UNIVERSITY OF SOUTHAMPTON

FACULTY OF HUMANITIES

Archaeology

Representing Roman Statuary Using Computer Generated Images

by

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ABSTRACT

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This thesis explores the potential of computer graphics as a means of producing hypothetical visual reconstructions of a painted statue of a young woman discovered at Herculaneum in 2006 (inv. 4433/87021). The visualisations incorporate accurate representation of experimentally derived data using physically accurate rendering techniques. The statue is reconstructed according to a range of different hypotheses and is visualised within a selection of architectural contexts. The work presented here constitutes both a technical and theoretical innovation for archaeological research. The methodology describes the implementation of physically accurate computer graphical simulation as a tool for the interpretation, visualisation and hypothetical reconstruction of Roman sculpture. These developments are underpinned by a theoretical re-assessment of the value of computationally generated images and computational image making processes to archaeological practice.

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List of Accompanying Materials

1) Data CD: Containing data used in the production of the practical component of the thesis. Please refer to the index file (index.csv) on the disk for information regarding the specific content of this disk.

2) Book containing Chapter 10: Results II. A book containing images produced using the methodology described in this thesis.

Academic Thesis: Declaration of Authorship

I, GARETH BEALE

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

REPRESENTING ROMAN STATUARY USING COMPUTER GENERATED IMAGES

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Either none of this work has been published before submission, or parts of this work have been published as: [please list references below]:

Signed:

Date:

This thesis is dedicated to my wife and to our next unexpected adventure.

It is also dedicated to my Mum, Dad, Jo, Tom and Elliot for all of their love and support.

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List of Abbreviations

3D	Three-dimensional
ABRDF	Apparent Bidirectional Reflectance Distribution Function
BRDF	Bidirectional Reflectance Distribution Function
BSDF	Bidirectional Scattering Distribution Function
BSSRDF	Bidirectional Surface Scattering Reflectance Distribution Function
BTDF	Bidirectional Transmittance Distribution Function
CC-BY-SA-3.0	Creative Commons Attribution-Share Alike 3.0 Unported
CPN	Copenhagen Polychromy Network
ELISA	Enzyme-linked Immunosorbent Assay Antibody
FTIR	Fourier Transform Infrared Spectroscopy
HDR	High Dynamic Range
inv.	Object inventory number
IOR	index of refraction
PTM	Polynomial Texture Mapping
RTI	Reflectance Transformation Imaging
SVBRDF	Spatially Varying Bidirectional Reflectance Distribution Function
XRF	X-ray Florescence

Chapter 1

1 Introduction

In what ways can images produced using physically accurate 3D computer graphics contribute towards the understandings of the colouration of Roman statuary as a materially constituted, contextually dependent and temporally variable process?

The importance of image making to Archaeology has been increasingly recognised in recent years (Molyneaux 1997; Russell 2006; Smiles and Moser 2005; Perry 2013). Growing numbers of practitioners and theoreticians have argued for acknowledgement of the central importance which images occupy within archaeological practice. At the same time image makers have identified new and creative ways to use images and image making as a means of generating and communicating archaeological understanding (Renfrew 2003; Renfrew, Gosden et al. 2004).

These developments have the potential to revolutionise the study of a phenomenon such as Roman painted statuary. The visual character of surviving examples of these statues is only ever partially preserved. Understandings of the materials and processes of statue colouration have become increasingly sophisticated but it can be difficult to understand the significance of these data in visual terms. This difficulty is compounded by the fact that the appearance of these objects would have been influenced by contextual factors such as lighting and orientation which would have changed through time.

This thesis will explore the role which computer graphical approaches to visualisation can have in exploring this complexity. The work presented here contributes towards understandings of the Roman painted statue not as an abstract or conceptual entity but as an object in the world. Computer graphics methodologies, about which more will be said later, enable the researcher to accurately replicate physical processes. It is possible for example to visualise the influence of sunlight, candle light and incandescent bulb light upon the appearance of an object. However in order to produce images which have meaning it is necessary to understand the variables that you wish to visualise.

This goal of this thesis is to articulate complex hypothetical statements in a reliable and accurate way using three dimensional (3D) computer graphics. In order to achieve this it has been necessary to understand the processes which inform appearance and which govern the behaviour of light. Consequently, it is out of this process of image making, as much as in the study of the images which result, that understandings of painted statuary have emerged. The thesis will review the role of computer generated images within archaeological practice and will propose that new theoretical approaches to the use of computer graphics within archaeological practice are required.

1.1 A Polychrome Statue

The research presented within this thesis originated with the discovery in 2006 of the head of a statue of a young woman at Herculaneum in Italy. The statue was immediately recognised as being highly unusual due to the extent to which the paint applied to the surface had survived (Borriello, Guidobaldi et al. 2008:249; Wallace-Hadrill 2011:194).

Figure 1.1 Statue of a young woman discovered at Herculaneum in 2006 (photograph author's own).

As an archaeological object the statue is extremely complex both in terms of its material properties and in terms of its construction. A number of different pigments are present on the surface of the statue, each made up of different chemical components. A variety of technologies have been employed in order to recover all available data from the statue. This has resulted in an extremely rich but highly disparate collection of data expressed using a variety of discipline specific conventions and data formats.

The statue offered a rare insight into the importance which colour could have in defining the appearance of Roman statuary. It provided confirmation of the scope of the use of colour but also began to offer insights into how colour was used. Different methods of application revealed a subtlety in the use of colour which had only very rarely been visible previously (Østergaard 2008:1). The statue has an immediately obvious set of characteristics which identify it as exceptional. It also contains a variety of data which are not visible but which are equally, if not more important in helping us to understand how this statue was formed. This knowledge has the potential to tell us a great deal about Roman sculptural polychromy in more general terms. Recent developments in conservation science mean that much of this data is now available for the first time. The excellent preservation of the layers of paint has meant that with the assistance of modern analytical technologies, conservators were able to identify the elements from which pigments are composed with greater clarity and greater confidence than had been possible previously. Rapid advances in chemical analytical technologies applied within conservation science mean that pigments can now be profiled based upon small samples. These technologies have fundamentally altered understandings of the materials and technologies utilised in the painting of sculpture in the Roman world, allowing a far greater understanding of the composition of pigments including the nature of colourants used and the type of binding agents used to apply these colours. The information provided by these pigment identification tests vastly increases the capacity of archaeologists, conservators and art historians to develop informed hypotheses relating to the character of Roman statue painting and the composition of the pigments used.

Knowledge of the statue has been highly interdisciplinary. Specific aspects of the statue have been understood by researchers from different groups. There have been problems however in understanding how to bridge these disciplinary gaps and how to express these data in forms which are intelligible and meaningful to the broader academic community. It is this challenge which this thesis confronts.

Through combining physically accurate computer graphics technology with a craft based conception of archaeological and image making practice the following chapters will demonstrate that images produced using 3D computer graphics techniques can constitute an insightful and highly versatile component of the archaeological process.

1.2 Academic Impact

The key objectives of this thesis are to develop a methodology for the use of physically accurate computer graphics as a means of studying Roman sculptural polychromy and to produce and to disseminate images which contribute directly to the study of this phenomenon. The images are intended to contribute to academic discourse on the subject of Roman sculptural polychromy and to enhance understandings of the phenomena through visualisations of all available data. Considerations of audience are essential in the production of images which are intended to communicate information. It is not anticipated however that the impact of this research will be felt by a single audience at a single time, nor is this section an attempt to pre-empt all encounters with the work. The academic impacts outlined below have been used to guide the development of the methodology and the production and publication of the images.

1.2.1 Methodological Impact

The development of the methodology can in some respects be considered separately to the production and publication of the images which will result. The results section will be divided into two parts; the first of these will present an analysis of the accuracy of the simulation, and the second will present a series of images which have been derived from the simulation. The reason for this separation is that the methodology represents one of the main outputs of this thesis and should be assessed separately. The methodology will describe a series of techniques which can be implemented in order to accurately visualise data relating to Roman sculptural polychromy. These methods are not applicable only to the study of this phenomenon. The principles outlined here can be applied in a wide variety of archaeological settings. Attempts have been made throughout the thesis to ensure that the broader applications of these technologies and techniques within an archaeological setting are evident. The methodology is particularly suited to the representation of objects which are painted and which are characterised in part by their translucency.

The thesis is situated at the intersection of research in Archaeology and computer graphics. An emphasis has been placed upon the use of software which are widely available to archaeological research communities. The use of experimental or unstable software has been avoided in order to ensure that the methodology can be re-used within an archaeological setting. The development of the methodology has been driven by the desire to find appropriate technological solutions with which to address archaeological research questions. It is hoped that the research presented here provides a methodological model (theoretical and technological) which might be built upon and expanded by archaeologists, computer scientists and other interested researchers in the future.

1.2.2 The Impact of the Images

The second major output of this thesis will be the production and publication of a series of images derived from the simulation. The images are intended to play a role in enhancing understandings of Roman sculptural polychromy and specifically the statue of a young woman which forms the focus of this thesis. The images have been designed and presented in order to provide a resource to a specific set of audiences. However, efforts have been made to ensure that the outputs are presented in a way which is meaningful and practically accessible to the widest possible audience. Images are presented in a printed volume. It features accessibly written introductions to the methodology and subject. The creation and publication of the images is preceded by a theoretical discussion of the role of computer generated images in Archaeological Computing and in Archaeology more broadly (see Chapter 4; 3D Computer Graphics: Image Making and Archaeological Practice).

Audiences

Archaeological and Art Historical Researchers and Students: The images have been produced with archaeological and art historical researchers in mind. The thesis will argue at length that working practice in these disciplines has, as yet, failed to realise the full potential of computer graphics technology. The images have been produced and presented in way which is accessible and meaningful within a Humanities research context. Captions and accompanying text are aimed primarily at this audience and are designed to provide a theoretical context within which the images can be interpreted which does not rely upon a pre-existing understanding of the technical aspects of 3D computer graphics. This group represent the key target audience for these images and as such, a group of specialists in the subject of Herculaneum and sculptural polychromy were selected to review and to provide commentary upon the images. Their analyses feature in the printed volume of images (Chapter 10) and in the Conclusions (Chapter 11),

Artists and Computer Science Researchers: In addition to the groups outlined above, the images are also aimed at artists working within Archaeology and also Computer Science researchers. Both of these groups have a peripheral role within Archaeology which might be more fully realised through the development of appropriate methodological and creative practice. The creation and dissemination of these images is intended to offer a single example of a process which has successfully engaged researchers in both of these disciplines in single piece of archaeological research.

A General Audience: The images are available online as a print on demand publication. The purpose of presenting the images in this way is to disseminate the images using non-academic channels of communication which are available to all. The images are accompanied in this publication by text and captions which are written in accessible language and which describe the methodology and subject as well as providing information about the content of each of the images. It is hoped that by presenting the images in this way they will be meaningful to readers from a variety of backgrounds including researchers who do not specialise in Archaeology, Art History or Computer Science.

1.3 Chapter Outlines

Chapter 2: The Statue and Architecture

The purpose of this chapter is to introduce the reader to the archaeological material which will form the focus of the thesis. This introduction provides the background necessary to understand the development of the methodology and introduces readers to the challenges of interpreting partially preserved materially complex objects. All of the objects which feature in the simulation are described, including the statue itself and the architectural settings within which the statue has been visualised. This chapter introduces some of the theoretical challenges which are an inherent feature of the study of objects of this type.

Chapter 3: The Colours of Statuary

Chapter 3 provides an overview of sculptural polychromy and describes the need to understand the phenomenon in material terms. The chapter describes sculptural polychromy with an emphasis upon the colouration of statuary and covers a wide range of materials and processes which are known to have been used to colour statuary.

In addition to describing the materials of statuary this chapter will emphasise the importance of context in understanding colour. Dealing with issues such as movement, lighting and the passing of time the chapter describes sculptural polychromy as a phenomenon which is unstable and profoundly affected by the context within which it is seen or recorded.

Chapter 4: Computer Graphics: Image Making and Contemporary Archaeological Research Practice

This chapter examines the relationship between archaeology and computer graphics. It discusses the way in which archaeological images produced using computer graphics have been conceptualised and perceived.

The chapter recasts the debate on the use of computer graphics as archaeological tools by drawing upon established theoretical discussions relating to the value of visualisation and artistic practice as forms of archaeological knowledge building. It provides a theoretical underpinning for the role of images and image making in the methodology by highlighting the importance of the image making process and choices relating to the mediation and curation of images.

Chapter 5: Physically Accurate Computer Graphics: A Guide for Archaeologists

This chapter introduces the reader to the concepts and technologies of physically accurate computer graphics. It discusses the meaning of physical accuracy within the context of 3D computer graphics and explains how these techniques might be usefully implemented within an archaeological setting.

The survey presented here includes all of the technologies which feature in the methodology, it also includes other technologies and concepts which will help the reader to understand the way in which the methodology is structured and the methods which were selected for inclusion. In addition to providing a summary of the technology which sits behind the methodology this chapter also provides a useful background to some of the aesthetic concepts which influenced the development of the visualisation strategy.

Chapter 6: Methodology I: Data Capture

The first part of the methodology deals with the acquisition of all data which were incorporated into the simulation. This chapter describes all of the techniques and processes which were used to experimentally derive the data needed to produce hypothetical visualisations of a painted statue. The chapter deals with the collection of data directly from the statue and from buildings at Herculaneum and also deals with the creation and collection of supplementary hypothetical data.

Chapter 7: Experimentally Derived Data

This chapter presents a summary of all of the experimentally derived data which were captured using the processes outlined in the first part of the methodology. The incorporation of these data into the simulation is described in Chapter 8: Methodology II.

