed an inextricable combination of evidence-based and skill-based knowledge. For example, our conversation with Neil led to him casting the swords using a 12% copper-tin alloy, which sits near the higher end of the spectrum documented for British Bronze Age swords (Northover, 1988). However, we chose this alloy as it improved the fluidity of the cast and reduced the risk of potentially dangerous defects developing within the objects; it is also the alloy with which Neil is most familiar. This was of paramount importance given the intended uses of the weapons in sets of controlled and actualistic field experiments involving real human beings, not rigs or robots (Crellin et al., in press).

Secondly, and closely related to the first question, what is the degree of authenticity we ought to achieve in the process? And conversely, how much inaccuracy are we prepared to accept, and how will it affect our tests? One of the principles laid out by Outram (2008, p. 4) provided us with guidance. As he perceptively noted, the key question for experimental archaeologists is whether any compromise involving modern materials and technologies will affect the testing of the research hypothesis. In our project, as the replica swords were to be used in fighting tests, and the edge damage thus created was to be compared with edge damage of archaeological swords, it was essential that alloy composition as well as microstructure and edge hardness would be as similar as possible to those of the originals – hence the amount of research that we applied to these problems. However, whether the bronzes were cast in silicon moulds, as they were, or in prehistoric-looking stone or sand moulds was a relatively unimportant factor, as use of a modern casting medium was not going to have any noticeable effect on the mechanical properties of the blades, notwithstanding that the blade edges were prepared correctly. For all these problems, the wheel chart provided us with assistance by highlighting the back-and-forth research process, which connected the theoretical question (hub) to the intended project outcomes (object selection and replication) via the evidence and skills (both scientific and artisanal) needed to replicate the objects successfully.

## 4 NU Digital Heritage: The Digital Replication of Objects

NU Digital Heritage was a project established under the *Frontiers of the Roman Empire Digital Humanities Initiative* that was a pilot study in the facility and utility of three-dimensional digital technologies. While the utility of the technology for research was and continues to be an issue of interest (Molloy et al., 2016; Russell & Manley, 2016), equally important was the desire to make use of the technology for teaching and engagement activities. Small finds and material culture is an important teaching and research strand at Newcastle, and the close relationship between the University and the Great North Museum: Hancock (GNM) also means that teaching and research resources are mutually beneficial, adding value to engagement and education in both the classroom and the museum (Doonan & Boyd, 2008).

NU Digital Heritage was initiated in 2014, just as 3D-scanning and printing technologies were beginning to proliferate. The primary aim was to identify the appropriate capture method(s) to digitally capture material culture in a range of sizes and materials that (a) retained a high resolution, (b) maintained fidelity to the original object, and (c) were suitable for professional use, in line with best practice (English Heritage 2009, 2011). Related to this aim was the desire to identify which methods offered 'the most bang-for-buck', that is to say high resolution/high-fidelity capture with relatively low investment in labour and equipment. The experimentation with NU Digital Heritage, therefore, was not in the faithful replication of a physical copy of the original object, but of a faithful digital replica. Under these conditions, NU Digital Heritage was able to create more than 60 replicas within its budget, and we were able to identify appropriate methods for future use to support research, teaching, and engagement activities.

Relative to the model proposed above, the project comprised the following major steps: object selection; object research; object capture; data processing and interpretation (digital modelling); evaluation of the digital replica against the archaeological record; and use of the digital replica (Fig. 4). Two steps are discussed here: object capture and evaluation.