Chapter 8: Methodology II: Modelling, Rendering and Display

This chapter describes the processes of modelling, rendering and display. The modelling process involves producing a 3D model and materials. Rendering is the process through which images are derived from the 3D model. The section dealing with display will describe the finishing and curation of these images. The chapter ends by describing the process of producing the publication containing the images.

Chapter 9: Results I: Verification of Results

The first results chapter presents the results of the experiments carried out in order to confirm the accuracy of the light simulation. The results of the simulation were compared to a range of experimentally derived source data. These comparisons allow the accuracy of the simulation to be measured in an empirical way.

Chapter 10: Results II: Notes on the Accompanying Book

The second results section takes the form of a glossy publication containing a selection of the images which have been derived from the simulation. As a result it is separate from this document. An introduction to the book can be found in Chapter 10 of this document. The book incorporates a selection of images and text which introduce the reader to the concept of Roman sculptural polychromy before demonstrating the importance of variables relating to context, materials, light and movement upon the appearance of coloured statues.

The primary visual content consists of images which are derived from the physically accurate light simulation but which have been composed in order to narrate the outcomes of the simulation.

Chapter 11: Conclusions

This chapter will reflect upon the outputs of the thesis including the methodology and the publication of the images. Commentaries on the published images by experts in the field of sculptural polychromy have been incorporated into this account. The conclusions chapter makes recommendations for further work including guidance for researchers wishing to employ a similar methodology elsewhere.

Chapter 2

2 The Statue and Architecture

The goal of this thesis is to use visualisation as a means of exploring statue painting as a contextualised phenomenon. The data which are included in the image making process will influence the final images in two ways. Firstly, the decision to include specific data or to represent the statue within a given context influences the content of the resulting images. Consequently it also dictates the impact which these images will have upon viewer's understanding of the subject. Secondly, the environment within which the statue is visualised will influence the nature of light which is present within the scene and the way in which that light moves around the scene. The inclusion or emission of a specific piece of data would influence this calculation and so consequently have an impact on the images which result, regardless of whether or not the data (for example a specific colour of paint on a wall) is visible within the final image.

It is the purpose of this chapter to provide an introduction to the objects which are the subjects of the visualisations presented within this thesis. Familiarity with these objects is essential in order to understand the decisions which will be described throughout the forthcoming chapters. This chapter also underpins the methodology by providing a description of why each of the objects which features within this study was chosen and how its inclusion is justified. Because the emphasis of this research is upon image making it is important to consider not only the statue itself but also those objects which allow the statue to be represented in context. Each of the objects which are included within the visualisations, or within the simulation process through which the visualisations are produced, are also described.

2.1 The Statue

2.1.1 An Introduction to the Statue

The study revolves around the analysis and interpretation of a single object; the head of the statue of a young woman discovered at Herculaneum in 2006. The statue represents one of the best preserved examples of Roman painted statuary to have been discovered and to have survived with paint intact. As a result it has been the subject of extensive analysis and documentation.

Figure 2.1 A close up of the statue of a young woman which is the focus of this study (photograph author's own).

Vast quantities of data exist as a result of an attempt, using the latest technologies, to document this object. These data differ greatly but together they provide an extremely comprehensive record. The forthcoming chapter will introduce the reader to these data. It will describe all that has been published and all that is known about the statue. The chapter will equip the reader with all of the knowledge necessary to critically engage with the theoretical and methodological decisions made throughout this thesis.

The level of preservation exhibited by the statue is unique, particularly amongst examples of painted statuary at Herculaneum. Intensive analysis of the statue using a variety of techniques which are described immediately below and throughout the methodology has revealed a great deal about the materials of the statue and the techniques which were used in its production. All of these data have the capacity to add to existing hypotheses relating to the appearance of the statue from its creation until the moment of the eruption of Vesuvius in AD 79. The statue also has the capacity to reveal a great deal about the phenomenon of Roman statue painting in a more general sense at Herculaneum and elsewhere. It represents one of the most complete archaeological records of a process which until recently has been very poorly understood (Østergaard 2008). Through visualising all of the available data, and through hypothetically reconstructing data which are absent, a fuller and more nuanced understanding of Roman polychrome statuary can be reached.

2.1.2 Description

The statue was discovered in 2006, close to the Basilica Noniana at Herculaneum. The find was remarkable in the degree to which the painted surface of the statue had been preserved and it represented a significant contribution to understandings of statuary at Herculaneum. The statue was recognised has having many formal characteristics in common with statues typically thought to represent a wounded Amazon. However it was noted at a very early stage that the statue did not conform to any known Amazon type (Moesch 2008, Wallace Hadrill 2012: 194). The arrangement of hair at the front and sides of the statue coupled with the angle of the head in relation to the neck are representative of the Sosikles type while the arrangement of the hair at the rear is of a style commonly associated with the Sciarra type (Guidobaldi and Moesch 2009:414). This deviation from recognised Amazon types is significant, particularly as the only other known example of a statue which exhibits similar formal characteristics comes from the Villa of the Papyri close to Herculaneum (Moesch 2008:413; Wallace-Hadrill 2011:194) (see Figure 2.1). Based upon the similarity between these examples it has been suggested that that the statue is of an original type and may have represented a locally produced innovation in style, possibly from the workshop at Baiae in the Bay of Naples (Mattusch and Lie 2005:281). This idea is reinforced by the similarity in style between these statues and a Pelophoros statue thought to represent Demetra (Moesch 2008:414; Borriello et al. 2008) (see Figure 2.4).

Following this analysis the statue has been identified variously as an Amazon and more simply as a *statue of a young woman* (Moesch 2008, Wallace Hadrill 2012: 194). Regardless of whether the statue is representative of an Amazon or not there are many clear formal similarities between this statue and other Amazon statues and they remain the closest formal correlates which have been identified.

The statue is acknowledged as being of extremely high quality (Moesch 2008:414; Wallace-Hadrill 2011:194). The skill with which the statue has been produced is evident in the fine detail of the carving and is also evident in the care and skill which has been taken in applying paint to the surface of the face.

The level of preservation which is present on the surface of the statue is highly unusual and reveals a great deal about the contribution that paint made to the appearance of the statue. It would be a mistake to think that the painted surface is exactly as it was at the moment of preservation. However, the surviving paint provides compelling evidence of the subtlety and skill which could be employed in the painting of statuary. Very few examples of statue painting from this period and location survive and so it is difficult to compare the level of skill and care which was exercised in painting this statue to other examples. However, the quality of the painting can be seen in Figures 2.5-2.8 and is discussed in greater detail below.

Figures 2.2 – 2.4 (Left) the head of a young woman speculatively identified as a Sciarra type Amazon discovered in the Villa of the Papyri. Inv 4296/80499 (image courtesy of HCP) (Middle) the statue which is studied in this thesis is thought to have been of the same type as the statue in the image to the left but was discovered in the Basilica Noniana. Inv 4433/87021(image courtesy of HCP) (Right) a Pelophoros statue thought to represent Demetra from the vicinity of the Villa of the Papyri 4331/81595 (photograph author's own).

The exploration of ambiguity is central to the research aims of this thesis. Damage to the statue means that despite being very well preserved, there are residual uncertainties relating to its appearance and form. It is not clear precisely how many layers of paint might have been applied to the surface of the statue. Nor is it clear whether those surviving areas of pigmentation are representative of the colours which would have been visible previously.

Chemical analysis (detailed descriptions can be found in Chapter 6 – Methodology I) of samples has indicated that the only pigments detected are the examples still visible on the surface of the statue. It is not clear how well preserved the areas of surviving paint are. There are clear signs of damage which are likely to be as a result of the volcanic eruption, including the loss of the lower part of the face. There are also signs of general abrasion to the surface with pigments being better preserved in cracks and crevices than on exposed surfaces. This would suggest that additional paint would have adorned the surface. The form which this might have taken is not revealed conclusively by surviving areas but it is likely that thicker layers of paint would have been built up using multiple layers of pigment, this has been the case on other examples of Roman painted statuary and it is a technique essential to contemporary painting with tempera (Brinkmann and Koch-Brinkmann 2010; Mayer and Sheehan 1991).

The level of preservation is high enough that a great deal of specific detail can be observed in the painted areas (see figures 2.5-2.8). It is clear from close visual inspection of this statue that different techniques were used in different areas in order to create specific visual effects. The eyelashes are highly distinctive in form. They are thick and tapered getting narrower as they proceed away from the eye and ending with a short sideways flick, all of the eyelashes are connected by a single line which traces the outline of the eye. The eyebrows are extremely finely applied in contrast to the eyelashes and have been built up using extremely fine strokes which appear to be representative of specific hairs. The irises and pupils have been painted in different contrasting colours.

As well as the addition of facial details the hair of the statue has also been painted. In this case the paint has been added as a consistent layer covering the hair. Current distribution of pigment across the hair is more or less uniform except that the pigment survives with greater intensity in grooves and crevices.

Figures 2.5-2.8: Close up images of the statue of a young woman from the Basilica Noniana show the differing levels of preservation in different areas and also the variety of application styles which were used (photographs author's own).

2.1.3 Materials

Stone

The stone from which the statue was carved has been identified by Moesch as being fine grained Pentelic marble (Moesch 2008:413). This analysis was based upon a visual inspection and the statue has not yet been subject to mineralogical and petrographic analyses which would allow the definite identification of the origin of the stone. Nonetheless, the general material characteristics of the stone have been identified and characterised as being a very fine grained white marble, fading to yellow with micaous veins throughout (Moesch 2008:413).

Paint

The paint on the surface of the marble has been analysed using X-Ray Flourescence, Fourier Transform Infra-Red Spectroscopy and Enzyme-linked Immunosorbent Assay Antibody (ELISA) Testing. The details of these analyses are presented in Chapter 7 (Experimentally Derived Data) but to summarise, all of the pigments analysed contained traces of iron and antibodies which are consistent with the presence of egg yolk which is likely to have been used as a binding agent.

2.1.4 Ambiguities and Hypothetical Reconstruction

While the preservation of the statue is remarkable, there are several areas of uncertainty which impact upon our understanding of the appearance that the statue might have had prior to the eruption which ultimately preserved it. Exploration of these uncertainties will form the focus of the analytical content of this thesis:

Layering

The practice of tempera painting is likely to have been used to apply pigment to the surface of the statue. This argument is supported by the probable presence of egg yolk in the pigments which were analysed (Torraca 2006). There is a limit to the volume of pigment which can be added to a binding medium before a paint produced in this way ceases to be viable. When this limit is exceeded pigments become powdery and can easily be brushed from the surface. In order to achieve densities of colour exceeding what is possible using a single layer of tempera paint multiple layers can be added. This technique is widely used in contemporary practice and experts have considered the possibility that Roman statue painters would also have used this technique (Mayer and Sheehan 1991; Østergaard 2008).

The use of layering as a painting technique has the capacity to fundamentally influence the appearance of paint and so different configurations of layering will be reconstructed. These reconstructions will be based upon experimentally derived data. The nature of the experimental process is described in Chapter 6 (Methodology I). The results of these tests are described in Chapter 7 (Experimentally Derived Data).

Reconstruction of the Face

One of the most significant and immediately obvious ambiguities is the fact that areas of the statue have been damaged are no longer present. These absent areas have been hypothetically reconstructed using geometry captured from other statues which are similar in type. The details of this process are presented in Chapter 6 (Methodology I).

2.2 Architectural Settings

Considerations of context are integral to visualisation. The context within which a statue was seen would have had a profound influence upon its appearance. The presence and nature of light is instrumental in dictating how an object will appear. Small changes in orientation or position can change affect the light which reaches the surface of the statue and consequently alter its appearance significantly. The identification of specific contexts within which statues were supposed to have been seen is far from easy. Many statues which are known today were excavated in the period prior to the development of modern archaeological recording. Where locations have been documented, as in the case of the Villa of the Papyri very little information is offered beyond an approximate find spot (Mattusch 2010; Mattusch and Lie 2005).

The relationship between statue and context is complex and the choice of contexts for visualisation reflects this complexity. It is very difficult to draw any clear cut conclusions regarding the relationship between types of statuary and contexts of display and it is also thought that statues were frequently moved. This is attested by the trade in sculpture which is understood to have taken place in antiquity and is confirmed by finds of statuary which are very likely to have been moved and re-displayed elsewhere (Bergmann 1995; Bartman 2010). Consequently it is not a straightforward exercise to connect a statue with specific environmental conditions within which it was supposed to have been seen. Appropriate conditions for display of statuary at Herculaneum seem to be pragmatic as much as they are aesthetic, being dictated by considerations of status wealth and personal preference as much as formalised codes of aesthetics (Bartman 2010; Mattusch and Lie 2005:354).

The focus of this research is upon developing improved understandings of Roman statuary as material phenomena. Consequently it is not necessarily in the interests of the methodology to visualise the statue only within the precise conditions in which it is known to have been displayed, even if it could be determined that the statue had been in only one location. The methodological goals of this study are best served by representing the statue within a range of contexts within which a statue of this general quality and style might hypothetically have been present. To this end, the statue will be visualised within three architectural settings:

- The cryptoporticus of the House of Stags
- The southern dining room of the House of the Stags
- The peristyle of the House of the Mosaic Atrium

The justification for having chosen these locations will be described in the remaining portion of this chapter. This section will discuss the nature of the display of sculpture at Herculaneum, the value of architectural comparators and the importance of different lighting and environmental conditions in interpreting the appearance of statuary. Finally the chapter will describe the specific architectural settings which have been chosen.

2.2.1 The Display of Sculpture and Statuary at Herculaneum

The contexts within which statues have been found at Herculaneum can tell us a great deal about the circumstances in which they would have been seen. Unfortunately the nature of the excavation, particularly in its earlier phases means that find locations are often vague and they where they are known the buildings within which statues were housed have been only partially excavated (Mattusch and Lie 2005). The Basilica Noniana (the find site of the statue which forms the focus of this thesis) is an example of this, as is the Villa of the Papyri home to one of the most renowned collections of sculpture known to have existed at Herculaneum. Both of these buildings remain poorly understood in an architectural sense (Wallace-Hadrill 2011). Nonetheless, by analysing what we do know about the display of sculpture it is possible to develop a sense of the variety of scenarios within which statue like the one which forms the focus of this study might have been encountered.

Understandings of how and where sculpture would have been displayed are compiled from a range of sources. Documented sculpture collections such as that discovered at the Villa of the Papyri reveal an eclecticism and scope which prevents us from reliably associating specific types of sculpture with specific locations in any systematic way. Sculpture of different ages, materials and themes were regularly displayed side by side (Mattusch and Lie 2005:183,354). The quality of sculpture tends to reflect the status of the building within which it is found, but aside from this it seems that sculpture would have been exhibited within a variety of settings (Stewart 2003; Borriello, Guidobaldi, and Guzzo 2008:354). Attempts to identify coherent themes within sculpture collections or to identify definite trends in display have achieved mixed results (Bartman 2010). It is possible however to observe broad trends.

An example of this is the statue which forms the focus of this thesis. Only two examples of statuary which share this form have been discovered, both were found at Herculaneum. One of these, the statue which will be studied here, was found close to the Basilica Noniana. It has been suggested that it would have been displayed within this building (Wallace-Hadrill 2011:194). It is possible that it would have been displayed as part of a scheme of sculpture depicting a particular scene. If, as has been suggested, the statue is a type of wounded Amazon it is quite possible that it would have been displayed alongside other Amazon statues as has been proposed elsewhere (Ridgway 1974). Whether or not this is the case, the certainty is that this statue would have been displayed within a civic context and would in all likelihood have been on public display. By contrast, the other example of this type of statue was discovered at the Villa of the Papyri and would have formed a single part of a large and very diverse collection of sculpture.

Analysis of statue collections may not provide definitive explanations regarding the contexts within which statues were intended to be seen, statues are inherently mobile and there is every chance that during their lives statues were moved from the location for which they were commissioned (Bartman 2010:73). Excavations of sculpture collections have shown that statues were often arranged in an eclectic way according to conventions or tastes which are no longer understood. A consequence of this eclecticism has been that statues of particular types are discovered in a wide variety of architectural contexts. Observation of sculptural collections such as that at the Villa of the Papyri presents a picture of sculptural collecting and display which was deeply personal and motivated by aesthetic imperatives which remain largely obscure to us now (Bartman 2010). Nonetheless, these collections do demonstrate in a broad sense the kinds of settings within which sculpture would have been encountered.

2.2.2 Architectural Comparators

Having established that a statue might reasonably be associated with a specific location type it becomes possible to locate appropriate comparative architectural examples which are fully excavated or which have been investigated using other means.

Naturally, the nature of the research question dictates the appropriateness of different methods of selecting ‘proxy’ locations. The goal of this research is primarily to provide a visual exploration of the material properties of a single instance of statue painting. Consequently, considerations of light and space within the immediate architectural context are paramount. Visualisations will be close cropped studies of a specific object and as such the context of visualisation is irrelevant except in the extent to which it influences the dispersal of light across the surface of the statue and provides a backdrop.

A consequence of this focus is that reconstructed contexts for visualisation can be chosen for highly specific localised reasons and need not take into account the broader arrangement of the building. This theme will be expanded upon below in the descriptions of architectural settings which have been used in this study.

2.2.3 Lighting Scenarios

The final criterion upon which architectural scenarios have been chosen is the fact that they offer specific conditions for the illumination of the statue. These settings are plausible in the sense that they are architectural spaces which either housed statuary or are architecturally similar to environments known to have housed statuary. Visualisations conducted in these settings move away from conventional conceptions of *the reconstruction.* The intention of these visualisations is not to offer an authoritative view of the statue within a known original context or a proxy for a known original context. Instead the purpose of these visualisations is to expose the statue to as wide a variety of lighting conditions as possible in order to explore the material characteristics of the statue.

This approach to the selection of contexts for visualisation is based upon the wide variety of settings within which statues are known to have been seen at Herculaneum. Within these visualisations the statue becomes a vehicle with which to explore the phenomenon of statue painting in more general terms. Assertions based upon these visualisations will necessarily be highly tentative offering a glimpse into a small set of variables, visualised within a specific setting. None the less they will provide a useful adjunct to conventional discourse surrounding the appearance of sculpture within different settings.

Simply representing the statue within known find spots presents the viewer with what can only ever be a small and almost certainly unrepresentative selection of environments within which statues similar to this one would have been seen. Even if our interest only extended as far as this statue, the variety of contexts within which similar works have been found coupled with the degree of uncertainty relating to whether or not these statues were commissioned for the locations in question justifies the inclusion of other lighting scenarios.

2.3 The Buildings

Two houses were chosen as data sources upon which to base the architectural contexts used within the simulation and visualisation. The development and modelling of contexts for visualisation and the relationship between these contexts and the underlying data is described in Chapter 8 (Methodology II). The capture of data from these buildings during fieldwork is described in Chapter 6 (Methodology I).

2.3.1 The House of the Stags

The House of the Stags offers a variety of architectural scenarios within which to visualise the statue and is well understood as a structure having been fully excavated. A notable feature of the House of the Stags is the cyptoporticus surrounding the garden. This space was chosen because of its enclosed nature and the diverse possibilities for simulating different lighting conditions including changes in the position of the sun according to the time of day and the potential for the use of artificial light. The locations in which the statue was visualised are marked on a plan below (Figure 2.9). This plan is reproduced in Chapter 8 (Methodology II) alongside a description of the modelling process.

Figure 2.9 The statue was simulated in the cryptoporticus (red) and the southern dining room (green) of the House of the Stags. The locations in which the statue was visualised are shown as blue dots (image author's own).

Images were also rendered in the dining room at the southern end of the property. This large covered room presented the possibility of creating images of the statue within a spacious indoor setting. The use of this room requires a considerable degree of hypothetical reconstruction regarding the decoration as most of the plaster has been lost. Hypothetical reconstructions were developed based upon wall painting from elsewhere in the house.

2.3.2 The House of the Mosaic Atrium

The House of the Mosaic atrium was also selected as a source of data from which to develop contexts for visualisation. One of the features most significant in selecting the house as the forum within which to represent the statue was the peristyle. While the enclosed peristyle garden is not on the same scale as the Villa of the Papryi it is an exceptional example and is very well preserved.

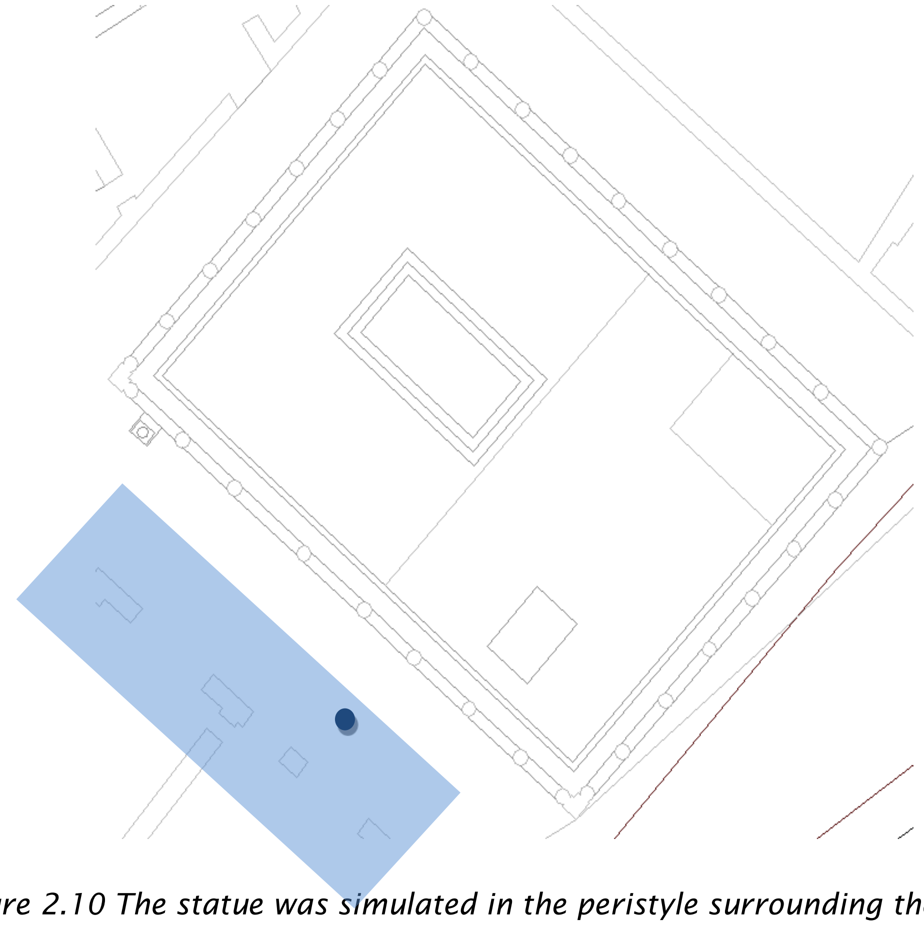

Figure 2.10 The statue was simulated in the peristyle surrounding the enclosed garden of the House of the Mosaic Atrium (image author's own).

The covered walkway around the peristyle represents a setting which parallels that within which much of the sculpture of the Villa of Papyri was found. The attraction of representing the statue within this context is based upon the fact that the other of the two statues with this form was discovered within the Villa of the Papyri and due to the fact that the peristyle of Herculanean houses frequently contain examples of sculpture of various types (Beard and Henderson 2001:93). The peristyle offers the potential for a variety of lighting scenarios including the changes in lighting in line with the movement of the sun overhead and the introduction of artificial light. The range of sculpture known to have been discovered in and around the equivalent part of the Villa of the Papyri certainly justifies the argument that sculpture similar in type to the statue being studied here might have been encountered within this context (Mattusch and Lie 2005; Wallace-Hadrill 2011:241).

Chapter 3

3 The Colours of Statuary

The colours of statuary are intellectually and physically inseparable from the materials out of which they are created. The purpose of this thesis is to develop a methodology which will contribute towards understandings of an example of Roman sculptural polychromy not in denotative, textual terms but in terms of materials and physical processes. Without an understanding of the materials which constitute Roman statuary, and without an understanding of how they were combined and used, this process cannot begin.

As in the case of all materially constituted phenomena the colour of Roman statuary was inherently dynamic and unstable. This instability coupled with material complexity and the fragmentary record presents a unique challenge to archaeological understanding. Physically accurate computer graphics represent an ideal tool for the study of an area of this complexity within which the role of light is so important. The ability to test hypotheses rapidly and easily has the power to advance our understandings of the appearance and material character of Roman statuary. The following chapter will lay the groundwork for this process through exploring the current state of understanding and highlighting areas of particular ambiguity or interest.

Recent years have seen a growth of interest in the phenomenon of sculptural polychromy. Notable amongst these efforts have been the work of Brinkmann and Brinkmann, who have sought to study and to physically reconstruct polychrome sculpture from a range of periods with an emphasis on the Greek and Roman (Brinkmann, Wünsche et al. 2007; Brinkmann, Primavesi, and Hollein 2010). Their work has been conducted in collaboration with a range of international partners and research centres including the Vatican Museum. This collaboration resulted in the notable physical reconstruction of the Augustus of Prima Porta (Bankel and Liverani 2004; Liverani 2004).

The work of the Copenhagen Polychromy Network (CPN) has also been of note. The network consists of a number of institutions from the Humanities and Sciences across Copenhagen, including the Ny Carlsberg Glyptotek the School of Conservation at the Danish Academy of Fine Arts, the Institute of Chemistry at the Technical University of Denmark and the Museum of Geology and The Natural History Museum of Denmark. The network has advanced understanding of the materials and processes of antique sculptural polychromy through rigorous testing and analyses (Østergaard and Copenhagen Polychromy Network 2009, 2010). The work of the British Museum and the Getty Research institute have been highly significant in having developed a more thorough understanding of how the materials used in the creation of polychromy might be identified using analytical technologies (Verri 2008; Potts 2008).

Efforts to study polychromy have been notable in the extent to which they have been highly collaborative and interdisciplinary in nature. Many of the institutions and individuals mentioned above (any many more besides) have collaborated in the production of exhibitions and the sharing of data. Furthermore, the nature of institutions involved has ranged widely across the Sciences and Humanities. Consequently, the work and data discussed here is representative of a broad spectrum of disciplinary practice.

Several factors appear to have contributed to the growth of interest in sculptural polychromy. Not least amongst these are technical developments which have assisted in the identification and analysis of polychrome sculpture. The growth in high quality colour publication has also played a part; there can be little doubt that low resolution black and white images did little to raise awareness of colour. Perhaps the greatest change though has been the increased application of critical theory and historiographical approaches to the study of art history, with many voices demanding that attention to be paid to this long neglected area (Panzanelli 2008; Østergaard 2008:40; Bradley 2009 a; Brinkmann, Wünsche et al. 2007).