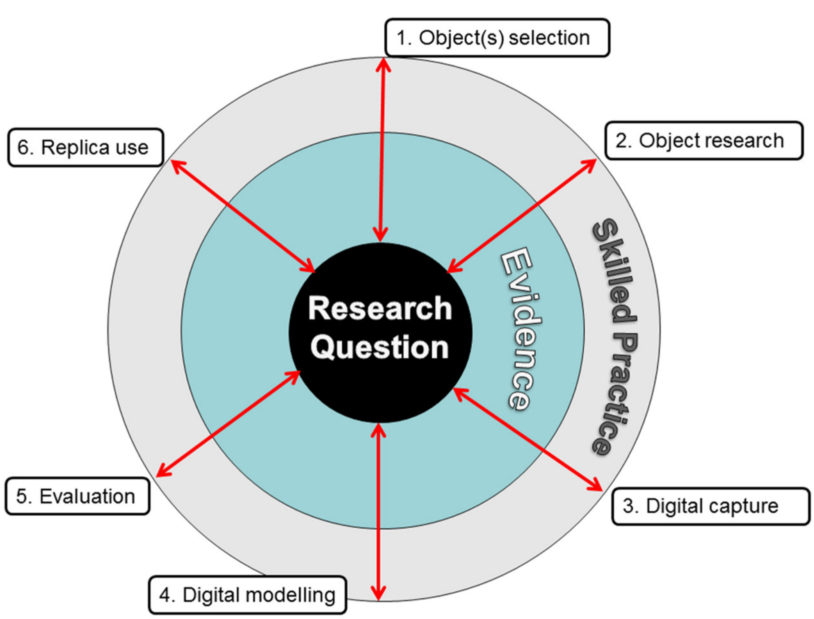


**Figure 4.** Our model, as utilised by the NU Digital Heritage project.

## 4.1 Object Capture

Two distinct categories of material culture were selected for capture: small finds and stone monuments. The physical properties of the selected material determined the preferred methods of digital capture, and it is easier to consider these discretely. Relative to our model, the evidential base of understanding the material and physical properties (including dimensions) of the selected material was gathered during step 2 (object research), and this informed the skilled practice of digitally capturing the material.

The Roman stone monuments included tombstones, altars, sculptures, and inscriptions that ranged in size from an approximately 300mm block and a large stone slab approximately 1.3m in height. Despite the considerable difference in scale, however, each monument was made exclusively in one type of stone, facilitating capture due to the uniformity of material.

The significant capture-challenge of the stone monuments was the portability of the monuments in respect to location within a museum or store. For example, a number of altars and tombstones were mounted against a wall or fixed to the floor in the GNM. This meant that some faces of the monuments were not digitally captured as they were inaccessible, or that fittings and clamps were included in the capture as they were unavoidable. Fortunately, the monument surfaces broadly conformed to a basic geometric matrix.

While the scale and the uniformity of material suggested that only one method was needed for digital capture of the stone monument, the location of the selected monuments presented a different challenge. Most of the monuments were firmly mounted in display areas in three different venues, requiring a method that was portable, could cope with irregular lighting conditions, and work in limited space/proximity.

The Artec EVA scanner and its accompanying software was chosen as the method most suitable for these conditions. The scanner itself is a lightweight mobile hand-scanner, approximately the size and shape of an electric kettle, which connects to a laptop computer for realtime capture and initial processing using structured light technology (Fig. 5a). The scanner has an accuracy of at least 100 microns and captures up to 16 frames per second within a specified volume, defined as 30 degrees horizontally by 21 degrees vertically from the centre of the sensor within a distance of 0.4m and 1m (https://www.artec3d.com/files/pdf/ArtecScanners-Booklet-EURO.pdf). The scanner and software was easy to use, capturing both topographic and colour data that the software aligned in realtime. Subsequent processing in the software was necessary to create a manifold (water-tight) mesh, reduce/remove errors during capture, and align the texture(s) with the topographic mesh. This resulted in a digital replica of the exterior surfaces of the Roman stone monuments that could then be adapted to the necessary file format depending on use.