Regardless of the reasons, the fact remains that the importance and nature of polychrome statuary is gradually becoming better understood, and critically, more widely accepted. The study of Roman sculptural polychromy is, for the first time, moving from the margins of archaeology and art history to the centre, and furthermore, the wide range of coloured materials employed in the production of art and architecture are for the first time becoming evident (Ball 2001:76). Many of these materials, far from being merely decorative in nature, were integral to the production and display of statuary. A cursory examination of the different media in which statues were produced reveals materials ranging from the finest white marble through to deeply coloured bronzes and richly coloured, often imported, stones (Penny 1993). Recent studies have demonstrated the extent to which these materials were supplemented through the application of surface treatments, pigments and adornments, demonstrating that the manipulation of colour was a subtle, complex and deliberate process (Brinkmann and Koch-Brinkmann 2010; Freccero 2002).

The simulation and computer generated images which will result from this thesis have a narrow focus and concentrate upon the representation and interpretation of a specific example of Roman sculptural polychromy. However, this introduction to the phenomenon will be much broader in nature covering a range of materials, processes and concepts. This breadth is necessary in order to emphasise the complexity of the phenomenon and in order to ensure that the different properties which influence the appearance of a statue such as paint, location, lighting and movement are not considered in isolation, but as a conceptual and physical whole. This breadth also reflects the broader ambition of the thesis; to raise awareness and improve understandings of Roman sculptural polychromy. The methodology which is described within this thesis can easily be adapted and applied to any of the phenomena described in this chapter. It is not possible to represent the full range of materials and variables described here within the scope of a single thesis. It is hoped though that by outlining the complexity and breadth of the phenomenon of polychrome sculpture and by demonstrating a methodology which can be used to study this phenomenon, this thesis will underpin and inspire further work in this area.

The following chapter will investigate and expose the extent of knowledge relating to the physical complexity of statue colouration. As highlighted in earlier chapters, efforts to understand the materials and techniques of Roman polychromy through systematic testing and analysis have advanced our knowledge of this area greatly in recent years. It will also make use of the accumulated knowledge of creative professionals and artists who continue to work with techniques and materials similar to those believed to have been used in the Roman world.

This account will also draw extensively on classical sources. Instances of classical authors discussing polychromy are widely documented, of particular note in this area has been Primavesi's survey of classical texts which discuss sculptural polychromy (Primavesi 2007). However, classical texts offer only a fragmentary view of the past, all too often we are forced to rely upon a passing reference, or brief description in order to inform our interpretations. Cases in point include Pliny the Elder's *Natural Histories*, which mention the materials and processes of sculptural polychromy several times and Vitruvius' *Ten Books on Architecture*. In the case of Pliny, it should not be forgotten that this work was written as an encyclopaedia and sought only to offer an overview. Vitruvius' writings similarly consist of a survey of an area and so do not speak with the authority or specific expertise which we might desire. This study will aim to use these sources sensitively and with an appropriate level of caution and will only refer to them where a lack of data exists.

The following chapter will seek to better understand those elements which were central to the use of colour in Roman statuary; materials, technique and context. It will seek to demonstrate the value of a physically rooted account of colour, rather than high level denotative descriptions of polychromy which have, until recently, predominated.

The ensuing account will focus primarily upon the statuary discovered at Herculaneum and Pompeii or upon phenomena which are very likely to have been encountered in these cities. Consequently, the range of materials and techniques described here do not describe the creative practice of a single place or time, nor do they offer a complete summary of statue colouration in Roman art. Instead, the polychromy described here takes the form of a series of phenomena as they were manifested at a particular moment, in a single place. A disparate range of style and technique are present in statues which originate from many places, are of many periods and which were coloured in many different ways. None the less, polychromy as it is described here is polychromy as it was experienced at Herculaneum in the mid to late 1st Century, perhaps unrepresentative and almost certainly unique but also staggering in its diversity and scope.

3.1 The Media of Statuary

A discussion of the nature of polychrome statuary must begin with media; the raw material of sculpture. The initial selection of a material from which to produce a statue determines to some degree the colouristic effects which will then subsequently be available to the creator or creators. A range of techniques were employed in the production of Roman statuary in order to manipulate colour, however, the choice of medium can, in almost all cases, be demonstrated to have been the most significant determinant of the predominant, lasting, colour of the statue.

3.1.1 White Marble

The classical statue is generally associated with white marble and in a sense, this association is reasonable (Wittkower 1977:12). The vast majority of surviving statues from the 1st Century Roman world (and indeed the classical world more generally) are of marble which could loosely be defined as white. There can be little doubt that a great deal of the statuary in other materials such as bronze or coloured stone have been lost, nevertheless, the volume of surviving statues in this material is clear testament to its ubiquity in the Roman world (Beard and Henderson 2001:84).

The problem of grouping statues into a 'white marble' category is that the limits of the term are unclear and subjective. They are certainly of limited use in attempting to develop understandings of statuary which are informed by the physical characteristics of the materials used in their production. The term has often been used as a proxy for monochrome or un-coloured statuary and yet even the most cursory comparison of a range of 'white' marbles will reveal a startling diversity in terms of colour and reflective character (Lapuente, Turi, and Blanc 2000; Lazzarini and Cancelliere 2000). A huge variety of white stone was used for sculptural purposes in the art of Herculaneum and of mainland Italy generally during the 1st Century. That much of this stone and some of the statuary from which it is produced apparently have their origins in Greece, demonstrates the extent to which specific materials were sought and would have been encountered both in the consumption and the creation of statuary. Perhaps we see evidence in the range of stone encountered in 1st Century Italy of what Penny terms "a connoisseurship of the different varieties" (Penny 1993:42). Whether or not this is the case, there is a strong likelihood that an interested party would have had an acute awareness of the range of available materials and their differing properties.

To the modern observer it is useful when considering the visual properties of marble to consider the characteristics which are commonly used to define all metamorphic and sedimentary rock. These include the granularity of the crystalline structure, the degree of translucency and the variability of the stone. While these factors may not relate obviously to a chromatic conception of colour, they are inseparable from colour in a physical sense and relate very closely to the visual characteristics of the stone. These subtle variations in the composition of different stones are an example of a variable which has been very difficult to study using existing techniques. While it has been possible to observe and to describe these characteristics using a variety of analytical techniques, it has not been possible to observe the impact which they have upon the appearance of statuary particularly when combined with other variables such as the addition of paint or varying lighting conditions. Physically accurate computer graphics provide a useful tool for combining these variables and observing the impact that they have upon appearance.

Marbles which have been labelled as being white vary considerably in their tone from almost brilliant white through to quite distinct shades of bluish-grey or gold. Furthermore, there are many varieties of marble which are not uniformly coloured, featuring streaks or patches of different colours. Examples of these variations can be seen overleaf in Figure 3.1.

Despite wide variation in their visual qualities many of these stones have been defined as white owing to the predominant colouration of the stone and the muted colour of the inclusions.

Another characteristic which clearly differentiates varieties of white marble is granularity. Coarser grained marbles have a crystalline structure which is visible to the naked eye; individual crystals can be seen clearly to shine causing a sparkling effect as light or viewer move in relation to the surface. Conversely, very fine grained marbles tend to have a uniform, homogeneous appearance (Mayer and Sheehan 1991:612).

Figure 3.1. Three Samples of white Pentelic sculptural marble (images are the copyright of The Sedgwick Museum and are used with their permission).

The final feature which will be dealt with here is translucency: the extent to which light is able to shine through the exterior surface of the stone and be reflected from within the material. Translucency is, perhaps, the most complex phenomenon described here, embracing a range of refractive and reflective characteristics. Translucency causes marble to appear to glow when exposed to light in a similar way to human skin, wax or milk. As with the other characteristics described here the nature of translucency need not be uniform but can alter through a piece of stone according to composition.

Within a broader, tonal definition of colour, characteristics such as granularity, translucency and homogeneity are all of great potential significance. The relative importance of each of these variables is difficult to establish. However, there is strong evidence that specific types of marble were sought for high quality statuary, indicating that the translucent, fine grained stones such as those from Pentelikon and Paros were particularly highly valued (Penny 1993:42). This interpretation is supported by the movement of specific stones around the Roman Empire for the purposes of sculpture production (Maxfield and Peacock 2001). The potential significance of these variable characteristics cannot be underestimated. If we accept, as Gage argues, that a Roman perception of colour was invested with a strong sense of tonality and an awareness of the behaviour of light, then these variables become extremely significant and a simple attribution of 'white marble' far less so (Gage 2009).

3.1.2 Coloured Stone

As well as these discrete but potentially highly significant differences in colour we also see the use of more dramatic effects caused by the use of more vividly coloured stone. The most memorable of these is perhaps deep red or purple porphyry. We also have examples of sculpture in coloured calcites (alabasters) and serpentine as well as coloured marbles, including the red stone known as *rosso antico* and the deep grey *bigio morato* (Penny 1993:93; The Metropolitan Museum of Art 2000). Dark, almost black, Egyptian stones such as basanite were also employed (Gregarek 2002:208; Mattusch 2009:94). The relative rarity of these stones would suggest that these were not common materials for statuary however this scarcity has certainly be compounded by the re-use of these desirable materials (Beard and Henderson 2001:84). An awareness of these materials is clearly demonstrated in Pliny's natural history, whereby the different stones of the empire are described in detail (Pliny NH 35.1). Pliny's words emphasise the possibility of a connoisseurship as mentioned above (Bradley 2009 b:90; Penny 1993:42). This point is further re-enforced by Pliny's observation that colourants were used to enhance the surface of marbles in order to simulate more exotic or interesting stone (Bradley 2009 b:90); Pliny NH 35.3). There does not seem to be any material evidence of this process being applied to statuary but it certainly highlights the value of particular varieties of stone and emphasises the complex role which they played in Roman aesthetics and economies. It is likely due to the high status contexts within which coloured stone statues are generally found that these objects were extremely desirable (Penny 1993:93; Gregarek 2002:128)

3.1.3 Colour, Stone and Form

One of the most subtle and complex manipulations of colour by the sculptor is to use form to indicate or to create the illusion of the presence of colour (Penny 1993:42). The majority of colouristic techniques are additive, involving the augmentation of the existing surface with additional materials. The manipulation of form to control colour differs in that it is generally subtractive, involving the controlled removal of material in order to affect reflectance of the existing surface.

This technique was used extensively by Bernini and it is perhaps through his work that we are able to most fully able to understand the potential scope of this practice (Hall 1999:135). There is however a wealth of material evidence which points to its use by Greek and Roman sculptors. It is particularly evident in the variable texturing applied to stone in order to create deliberate contrasts between rough and smooth surfaces. Examples include the relative roughness of hair compared to skin or the incision of irises, pupils and eye brows into the smooth surface of the stone, examples of these phenomena can be found throughout the statuary of Herculaneum (Borriello, Guidobaldi, and Guzzo 2008:115,118,119,145).

Durnan speculates that this practice of using texture in this way might have developed out of, or led to a reduction in, the painting of statues which in turn allowed the colour of stone to be appreciated (Durnan 2000:34). However, a study of known examples of polychrome statuary reveals that texturing techniques were frequently used in conjunction with colouration of other types. Numerous examples survive from Herculaneum including, but by no means limited to, the texturing of the hair and eyebrows of the probable Amazon statue heads from the Basilica Noniana (inv. 4433/87021) and the Villa of the Papyri (inv. 4269/80499(Borriello, Guidobaldi, and Guzzo 2008: 158, 159), the statue of Demeter from the Villa of the Papyri (inv. 4331/81595), the hair skin and clothes of which are differently textured, polished and painted (Borriello, Guidobaldi, and Guzzo 2008: 111) and the statue of Titus discovered in the Augusteum (inv. 6059) which is painted and exhibits very fine incisions suggestive of detailed fabric as well as having roughened and painted hair (Borriello, Guidobaldi, and Guzzo 2008:113).

This does not invalidate Durnan's assertion, but it does however emphasise the diversity of sculptural technique which might have been encountered at Herculaneum, or indeed, in any inhabited, dynamic environment. The juxtaposition of technique and style present within in a statue collection or across a city at a given time is likely to have been broad and varied and perhaps at apparent odds with the broader trends of stylistic change which can be observed in retrospect.

The manipulation of form in this way is not unique to any single variety of stone, and related techniques can be seen to have been used in the production of Bronze statuary from Herculaneum and elsewhere (Borriello, Guidobaldi, and Guzzo 2008: 146, 147). The manipulation of shade and texture to create the illusion of colour is of particular interest as a method of surface manipulation within the context of this thesis. It serves to highlight the breadth of what might constitute the manipulation of colour. It also highlights the divergence between typical, generally additive, colouristic techniques and the enormous range of physical practises which might cause the apparent colour or level of reflected light to vary. The technique of 'texturing' the marble surface of a statue provides a useful opportunity to consider the essential physicality of colour. The manipulation of the surface of the stone in order to control the behaviour of reflective light demonstrates in a very real sense the fact that the manipulation of colour constitutes a manipulation of the material of the statue in order to control its reflective characteristics. Whether this manipulation is achieved through the addition of a substance which reflects light at a particular wave length (such as pigment), or whether it takes the form of creating a rougher surface thereby limiting the capacity of that surface to reflect, the physical result is similar.

Furthermore, the physicality of this manifestation of colour manipulation highlights the inadequacy of more denotative, schematic descriptions of colour, such as watercolours, textual descriptions or line drawings, to account for the full range of colouristic phenomena which may influence the appearance of the statue. The shadow created by an incision cannot be described in typical chromatic language, or represented through the simple application of a single colour to a drawing.

This is a manifestation of colour which is bound to, and in a sense entirely dependent upon, environmental factors such as the brightness, colour and position of light. Under certain lights and lit from certain directions an incision may appear dark and well defined, under others it may become all but invisible. As we shall go on to see, this is not the only colouristic component of the polychrome statue which is highly light and context dependent.

3.1.4 Bronze

The extent to which bronze was used by statue makers in the Roman world is not fully understood. There are a vast number of surviving bronzes but it is likely that due to the desirability of bronze as a material, a great many more have been lost through re-use. Consequently the proportion of bronzes relative to statues of other materials can be expected to have been much larger than surviving collections might indicate.

Bronze is a metal alloy, generally composed of copper mixed with a lesser proportion of tin. Modern sculptural bronze is mixed at a ratio of 90% copper to 10% tin. It is known that in antiquity other metals would often be added to the mix including quantities of lead and possibly also gold or silver (Hemingway 2000:37; Rich 1974:135). Due to variation in the composition of bronze there is considerable potential for the manipulation of colour at the production stage. Data from statues which have been analysed, clearly demonstrate that the composition of bronze was carefully, and deliberately, controlled throughout antiquity resulting in a considerable range of colour (Oddy et al. 1990:119; Rich 1974:135). It seems highly likely that the variation of metals included within the alloy related at least partially to the manipulation of colour, although other factors such as resistance to corrosion or strength may also have been considered.

Surviving bronzes have often been subject to corrosion and as such the original exterior surface is often lost. Similarly to marble this loss presents problems in attempting to hypothesise as to the original appearance of a statue. However, there are surviving examples which show clear evidence of the use of paint work, deliberate patination and gilding (Oddy et al. 1990). A clear and compelling example of these techniques can be seen in the statue of Bacchus with a Leopard skin found at Herculaneum (inv.2292/77588) (Borriello, Guidobaldi, and Guzzo 2008 :116). Inlays were also used in order to enhance certain features of statues, perhaps most notably the eyes of bronze statues which were frequently inlayed with stone and glass (Borriello, Guidobaldi, and Guzzo 2008:190-209).

Bronze is unlike marble in the sense that its appearance depends directly upon decisions made during the production process. Whereas with marble colour is dependent upon the mineral composition of available materials, the sculptor in bronze has considerable control over the very fabric of the material being used. There has been a tendency to see bronzes as being in some way intrinsically different to statues in other materials. Whilst at a visual and stylistic level this distinction might be wholly justified it is also important to consider that these statues are often known to have been displayed in the same architectural settings and were not necessarily encountered separately from those made from stone (Mattusch 2009:109; 2010:87). Furthermore, physically speaking, many of the techniques employed in the colouration of

Bronzes are closely related to those employed in the colouration of marble statuary, including the use of incisions, the use of colour to highlight and to accentuate form, and the figurative use of colour to supplement and enhance simplified forms.

3.2 Paint

The process of statue painting is unfamiliar within the Modern Western context. It is perhaps for this reason that the process seems to be far and away the most significant of the processes used to manipulate the colour of statuary. It is quite possible however that this apparent predominance is based upon a lack of familiarity with painted sculpture amongst modern audiences. As we shall go on to see, the process of painting probably formed only one stage of a very complex multi-phased process of colour manipulation, beginning with the choice of materials and perhaps lasting for the entire lifespan of the statue.

The frequency with which painted statues were created or encountered in 1st Century Italy is not known. However, numerous surviving examples from Herculaneum and Pompeii as well as other surviving examples from different Italian sites are testament to the fact that the practice was not at all uncommon (Panzanelli 2008; Østergaard and Copenhagen Polychromy Network 2009, 2010; Borriello, Guidobaldi, and Guzzo 2008). Despite the number of statues which exhibit traces of pigment there is a paucity of evidence relating to the intended appearances of painted statuary. Many surviving traces of paint are minute and are often invisible without the assistance of analytical techniques. Several examples are known to have survived however and many more are partially preserved providing a compelling, if highly fragmentary, record of style and technique.

The poverty of evidence relating to the practice and prevalence of statue painting means that the available data takes a great many forms. It is comparatively rare that we find an example of painted statuary which is sufficiently well preserved as to allow the unaided observation of style or the form which statue painting took. It is much more common to have fragmentary data sets, consisting of pigment traces found at specific points on a statues surface, or ghost-like silhouettes or variable weathering of areas which were once coloured. These data do not lend themselves to immediate visual inspection and yet they hold enormous latent potential in the hypothetical reconstruction of surface appearance. Physically accurate simulation of these pigments offers an opportunity to hypothetically re-construct these paints and to create visualisations which incorporate these phenomena. While simulations based on these fragmentary sources of data are necessarily very tentative they offer a valuable and novel means of engaging with data.

It is possible to identify certain trends in the use of pigments in Roman statuary. It is clear for example that paint would often be used to enhance facial features, a technique which seems to persist throughout almost all known examples of painted statuary found in Roman contexts, Herculaneum Included. Often this painting could be extremely delicate highlighting such features as eyelashes or pupils. Paint would also often have been used to colour the hair of the statue (Østergaard 2007). Apart from the use of paint to highlight the facial features of a statue the use of colour to highlight elements of clothing was also common. Notable examples of this include the armour of the Augustus of Prima Porta (see figures 3.2-3.3) with its symbols vividly picked out and also the statue of Venus from the house of Julia Felix at Pompeii which has clothing painted directly onto the surface (Østergaard 2008) (see figure 3.4).

Figures 3.2-3.3 (Left) A painted plaser cast of the Augustus of Primaporta on display in The Vatican illustrates the areas of the statue which are known to have been painted. (CC-BY-SA-3.0 Archer). (Right) The statue photographed in 2007 (CC-BY-SA-3.0 Till Niermann).

Figure 3.4 Gilded statue of Roman Goddess Venus found in Pompeii, currently in the Museo Archeologico in Naples (CC-BY-SA-3.0 Ho Visto Nina Volare).

It is unknown to what extent these techniques of painting were subject to changes in trend, it seems highly unlikely that they were not. Unfortunately the granularity of available data cannot currently provide anything other than the most speculative of hypotheses on this subject. A complete survey of surviving examples of painted statuary has yet to be completed and depending on the number of examples which come to light may prove to be an enormous task.

3.2.1 Pigments

The colour palate available and suitable for the painting of stone in the Roman period was considerable. A range of pigments have been identified as having been used to colour statues. Unfortunately the identification of a single pigment does not provide a definite indication of original appearance. Firstly, it is possible that exterior layers of paint have been lost. In this case the pigment identified may be a base layer and form only one component of the colouring process. Secondly, pigments may have been mixed, meaning that a pigment which has been identified may constitute only one of the colourants used in a single area. Finally, as we shall see in this section, the appearance of a pigment is dependent upon the vehicle used to create the paint and the volume of colourant used. However, the identification of pigments and an understanding of their physical properties has the capacity to inform visual hypotheses and to improve understandings of the range of appearances possible with the materials detected. This process of hypothesis testing and development will be described at greater length in Chapters 6 and 7 (Methodology I & Experimentally Derived Data).

Red pigments were often achieved using cinnabar or red ochre. The latter particularly has been frequently identified as having been used in Greek and Roman sculpture (Panzanelli, Schmidt, and Lapatin 2008; Brinkmann, Primavesi, and Hollein 2010). Blue colours could be achieved using azurite, however as azurite decomposes it can take on a green colour, often evident in surviving samples. Egyptian blue was also widely used during the Greek and Roman periods, a synthetic colourant made from lime, quartz and copper ore (Østergaard and Copenhagen Polychromy Network 2010; Ball 2001:76; Verri 2008). Green pigments were generally made using malachite (a decomposed form of azurite). Yellow and orange pigments were occasionally produced from arsenic compounds but more usually from yellow ochre. Black pigments were generally produced using soot from burnt materials such as vine, bone or brushwood or resin (Brinkmann, Kellner et al. 2007:211; Ling and Ling 2000:58). The purpose of summarising the range of pigments available here is principally to demonstrate the complexity of the colouring process, for a more detailed discussion of colourants refer to the texts referenced in this section. Unlike synthetic colourants widely employed today which tend to be highly stable, consistent and available in a rich variety of colours, the Roman colourist would have been far more materially constrained (Ball 2001:56). Furthermore the characteristics of individual colours, their cost, intensity of hue and their status would doubtless have informed use of colour in ways that are hard to imagine today. Østergaard highlights this possibility mentioning specifically that the painting of clothing, a common feature of Roman statue painting, would almost certainly have communicated the social status of the subject of the statue to the viewer (Østergaard 2008:52).

It is possible that certain unstable pigments were used in the painting of statues in 1st century Italy and that these may further cloud our ability to appreciate the visual appearance of even the best preserved examples.

However, very few of the pigments detected on statuary from this period are known to be unstable. In fact, many of the most common such as red ochre are extremely stable (Hradil et al. 2003:230).

However, even those pigments which are chemically stable will have been subject to fading and change due to weathering and abrasion both during the active life of the statue, during the intervening period of preservation, and since discovery. This inherent instability of colour raises the idea of the statue as an object which required maintenance and on-going creative input throughout its life, given the physical durability of stone compared to the waxes and pigments which were used to colour them it is likely that re-applications of colour and surface treatments occurred and also that statues in differing states of decay would have been encountered regularly. Certain analyses have suggested the presence of evidence of the re-application of colour in Roman and Greek statuary. Notable cases include the Augustus of Prima Porta (Figures 3.2 & 3.3) analysed by the Vatican Museums and the Peplos Kore analysed by The University of Cambridge (Potts 2008:116; University of Cambridge Faculty of Classics Museum 2007). These cases encourage us to consider the statue as something changeable and unstable. This conception of the statue stands in opposition to the notion of ideal form which has tended to emphasise the stability and permanence of the statue.

3.2.2 Application

Little is known about the way in which pigments were physically applied. This is in large part due to the poor preservation of pigment layers overlaying the surface of the statue which might otherwise hint at the mode of application or of the precise makeup of the pigments used (Østergaard 2007:183). We do however, know that paints were often applied using a tempera method, and chemical analyses have revealed that binding media include oils, egg yolk and animal derived glues (Thompson 2007; Mayer and Sheehan 1991; Østergaard and Copenhagen Polychromy Network 2009). Tempera painting involves the use of paints which are created by mixing a ground pigment with a binding medium such as egg yolk which will harden and adhere to a surface when dry. There is also mention by Pliny the Elder of an encaustic wax based method being used although it is not clear from his description whether this method would have been employed in colouring statuary (Østergaard and Copenhagen

Polychromy Network 2009:15); Pliny NH 35.149). Circumstantial evidence raised by Marvin in her study of the statues of the Baths of Caracalla indicates that this may have been the case (Marvin 1983). The suggestion made by Marvin is that the absence of statuary from the very hot rooms of the baths can be attributed to the damage which would have been done to the wax based pigments used to paint the statues. Physically speaking, this hypothesis is reasonable. It identifies one of the few physical characteristics of statuary which might necessitate the absence of statuary from these rooms; the temperatures possible in these rooms may well have exceeded the melting point of wax (Marvin 1983:353). However, recent studies have demonstrated the use of media other than wax, such as egg, which might have been equally susceptible to the effects of humidity and heat. Furthermore, wax is likely to have been used in the varnishing of statues (for more information on this process see the *Surface Treatments* section below). Marvin's observation does not necessarily indicate the use of wax as a binding media *per se* but is perhaps indicative of the ubiquity and fragility of statue colouration and surface treatment.

Figure 3.5 A close-up photograph of the eye of a statue of a young woman from the Basilica Noniana at Herculaneum, intricate painted details are evident such as the carefully applied eyebrow hairs and the stylised lashes (photograph author's own).

The methods of application, while ambiguous, are to a certain extent rendered clear through a careful study of painted statuary and through consultation with those who possess knowledge, still very much alive, of the colouration of stone with tempera painting and other related techniques. Careful inspection reveals areas in which paint has clearly been very carefully applied with a small tool or brush (see figure 3.5). Techniques of application are as significant as the choice of pigments themselves. As we see in figure 3.5, the tone of the pigments is affected by the colour, and the reflective characteristics of the underlying material. There is a clear interplay between the applied paint and the material beneath. This effect is amplified here by the fact that the layers of paint have become thinner than they would otherwise have been. However these effects would have been very difficult to eliminate entirely and we have little or no reason to assume that this would have been the intention. This interplay of colour could have been further complicated by the addition of further surface treatments.

The use of tempera painting limits the range effects which can be achieved by the painter. These limitations are particularly evident in the limited ratios of pigment to binding medium which will constitute a functional paint. If the quantity of pigment is too low then it will be very hard to achieve a uniform finish with flecks of pigment suspended in the medium being distributed unevenly across the surface of the statue. Conversely, too much pigment relative to the quantity of the binding medium will produce an opaque but fragile layer which will not adhere effectively to the surface (Harland 2010; Stege, Fiedler, and Baumer 2007; Mayer and Sheehan 1991:264). Experiments into the limits of functional tempera paint were conducted as part of this study the technique used will be described in Chapter 6 (Methodology I) and the results will be presented in Chapter 7 (Experimentally Derived Data).

3.3 Surface Finish

In contrast to the explicit colouration of paint, a range of patinas and finishes may also have been used to alter the appearance of the statue (Rockwell 1993:50; Stieber 2004:57; Bradley 2009 a). These surface treatments represent probably the most ephemeral dimension of statue colouration. Very little material evidence survives beyond the presence of mineral deposits which may hint at the materials used. As a consequence of this, the following section will be reliant to a greater extent than successive sections have been upon secondary sources, but where possible primary data will be included and discussed in detail.