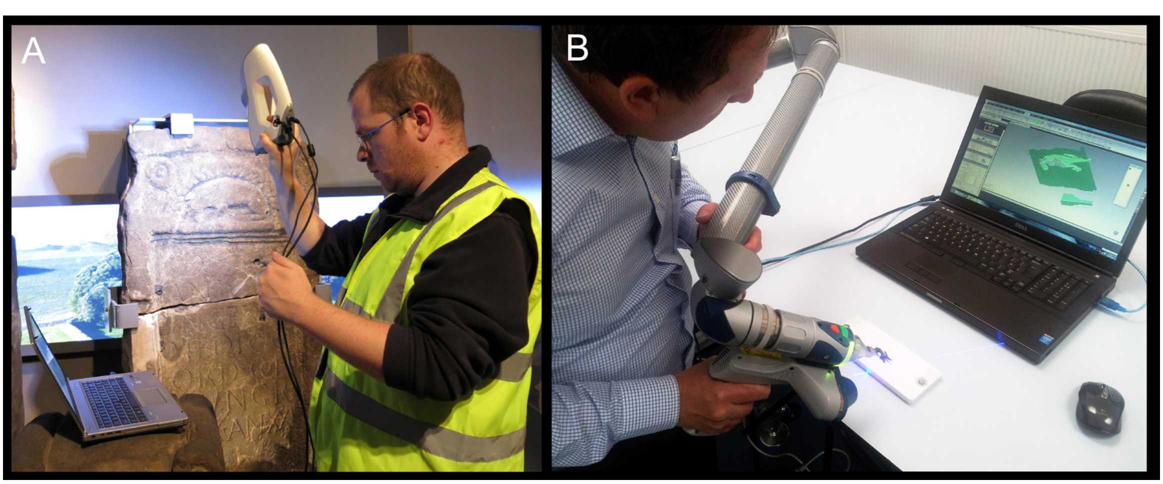


**Figure 5.** A. Scanning of medium-large Roman stone monuments using an Artec EVA scanner connected to a laptop. B. Scanning of Roman artefacts using a Faro Arm scanner connected to a laptop (Image: R. Collins).

**Figure 6.** Comparison of an untextured orthographic render of the Housesteads archer captured by the Artec EVA (left) with a photograph of the monument in its present condition (right) (Image: R. Collins).

The small finds encompassed an impressive diversity of attributes, which contributed to challenges in digital capture. The smallest object to be captured was approximately 10mm in width (its smallest axis), with some larger objects having faces of less than 1mm in thickness, while the largest was approximately 200mm in length. Moreover, the finds were made from a variety of materials including glass, polished bone, jet, copper-alloy, silver, gold, iron, polished stone, and enamel. These different materials created a technical challenge, particularly on composite objects made of more than one material. In contrast to the stone monuments, the smaller size of the small finds and their more diverse morphology presented further challenges in capture, particularly in terms of minimising 'shadow' – faces that were not captured; fortunately, their small size meant that they could be positioned and moved to enhance their digital capture.

From a technical standpoint, the small finds were a greater challenge and we experimented with three different methods, adapting our protocol to appropriately address problems directly related to capture. The first two methods attempted, a NextEngine desktop laser scanner and structure-from-motion (photogrammetry), respectively, were deemed unsuccessful as they did not meet the conditions set by the experiment, in terms of resolution and fidelity relative to time required for capture and process. The third and most successful method trialled was a combination of laser-scanning for high-resolution, high-fidelity topographic capture combined with photogrammetry for accurate texture rendering. The laser scanning was completed with a Faro 9ft Edge Arm mounted with a V6 HD Laser line Probe (scanner). The scanner was connected to a laptop running Geomagic Studio software, with the artefacts in a static position while the scanner was moved around the artefacts for capture (Fig. 5b). Significantly, the V6 HD Laser line Probe utilised a blue laser, which combined with software improvements to both reduce reflection and automatically eliminate 'noise' from the raw scanning data. The software provides realtime processing and alignment of pointclouds, but subsequent processing in the software is necessary to create a manifold (water-tight) mesh, reduce/remove errors during capture, and align the texture(s) with the topographic mesh. This resulted in a digital replica of the exterior surfaces of the artefacts that could then be adapted to the necessary file format depending on use. This final method produced the most reliable and faithful replicas of the objects, coping with the diverse materials being scanned and challenges of maintaining high resolution with smaller objects.

Use of the Artec and Faro scanners was not difficult, but there were clear benefits achieved from making use of an experienced operator for capture, as well as maximising the potential of the software to streamline data capture and processing.

### 4.2 Evaluation

Evaluation of the digital models was a relatively straightforward process. The models were compared with the original monument or object, as well as photographs (Fig. 6). This evaluation process was used to eliminate those methods that failed to meet the minimum standards in digital replication that were set, as well as identify those methods that met the standards.

For the Roman stone monuments, digital capture and processing using the Artec EVA was extremely successful and exceeded expectations, allowing us to capture more monuments than were originally anticipated. Comparison of the models with the archaeological specimen was useful, and it is significant that when untextured orthographic models were used, greater detail could be observed than is immediately noticeable from direct observation of the monument. Lighting conditions and individual perception of colour significantly influenced the observer's experience of the monument. We also demonstrated, unsurprisingly, that both textured and untextured 3D renders were superior to photographs of the stone monuments in terms of communicating detail.

The small finds were more technically challenging, but the combination of laser scanning with photogrammetric texture overlays proved the most successful method. As with the Roman stone monuments, untextured orthographic renders were useful in identifying detail that can be difficult to visually interpret due to the scale of the objects. The use of textured (colour) overlays was comparable to a high quality photograph.

The greatest benefit, however, is that the digital replicas are 3D models, and thus can be manipulated safely by a wide array of users in a fashion that is either impossible with the original object (e.g. a two-tonne stone monument) or unrealistic (e.g. for small finds). The movement of the digital model allows the viewer to perceive it from varying perspectives, as well as to visually interrogate the object.