The process about which we have the most information is *ganosis*. Few, if any, positive traces of this technique exist or can be identified on the surfaces of surviving statuary. Consequently, our knowledge of this process derives primarily from classical literature, although physical experiments have sought to clarify the precise nature of the process (Freccero 2002; Richter 1944; Freccero 2011). It has been suggested by Brinkmann that this technique consisted of the polishing of a painted surface to create a sheen without the application of additional coatings (Potts 2008:123). However, the presence of extensive literary references suggesting the use of what would today be termed *saponified wax* as a polishing agent has maintained interest in this area.

The process of production and application and the composition of the necessary ingredients have been the subject of considerable interest to art historians, archaeologists and conservators (Freccero 2002; Richter 1944; Stieber 2004:57). It is described by both Pliny and Vitruvius (Pliny NH33.122; Vitruvius 7.9.3-4) as being the process by which a mixture of heated Punic wax and oil are applied to a surface, heated again and burnished. In this account, Pliny is in fact referring to the polishing of wall paintings, but he states that the same process is used to shine marble. Vitruvius makes explicit reference to the use of this technique in the production of statuary.

The experimental work carried out separately by Richter and Freccero seems to confirm that the technique described is effective as a means of creating a protective layer (Freccero 2002:80). Despite the apparent effectiveness of the technique there is no evidence to suggest how widespread the use of this technique might have been. Neither Pliny nor Vitruvius' accounts suggest that the technique was at all unusual and so as a working hypothesis it is reasonable to assume that the technique was employed as a means of creating a protective outer layer.

While the results of Freccero and Richter's experiments apparently confirm the detailed descriptions offered within the classical literature it will be necessary to undertake further experimental reconstruction. This will be important for two reasons, firstly, neither Richter nor Freccero described their methodology or results in detail, secondly, neither author collected quantitative data relating to the colour or reflective properties of the result. As part of these tests, Brinkmann's hypotheses that *ganosis* of polishing a painted surface will also be tested. The influence of *ganosis* upon the appearance of the surface of painted stone will be tested using samples of marble and the method and results will be presented in Chapters 6 and 7 (Methodology I & Experimentally Derived Data) respectively.

Another varnish which is mentioned by Pliny is *atramentum*; said to have been used exclusively by Appelles and never successfully imitated (Pliny NH 35.36.97). It seems to have been a form of brown treatment intended to enhance the appearance of the underlying colour or surface. The precise nature of this varnish remains obscure and its function even more so. Pliny's account does not provide any specific details regarding the composition or method of application. The description is situated within a lengthy celebration of the work of Appelles and is more effusive than detailed. Consequently, Pliny's words are able to offer very little in terms of practical advice. They do however demonstrate an awareness and appreciation of the subtle distinctions and nuances of tone and colour. Furthermore, they demonstrate the extent to which Pliny assumed the production of colour to be a complex multi-phase process incorporating great skill and, crucially, dependent upon the physical context within which it was supposed to function (Gombrich 1962).

As Bradley (Bradley 2009 a:438) observes, one thing which we can take from the discussion of these surface treatments is a certainty that colour was not only present but that it was the subject of subtle and complex manipulation. The addition of surface finishes, regardless of their precise nature or purpose, implies that the visual surface properties of the marble were important and were closely bound to the painted colours which overlaid them and to the visual effect of the statue as a whole (Potts 2008).

3.4 Adornment

There is a great deal of evidence to suggest that statues would often have been furnished with components made from a variety of materials. As we have already seen in the section on Bronze in this chapter, bronze statues often had enamel or glass inlaid eyes or hair of materials other than that from which the main body of the statue had been made (Kleiner 1992:67). Statues were also frequently adorned with accessories in different materials. These often included weapons, sceptres and jewellery (Penny 1993:93). Examples of these accessories rarely survive, however the physical traces of their presence, drilled holes and fixing points, are often apparent. There is also evidence, in Roman images and text, to suggest that statues were draped with clothing (Primavesi 2007; Weedle 2010:57). Clearly, material evidence for the dressing of statues is extremely unlikely to have survived and no examples have been discovered. One possible source of material evidence supporting this idea is the presence of what appear to be clothes racks in temples housing cult statues. There are numerous literary references which appear to refer to the practice (Eclogues 7; Metamorphosis 10). There is also a possibility that the dressing or adornment of statuary may have taken on a ceremonial role whereby they were temporarily decorated with flowers, garlands or other objects (Mau 1973:446; Stewart 2003:263; Weedle 2010:57).

There can be little doubt that, as well as acting as symbolic notations, such additions were also employed as visual devices drawing attention to or augmenting the statue's appearance (Elsner 2007:115). Adornments are unique in the sense that the degree to which they offer the possibility of temporary additions to the statue's texture and colour (Pollini 1995:263; Hanfmann 1964). Further exploration of the significance which adornment might have held within a Roman conception of statuary is certainly necessary. However, a reasonable treatment of this subject will necessarily be theoretically complex and reliant upon a substantial review of classical literature and cannot be justified within the scope of this thesis.

3.5 Colour Beyond Materials

The problem that Latin terms for colour used by Roman authors do not map straightforwardly to those used within contemporary English has been acknowledged and discussed by a number of authors (Bradley 2004; Bradley 2009 b; Cleland, Stears, and Davies 2004). Part of the reason for this disparity of language can be attributed to the extent to which Roman expressions of colour are frequently connected to the appearance of objects in the world, and do not employ straightforwardly chromatic abstract vocabulary (Bradley 2009 b:76). Also though it should be considered that equivalent terms for *colour* within the Roman lexicon extended beyond what would typically be encompassed by this term within modern English (Gage 2009:56; Primavesi 2007:198; Bradley 2009 b:76). An example given by Gage is a poem by Lucretius on the value of the simple life:

"...but what matter if there are no golden images of youths about the house, holding flaming torches in their right hands to illuminate banquets prolonged into the night? What matter if the hall does not sparkle with silver and gleam with gold, and no carved and gilded rafters ring to the music of the lute?"

Lucretius *De rerum natura II* 59-63 Trans. Latham

This description reveals to the contemporary viewer the potential significance of the materials of statuary, not only for their colouristic properties, but also the other aspects of appearance which in part characterise them. They raise the possibility that chromatic conceptions of colour cannot be straightforwardly considered independently of the other facets of materiality which collectively comprise appearance. To acknowledge that the occurrence of colour is dependent upon its material realisation is relatively trivial but in the examples of material and technique presented above we see clearly the extent to which each process and each material combine to form an overall effect.

However, at this stage, even acknowledging this material complexity, our conception of statue colouration as a physical phenomenon remains incomplete. To talk about the material of statuary is important, but it is also essential to talk about the worlds which statues inhabited; the physical contexts within which they were seen. Several discussions of perceptual engagement and subjective encounters with statuary exist (Mattusch 2010; Elsner 2007:113; Marvin 1983; Stewart 2003). For the time being though, let us concentrate on the physical impact of context upon the colour of statuary. In the physical sense, context defines the appearance of colour through exposure to light, reflection, shade and the angle from which the statue can be seen. These are unstable phenomena liable to change with time. They are also variables which were, potentially, subject to the same level of control as the physical manipulation of the statues themselves.

3.5.1 Colour in Context

The discussion of colour in this chapter has, until now, focussed primarily upon the materials of statuary in isolation. It is essential however, also to consider light. Objects, through their reflective characteristics, carry with them the latent potential to affect the colour of light, and to influence their appearance through reflecting or refracting light in different ways. However, the nature of the incident light, its colour, intensity and direction will all play a part in dictating the qualities of the light which are reflected and which characterise the appearance of the object. Consequently, the nature of light is as significant in defining colour as the materials themselves. Objects look entirely different under different lights.

It is necessary then, to consider context; the environments within which statues were encountered; environments which (in a visual sense) were characterised by unique configurations of light, shade, reflectance and space.

Each of these factors would have had a profound impact upon the appearance of colour and furthermore, each of these variables would have been subject to constant change. It is easy, for example, to imagine the movement of the sun across the sky, changes in weather, or the proximity of a flickering lamp or torch. In the longer term we can equally imagine the statue in question to have been moved, to have been draped in brightly coloured fabric, for the colour of a nearby wall painting to have been altered. The number of contextual variables which have the capacity to effect colour are beyond counting and each imagined change further emphasises the extent to which colour, rather than being a stable characteristic of materiality is in fact a perpetually unstable process of interaction between the statue, the physical environment, and the viewer.

This instability has been one of the major barriers standing in the way of a meaningful, contextually informed interpretation of Roman polychrome statuary. The majority of attempts to hypothetically reconstruct coloured statuary have been physical and so, as a consequence, highly contextually constrained. Surviving examples of polychrome statuary, as well as physically reconstructed ones, tend only to be seen within modern architectural contexts; situated within environments and subject to lighting conditions entirely different to those which would have informed their appearance in the Roman world. Consequently, interpretation of their polychromy remains extremely difficult. There can be little doubt, and this research will set out to demonstrate, that the appearance of a painted statue would be fundamentally different under modern artificial lights than it would in, for example, a Herculanean villa lit by natural light or by flame.

Quantitative measurements of coloured statuary which have characterised and advanced recent investigations into coloured statuary and sculpture offer great insights into the physical properties and behaviours of polychrome surfaces. However, as yet, they are able tell us very little about the appearance of these surfaces under the conditions which they might have been seen within a Roman context.

3.5.1.1 Viewing and movement

A consideration of context as an influence upon appearance at once raises the question of the viewer. To consider the object, not in isolation but as part of a greater physical world immediately requires the situation of a viewer within this world. Without this we are presented with an almost infinite number of visual possibilities. At this point the viewer will remain anonymous because it is the purpose of this section not to deal with questions of perception but rather to highlight the variation of physical experience which can be achieved by moving in relation to an object or through a space. In other words, the viewer here will simply provide a position within the physical environment. Their activities, for the present, will be considered only to the extent that they effect this position. For a lengthier discussion of the treatment of questions of perception within this thesis refer to Chapter 4 (3D Computer Graphics: Image Making and Contemporary Archaeological Practice).

If we consider the viewer in this most elementary sense, we introduce concepts of perspective and motion. Both of these variables dictate to a profound degree the way in which statuary and as part of this, the colour of statuary, are seen. At once the appearance of the statue ceases to be immobile and subject only to variation in the physical environment. Instead the appearance of the statue varies according to the participation of the viewer. The viewer can, through alteration of their position effect the apparent behaviour of light and can alter that which is visible.

Stewart argues that the conventional relationship between viewer and statue in the Roman world would have been one of separation, of display and observation from specific viewpoints (Stewart 2003:262). It is important to consider however that statues, even presented in niches or other controlled environments, were viewed from many angles in the course of many activities. Furthermore, statues themselves may have been moved, as part of a procession or in the course of normal transportation and movement (Weedle 2010). The ubiquity of statuary in a town like Herculaneum would have ensured that statues performed a peripheral role in the continuation of everyday life in civil and domestic settings and would, as a consequence, have been encountered from many different visual perspectives (Mattusch 2010:84).

It is not the intention of this argument to suggest that statues were created without the intended angle of view in mind. Evidence, such as the low levels of finishing of the backs of statues, clearly demonstrates that this is not the case. Rather it is intended to propose that polychromy, as a visual phenomenon is more effectively and more usefully understood, through the device of the hypothetical encounter, than it is through the hypotheses relating to specific function or purpose. It is the purpose of this argument to suggest that while laws of convention might have governed a great many interactions with statuary there will, within the life of any person have been instances during which these conventions did not apply and were not followed. Stewart gives the example of statue cleaning but asserts that these activities are peripheral if the goal of our enquiry is to more fully get at the meaning of statuary (Stewart 2003:262). This argument presupposes that meaning be approached through a better understanding of the intended purpose and role of statues. This presupposition, within the confines of Stewart's work is entirely rational. If however, the intention is to better understand statuary as part of a physical process resulting in appearance, then the angle of enquiry should be different and must begin with an approximation of the actions of the viewer rather than an approximation of the intentions of the actor who contrived either to manufacture the statue or to engineer the conditions of display.

In the most simplistic sense a meaningful understanding of the colours of statuary cannot be arrived at without incorporating the idea of motion. Surfaces differ profoundly in appearance depending upon the angle from which they are viewed, as the viewing position alters, the appearance of the surface is likely to change. This phenomenon preoccupied computer graphics for many years and is now widely recognised as being one of the pivotal factors in the accurate simulation of the appearance of light in a virtual scene (Westin, Arvo, and Torrance 1992; Blinn and Newell 1976; Schwartz et al. 2011). This is particularly true of several of the surfaces and materials which were frequently employed in statuary found at Herculaneum. For example, the highly specular reflectance of the polished marble surface has the effect of causing the marble to appear highly reflective from certain angles while appearing smooth from others, while the crystalline matrix of coarser statue marbles can appear to glisten and shine as the light source or the viewer move.

Like context, movement is central to understanding light as a physical process; as something active and participatory, not static or arbitrary. However, both of these variables lead inevitably to the consideration of a third factor central to an understanding of colour, the passing of time.

3.5.1.2 Temporality and Change

The changing through time of the appearance of the coloured statue can be understood in two closely related, but for the purposes of this discussion, discrete, ways.