This evaluation is based upon visual comparison, and in this regard highlights the problems of digital replicas in comparison to a physical replica or the original object (Renaud, 2002). Specialists in material culture utilise a broad range of integrated sensory data combined with direct experience when handling artefacts and other objects, assimilating these into 'bodily practices' (Ingold, 2000, p. 166; Gallace & Spence, 2008). Unfortunately, the digital realm only provides a visual replication. However, when combined with haptic and 3D-printing technologies, the visual experience can be supplemented by a tactile experience (Zimmer et al., 2008).

## 5 Conclusion

Experiment and experience are often conceptualised as irreconcilable pursuits, the former firmly located within the noble realm of scientific enquiry and the latter in the hazily defined, and perhaps embarrassing, sphere of 're-prefixed' activities such as historical re-construction and re-enactment. According to this reading, object replication would be a valuable endeavour in the former context and a meaningless exercise in the latter. In this paper, we have argued that maintaining such a clear-cut hierarchy of value does not do justice to the many purposes for which past objects are made and used, and to the increasingly numerous media that are available to the modern practitioner. For this reason, we propose considering experiment and experience as two ends of a broad spectrum, within which multiple investigators should be able to move freely depending on the specific aims and methods guiding their reconstructions, as well as the intended uses of such reconstructions.

The model we have proposed intends to break the boundary between experiment and experience by showing that a wide and diverse range of replication exercises, conducted with both physical and digital technologies, can ultimately be reconciled under a broad theoretical umbrella. The model has three important elements to it, which – we have argued – must characterise all meaningful activities involving archaeological replication and experimentation: it is goal-oriented; it is research-led; and it is informed by evidence and skilled practice. We have also argued that, in this context, skilled practice must be understood in the broadest of senses to include the theoretical and practical knowledge needed to replicate and use the objects, be this ancient/traditional or modern/technical *savoir-faire*. While all these elements are central to the replication and experimentation process, we wish to stress here the special importance held by the research that, in our model, informs each and any step of the process (as expressed by the spokes of our wheel-shaped flowchart: Fig. 1). In either case study discussed above, it was the stress we placed on the research that allowed us to develop an awareness of the problems and limitations inherent in our projects, including any methodological pitfalls. In the Bronze Age Combat project, for example, it was by researching the varying alloy composition of Late Bronze Age swords, as well as the wide range of work-hardening practices that prehistoric smiths applied to them, that we could assess simplifications or deviations of our replicas from the ancient objects. This prompted, on one hand, constant dialogue and interaction with Neil Burridge (our expert smith) and, on the other hand, further targeted research aiming to compare and contrast the microstructure and hardness values of our replica swords vis-à-vis those of the original Bronze Age swords.

Importantly, the research focus inherent in our model enables unambiguous discrimination between valuable and futile exercises in experimenting with, and experiencing, the past, for it establishes a clear conceptual framework grounded in the scientific method. As we have tried to show in the article, this framework hinges on a reflexive approach to replication that ties together aims, evidence, and skills, regardless of the context, purpose, and method informing the work. Furthermore, the model intends to have a universal utility by enabling researchers (both academic and non-academic) to locate their work, and contextualise it, within the broader realm of experimental archaeology.

However, while applying this model to our experimental work, we have realised that any exercise leading to the creation of replicas, be they physical or digital, raises the question of authenticity. For physical replicas, this is frequently hidden by the deceptive feeling of genuineness brought about by traditional materials such as leather, stone, and bronze. In the case of digital replicas, the issue can be hidden no longer due to the sheer technological modernity of the medium and the myriad choices it offers. For example, a digital model can be readily manipulated for visual enhancement by increasing contrast or modifying the colour-balances in the texture. When combined with 3D-printing, more issues around authenticity arise. The shape or morphology may be replicated accurately, but are the tactile experience and its weight replicated? How has colour-fidelity been achieved?

At the heart of the problem lies the realisation that archaeological artefacts are often incomplete or damaged, and recreating the missing or deteriorated components involves difficult decisions that are, at best, only partly tied to past realities. Such decisions may be useful or indeed necessary for experimentation, but is the resultant object a *replica* of the original? This brings us back to the central hub of our model – what is the research question and aim of the project? Both physical and digital replication technologies compel us to explore the manifold complexities of this deceptively simple question in order for us to reconstruct 'authentic' past objects – however we choose to define such an ambiguous and ever-shifting term as 'authenticity'.

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