As alluded to in the preceding sections, time is essential in fully understanding the appearance of polychromy. The reflective behaviours of the statue can only be fully understood through movement which equates to, and requires, the passing of time. Within a short space of time we might also consider variations in light; the flickering of a torch, the rising of the sun, the passing of a cloud. Movement of other objects within the scene should also be considered, the movement of adornments, decorations or drapes which have been added to the statue, either at the hand of an actor or due to the wind, or the movements of other objects close to the statue, of doors, drapes and furniture. All of these minute changes sound trivial but they are not. They serve as a reminder that colour is essentially non-static. While it may be easier to conceptualise as a static phenomenon, to do so is deceptive. Each of these changes, insignificant in their own right, maintain the natural state of colour, or rather of the perception of colour; that is perpetual change and instability. This sensitivity to colour as a manifest process, rather than as an abstract phenomenon is particularly important when the subject which we are attempting to understand is something as profoundly alien to our intuitive sensibilities as a Roman scene. The ahistorical nature of the photorealistic still image has been remarked upon previously and will be dealt with in more detail in Chapter 4 (3D Computer Graphics: Image Making and Contemporary Archaeological Practice).

Temporality also has a central role in helping to overcome another barrier to meaningful understanding of Roman statuary; the idea of the *original state.* There has been a tendency to describe and to represent polychrome statuary in terms of its 'original form' (Cook 1978; Brinkmann, Kellner et al. 2007:189; University of Cambridge Faculty of Classics Museum 2007; Holloway 2008). The use of this term though is, as we shall go on to see, problematic (Ingold 2010). This is due in part to the ambiguity of the term, but is further complicated by the fact that it implies a number of assumptions about the way in which statues were created, engaged with and responded to.

The connections between, colour and materiality, reflection and light, bind the object to the context within which it is encountered and by extension require that manifestations of colour are interpreted, to as great an extent as possible, within the context of these encounters. A belief in the importance of an 'original form' forces one to isolate a point at which the statue can be believed to have been 'complete' or 'finished'. And all of this, despite the fact that the vast majority of the life of the statue was not spent in this state, if indeed this state ever truly occurred. Changes in light, context and materials, not to mention the position of the viewer ensure that each encounter with a statue is, and would have been, physically unique.

Descriptions, such as those above, of the various techniques and processes of polychromy provide evidence of a complex process but do not, on their own, provide an adequate vehicle for its interpretation. It is necessary instead to consider polychromy as an entire physical event, subject to the influence of viewer position, movement, light, reflectivity and the myriad of other variables which inform the appearance of a scene in the physical world (Cleland 2004:141). Only when polychromy is considered in this way will an interpretation, encompassing a consideration of its visual characteristics, as one would hope that any consideration would, be possible.

The transitive nature of colour and so by extension, statuary, requires us to consider the temporal depth of the statue. The focus of this study is, in the first place, upon the visual, specifically that which is there to be seen. This requires that the statue to be considered not at a specific point, or in an arbitrary state, but rather as something which is and has been constantly encountered throughout a history during which it and its context have been subject to constant physical change.

Without an incorporation of temporal depth, and more importantly change, a conception of polychromy is necessarily rather abstract and contradictory. A description of any sort which seeks to provide a definitive representation of a statue (or any other object) necessitates the compression of a huge range of potential physical states, and by extension potential appearances, into a single description.

This can, and has, been achieved in a number of ways. The most common of which has been to attempt to identify an 'original' or 'intended' state. As mentioned above, the identification of an original physical state is highly problematic and, as Ingold has argued, inherently Modern (Ingold 2010). The idea of an object being 'finished' according to a preconceived notion is problematic within the context of this thesis, not only because it assumes the presence of what Ingold has termed "hylomorphic creation" (Ingold 2010:92), but also because it requires the creator of the representation to be able to accurately identify an intended appearance and to identify which data relate to this. The intended appearance and related data must be isolated from other visual components of the object which must be considered to have been brought about by a move away from this intended appearance, potentially brought about through alteration, decay, movement or any number of other visually significant variables.

3.6 Conclusion

As stated at the start of this chapter, the ultimate goal of this thesis is to represent, and as a result of doing so, better understand, the colouring of statuary as a physical and material phenomenon. If this goal is to be achieved effectively then a necessary prerequisite is a meaningful and complete understanding of both the material composition of polychromy and also of some of the characteristics which caused this phenomenon to be seen in different ways.

The purpose of this chapter was, in the first place, to set out to describe the primary material characteristics of Greek and Roman statue colouration in order that they might be more fully understood both in terms of the materials used but also the processes and techniques through which they were applied. This description was undertaken but in doing so only a partial understanding of colour was reached.

The secondary function of this chapter has been to explore some of the contextual and environmental considerations which might have affected the way in which coloured statuary was perceived and the way in which these statues changed and were changed by the instability of the physical world which they inhabited. All of these things profoundly affect a meaningful understanding of colour, because, a meaningful understanding of colour must be borne out of an attempt to understand colour not only in physical or material terms but also in terms of the way in which it was seen.

Colour as a concept is necessarily perceptually mediated, otherwise our conversation is not one of colour at all but of an arbitrarily selected band of radiated wavelengths. The desire to visualise is the desire to understand visually, to see that which others might have seen and to interpret these views accordingly. If these visualisations are to be of use they must be technically correct and they must seek to understand polychromy not as a phenomenon at a single moment from an arbitrary viewpoint, but rather, as a materially complex, feature of a physical world.

The next chapter will begin to look at the role which visualisation using 3D computer graphics might have in the creation of more profound contextualised understandings of complex archaeological phenomena.

Chapter 4

4 3D Computer Graphics: Image Making and Contemporary Archaeological Practice

4.1 Introduction

Images produced using 3D computer graphics are an integral component of contemporary archaeological practice. From the moment that 3D computer graphics technologies were introduced to Archaeology in the early 1990s, they have been utilised in order to fulfil a variety of methodological roles ranging from the experimental to the illustrative. Despite this proliferation there remains an unresolved contradiction between the theory and practice of archaeological computer graphics.

Throughout this period, still or moving images have been the primary media through which people have engaged with simulated 3D environments. This emphasis upon the use of visual media has tended to sit at odds to the body of theoretical literature surrounding the use of these technologies. It has been repeatedly suggested within literature related to computer graphics in Archaeology that reliance upon images has impeded the development of these technologies as archaeological tools and prevented their full potential from being realised (Gillings 2005; Forte 2010; Frischer and Dakouri-Hild 2008). Instead, an emphasis has been placed upon the potential of virtual worlds and interactive, immersive spaces.

The concept of the *virtual world* was popularised within the cultural and theoretical milieu surrounding the idea of virtual reality in the 1990s. The notion of an immersive and interactive digital environment entirely separate from the real world was integral to ideas of virtual reality. This perceived dualism between the virtual and the real has had profound implications on the perception of 3D computer graphics technology and has remained prevalent up to the present day within archaeological thought and practice. Within this dichotomy there has been a tendency to dismiss the image as representing a simplistic, static and ocularcentric alternative to the interactive, apparently embodied experience offered by virtual environments. These critiques have persisted in spite of the widespread use of images within research and publications dealing with 3D computer graphics in Archaeology and the relatively limited uptake of interactive, let alone immersive virtual environments (Gillings 2005). This chapter will explore the disparity between implementations of computer graphics methodologies and the theoretical discourse which has surrounded their use. It will argue that the tension between the theoretical and the actual has had profound implications on the methodological form which computer graphics in Archaeology have taken.

According to Sterne (2003) this disparity between the theoretical conception of technology and the practicalities implementation has become an endemic feature of technologically orientated research within the Humanities. Sterne asserts that this disparity can be attributed to the uncritical adoption by Humanities researchers of epistemological assumptions which were developed elsewhere and in isolation from the specific disciplinary demands and sensitivities of the Humanities. These ideas draw upon Bourdieu's development of reflexive sociology in response to the commercial and political pressures which he perceived to be shaping the sociological research agenda (Sterne 2003; Waquant 1989; Bourdieu and Wacquant 1992:251). Sterne suggests that the research agendas and conceptual language of technologically focussed discourse in the Humanities are frequently influenced by pre-formed ideas which have not been the subject of sufficient critical attention. He argues that an epistemological break is required in order to critically engage with technological subjects and that in order to do this, disciplines must assert their intellectual independence by drawing upon their own traditions of theory and practice. The purpose of the epistemological break or rupture in Sterne and Bourdieu's writing is to describe the process of self-conscious re-examination of terminology, practices or ideas which have been uncritically incorporated into a research area. The ideas can assist in the development of a critical assessment of the theoretical assumptions which currently surround Archaeology's use of 3D computer graphics. Building upon these ideas this chapter will consider how these technologies might be more meaningfully integrated into archaeological thought and practice.

This chapter will explore the extent to which traditions of archaeological image making and contemporary discourse relating to the role of images in Archaeology offer a theoretical basis upon which new understandings of the role and value of computer generated archaeological imagery can be built. The marginalisation of the computer generated image as an archaeological tool is at odds with a growing acknowledgement of the diverse and highly nuanced role which images of all kinds play within archaeological practice. There has been a tendency to emphasise the dynamic character of images, not just as a means of expressing pre-existing understandings but as a means of exploring archaeological subjects and building archaeological knowledge (Bradley 1997; Molyneaux 1997; Shanks 1997; Renfrew 2003; Renfrew, Gosden, and DeMarrais 2004; Smiles and Moser 2005; Perry 2013).

4.2 3D Computer Graphics & Archaeology

The introduction of 3D computer graphics into Archaeology in the early 1990s took place at a time of great technical and theoretical innovation within the computer graphics industry. 3D computer graphics were becoming increasingly complex and nuanced. Increases in the processing power of home computers were putting 3D graphics into homes and workplaces for the first time. These innovations took place within the context of a broader socio-cultural discourse surrounding the notion of *virtual reality* a phrase which had, for many, become synonymous with the emerging field of computer graphics (Rheingold 1991).

It was during this period and against this background that archaeologists first began to consider what these technologies and the barrage of theoretical concepts which were beginning to coalesce around them might mean for Archaeology. It was within this theoretical context that many of the epistemological and ontological assumptions which have come to underpin the use of computer graphics in Archaeology were first articulated.

The term *virtual archaeology* was first employed by Paul Reilly in his paper *Towards a Virtual Archaeology* (Reilly 1991:3; Barceló, Forte, and Sanders 2000; Niccolucci 2000; Goodrick and Earl 2004). This paper is significant because it provided the first articulation of what the methodological significance of 3D computer graphics might be for Archaeology. The virtual, Reilly observed, relates to 'the notion that something can act as a surrogate or replacement for an original' (Reilly 1991:133). Reilly avoided using the term *virtual reality* and argued for a broader conception of the interplay between digital and conventional archaeological practice. By invoking the concept of *virtuality*, Reilly invited archaeologists to draw connections between archaeological practice and the nascent but theoretically vibrant field of cultural and technological discourse which surrounded 3D computer graphics at that time.

These associations would prove persistent and during the following decades many authors would further develop the theoretical ties linking archaeological computer graphics with concepts and theoretical language borrowed from virtual reality and cyber-cultural theory (Barceló, Forte, and Sanders 2000; Earl and Wheatley 2002; Fernie and Richards 2003; Forte 2008, 2010; Frischer and Dakouri-Hild 2008; Frischer et al. 2000; Reilly 1991; Forte and Pescarin 2012:189).

Theoretical trends with origins in the cultural-theoretical discourse surrounding virtual reality have had a particularly significant influence upon the use of 3D computer graphics in Archaeology and the role which the image has occupied within this work. Ideas of immersion and of a digital surrogate reality have had a profound impact upon the perceived relationship between the viewer and the image within archaeological computing literature.

In spite of the significant influence which these ideas have had upon archaeological computing practice, the origins of much of this theoretical work remain obscure within archaeological literature. They have very infrequently been explored in any meaningful sense. In order to understand the influence which these ideas have had upon the form of computer graphics methodologies within Archaeology and more specifically the role of the image within these methodologies it is necessary to return to the point at which they were initially developed.

4.3 The Origins and Character of Virtual Reality

In order to understand the role of the image within the contemporary archaeological use of computer graphics it is necessary to return to the theoretical discourse which surrounded the development of virtual reality systems in the late 1980s and early 1990s (see figure 4.1). The origins of many of the epistemological and methodological tenets which have underpinned archaeological applications of archaeological 3D computer graphics can be found in these works.

Firstly, it should be said that *virtual reality* has proven to be a problematic concept to define (Brodlie et al. 2000:7). When the term was initially used, probably by Jaron Lanier during the 1980s, it was intended to constitute a technical definition of a specific range of technologies (Pimentel and Teixeira 1993; Steuer 1992). Quickly however the term acquired a raft of theoretical definitions and associations, often causing the term to have been used with considerable ambiguity. The amorphous and highly disparate theoretical character of virtual reality have helped to ensure that it has been re-appropriated and re-interpreted within a variety of often contradictory theoretical scenarios.

Figure 4.1 Immersive experiences of virtual worlds required specialist equipment. This example from December 13th 1994 shows Steve Mann wearing a Wearable Wireless Webcam (CC-BY-SA-3.0 Glogger).

The most elementary definitions of virtual reality are technical and relate to the use of specific technologies to interact with digitally simulated 3D environments. These technologies are a precondition of the *interactivity* which to Rheingold represents the first of two pillars of virtual reality, the second is immersion which will be dealt with below (Rheingold 1991:112). Pimentel and Teixeira state that, at the very least, this should include the use of 3D goggles as a means of interacting with a 3D virtual world (Pimentel and Teixeira 1993). However, they and other authors would generally expand upon this to include technologies such as haptic response (Pimentel and Teixeira 1993:285; Rheingold 1991:28; Burdea and Brooks 1996) and other sensory stimuli such as sound, smell and taste (Dinh et al. 1999) . An excellent survey of these technologies as they existed in the mid-1990s, when the terminology and underlying philosophical assumptions of virtual reality were conceived, is provided by Pimentel and Teixeira (Pimentel and Teixeira 1993:254).

The second common theme amongst literature dealing specifically with virtual reality has been the concept of immersion. This is labelled by Rheingold, along with *interactivity,* as being one of the twin pillars of virtual reality (Rheingold 1991:112). Rheingold is clear that the concept of immersion is not technologically specific, and with such a broad range of technologies falling under the umbrella of virtual reality it is clear that the level and nature of this immersion was going to vary considerably. An immersive experience is, by definition, an (apparently) unmediated experience, a concept to which we shall return below (Bukatman 2007). Immersion implies that one has a direct and apparently unmediated experience of the digital, Pimentel and Teixeira describe this sensation as being the impression of being in the virtual world (Pimentel and Teixeira 1993:288), while Heim takes this concept to another level by stating that, unlike traditional digital media which offered a subtle shift in reality, "VR [offered] a full-fledged, aggressive, surrogate reality". To Heim the experience of virtual reality represents a fundamental ontological shift (Heim 1993:xii).

Heim's words are highly significant. His assessment that virtual reality was capable of this degree of immersion clearly has resounding ontological implications; removing the notional viewer and replacing them with an apparently embodied participant. The consequence of this shift is that the viewer's awareness of the image moves from being potentially explicit to necessarily implicit. These ideas were echoed by Bukatman when he described the idea of "a perfect simulacrum of reality which denies its own technical origins" (Bukatman 2007:171). This self-contradictory idea of the apparently unmediated image is central to understanding the role of images within archaeological computer graphics and it is a concept which will be dealt with below.

These ideas are also very important in the extent to which they reflect a tendency amongst writers during this period to describe what virtual reality might *come to be* or what they expected to happen (Gillings 2000:18). This tendency towards the aspirational or utopian readings of technology is not unique to virtual reality and has accompanied the development and introduction of many technologies into fields of academic research (Sterne 2003:368). These periods of technological enthusiasm are, very often, the periods during which novel language and understandings of technology acquire the veneer of self-evidence. Frequently, where a technology appears to offer a great deal to a discipline, as in the case of virtual reality and Archaeology, concepts and language are accepted without the necessary level of critical attention.

The implications of this uncritical acceptance of existing discursive tropes and conventions have a twofold impact. As Sterne notes, the appropriation of technological neologisms and assumptions can influence directions of study; dictating which problems, approaches and issues seem to be of the most immediate relevance (Sterne 2003:168). The secondary impact can be the proliferation of language and epistemological assumptions which are inadequate or contradictory to the pre-existing intellectual traditions or goals of the discipline into which they have been assimilated. Let us look in more detail at the uses which concepts and terms with their origins in virtual reality found within archaeological discourse, before returning to Sterne's ideas.

4.4 Virtual Reality and Archaeology

The idea that technologies carry with them a range of associated ideas and assumptions is by no means new. We need only look to the introduction of photography to Archaeology to see the impact which theoretical discourse formed outside of the discipline can have upon archaeological thought and practice (Shanks 1997; Bohrer 2005). However it is important to understand how this process works and how this can influence the use of technology (see figure 4.2).

The process by which theoretical approaches may be more or less tacitly appropriated by users of technology is dealt with by Sterne in his re-working of Bourdieu's idea of the *force of the preconstructed.* In his paper *Bourdieu, Technique and Technology* (Sterne 2003), Sterne describes this process and also proposes methodological strategies with which the Humanities might re-appropriate technology. Sterne asserts that understandings of technology and the ways in which they are theorised frequently emerge as a result of popular discourse or as a result of commercial activities (Cavanagh 2007; Sterne 2003). This can certainly be said to have been the case in the development of the theoretical landscape which surrounded the development of virtual reality (Earl 2005:204). The origins of virtual reality technologies and the epistemological and ontological assumptions which accompany their use are discussed above. Suffice to mention here that when 3D computer graphics were introduced into Archaeology in the late 1980s a thriving cultural and commercial discourse existed surrounding the technology and its potential (Gillings 2000). It is from this discussion that much of the terminology and many of the theoretical concepts which have defined the perceived potential of this suite of technologies for Archaeology were developed.

Figure 4.2 Archaeological computer graphics have frequently adopted perspectival and compositional conventions from photography (CC-BY-SA-3.0 http://archive.cyark.org).

The widespread adoption of theories and concepts associated with 3D computer graphics characterised archaeological discourse as it attempted to justify and describe the potential value of these technologies as archaeological research tools. Concepts such as *virtuality, virtual reality, cyber-culture, surrogate reality and sensory immersion* were frequently associated with descriptions of these technologies (Reilly 1991; Arnold 2000; Barcelo, Forte, and Sanders 2000; Barceló, Forte, and Sanders 2000; Frischer et al. 2000; Forte 2008). Very rarely though were these terms explained or critiqued in order to ascertain their precise meanings within an archaeological setting, or their relevance to existing intellectual traditions within Archaeology. The neologisms of virtual reality had acquired what Bourdieu termed: "the cloak of the self-evident" (Sterne 2003:368; Bourdieu and Wacquant 1992:251).

In his development of the idea of a reflexive sociology, Bourdieu criticised the willingness with which the Social Sciences would adopt intellectual agendas or posit issues in terms which were defined by popular or commercial culture. This tendency, he argued, called for a stronger trend of self-criticism, a reflexive approach to Sociology, whereby the language, concepts and theoretical agendas which are taken up by the discipline are more readily criticised (Sterne 2003:369). The power of externally conceived concepts and language to influence the discipline within which they are employed was termed by Bourdieu as: "the force of the preconstructed" (Bourdieu and Wacquant 1992). Bourdieu's research in this area provided a critique of the adoption by sociologists of intellectual agendas developed in political, commercial and popular discourse. It was the responsibility of the researcher, argued Bourdieu, to assert independence through a critical application of conceptual and theoretical language. In practice he argued, this independence could only be achieved through an *epistemological break* or *rupture* between established modes of conceptualisation and a 'new gaze' (Bourdieu and Wacquant 1992:251). Central to achieving this break is the critical reading of concepts, language and method (Sterne 2003:369).

Bourdieu's ideas have been further developed by Sterne in order to better understand the study of technology within the Social Sciences and Humanities (Sterne 2003). Sterne argues that Bourdieu's critique of the use of cliché and apparently self-evident language can be used to understand the study of technology. Just as the sociological discourse with which Bourdieu was concerned is liable to be influenced by predominant trends in politics and the media, so argues Sterne is the study of technology liable to be influenced by popular assumptions relating to the value and meaning of technology. Sterne cites as an example the academic interest in *new media* (Sterne 2003:381). Conceptions of *new media* are, he argues, almost invariably associated with utopian descriptions of disembodied communication which stand at odds to the inherent physicality of entering text into a machine and looking at a screen. This void between the aspirational theory and the grounded reality certainly has echoes in Archaeology's use of virtual reality (Gillings 2000).

Bourdieu's ideas, and certainly Sterne's reading of them, are highly useful in attempting to understand the origins and influence of language and concepts which have shaped the archaeological perception of and reaction to 3D computer graphics. Virtual reality may seem like something of an anachronism within an academic context, ideas of elaborate 3D headsets and direct sensory stimulation have all but vanished from intellectual discourse, just as they have from popular culture. However, the residual influence of virtual reality upon archaeological conceptions of 3D computer graphics is powerful. This is particularly true of the epistemological and ontological assumptions which accompanied its introduction into archaeological discourse.

4.4.1 Immersion and the Viewer

One of the characteristic features of virtual reality is immersion and the attendant assumption of the possibility of unmediated experience (Rheingold 1991:112). The very existence of a *virtual reality* was predicated upon the assumption that through direct sensory stimulation one might "create a perfect simulacrum of reality which denies its own technical origins" (Bukatman 2007:171). The ambitiousness of these ideas in both technological and theoretical terms is self-evident. This is especially true if we consider the relatively primitive state of 3D computer graphics at the point that they were first articulated. Despite the problems implicit in implementing systems of this type, the idea of an immersive surrogate for reality has been influential in Archaeology and has characterised the use of the image within archaeological 3D computer graphics. Ideas of immersion were championed from the outset and remain prevalent within contemporary practice (Forte 1995; Dawson, Levy, and Lyons 2011; Niccolucci 2000). This focus upon immersion impacts upon the way in which the image is conceptualised, the way in which the image is used and most importantly of all it impacts upon the form and content of the image itself.

There has been a near uncritical acceptance within archaeological computer graphics of specific visual tropes which reveal underlying assumptions about the status of the viewer and by extension the nature of the image. Images are very often naturalistic in style, they tend to imply that the viewer is situated within the scene. Consequently the image becomes an inherently inadequate proxy for sensory engagement with a scene. The representation of the subject is inherently ocularcentric in that it fails to encompass any of the other sensory information which is integral to bodily experience. The scene is also an inadequate as a simulation of vision offering none of the intensity of light or breadth of colour which are an integral part of visual engagement with the physical world.

Attempts to make use of technologies which seek to provide any degree of immersion through direct sensory stimulation have been limited in number in Archaeology. Consequently, reliance upon the expression of the virtual environment through derivative imagery has been commonplace. It is perhaps surprising given this disparity that ideas which are predicated upon the concept of immersion have retained the influence which they have (Forte 2010; Frischer and Dakouri-Hild 2008).

Increasingly, theoretical accounts of computer graphics in Archaeology have become critical of established methodological approaches which have relied exclusively upon visual mediation. Accusations of ocularcentrism and mono-vocality find parallels in arguments for multi-sensory or embodied archaeological approaches championed by authors such as Hamilakis and Thomas (Hamilakis 2007; Thomas and Jorge 2008). Thomas identifies the 'distanced gaze' as being an endemic feature of particular kinds of representation (Thomas 2001). However, rather than incorporating the embodied, reflexive and experiential approaches which these authors have proposed, there has been a tendency within archaeological computer graphics to maintain a focus upon technologically facilitated immersion and the need for surrogate digital realities.

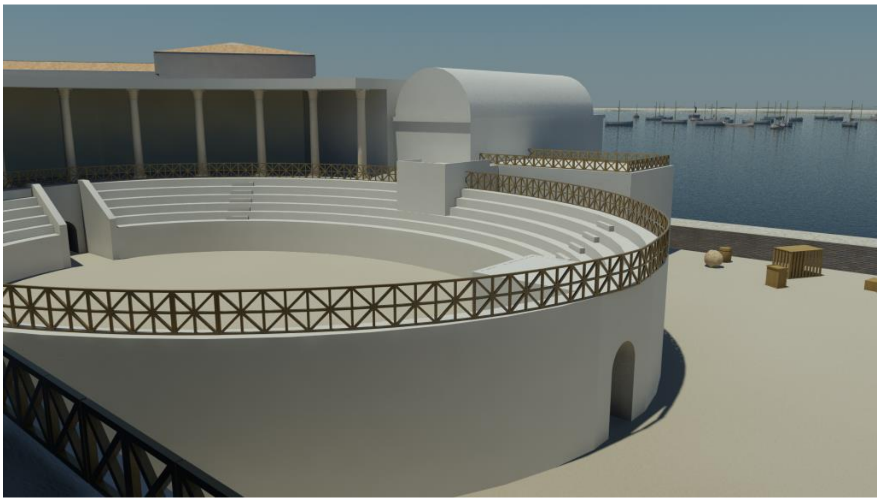

Figure 4.3 The Roman Harbour at Portus. Archaeological computer graphics are often presented as windows into virtual worlds rather than deliberately composed images. (Image author's own).

This emphasis is frequently expressed passively, in the use of terminology which maintains the notional otherness or separateness of the virtual from the real without making explicit arguments for immersive surrogate realities (Barcelo, Forte, and Sanders 2000; Niccolucci 2012), often though it is expressed in the form of an active argument for immersive, interactive virtual worlds (Barcelo, Forte, and Sanders 2000; Forte and Pescarin 2012). These approaches have sought to maintain the dualism between the virtual and the real and consequently between immersion and images; implicit and explicit modes of representation.

In his critique of virtual archaeology, Forte argues that we should move beyond a definition of virtual archaeology towards what he terms a *Cyber-Archaeology* Forte states that: "if in VA [Virtual Archaeology] the keyword is "seeing", in CA [Cyber Archaeology] it is "playing"" (Forte 2010:13). In erecting this dichotomy Forte consciously distinguishes between the image and the experience. Forte goes further, bemoaning the occularcentricism and univocality of virtual archaeology and argues that we should focus instead upon a *Cyber-Archaeology* which is totally "digital, immersive, autopoietic, interconnective and based on affordances" (Forte 2010:13).The status of the image within Forte's vision of cyber archaeology is didactic, external and mono-vocal, while the immersive experience is reflexive, immediate and inherently discursive.

These descriptions share a common understanding of the virtual world as something separate from the media through which they are invariably expressed. Within each of these texts the assumption has been that, despite previous failures, the future of 3D computer graphics is in the immersive, rather than the explicitly visually mediated, and that an insurmountable divide exists between these categories.

This tension creates something of an ontological crisis for the viewer. The naturalistic image invites the user to feel like a participant in the scene, as though they are seeing through their own eyes, but by equal token the fact that this is an image reproduced using conventional screen or print media means that the viewer is aware that they are just looking at a picture. Even more troubling to the viewer may be the invisible hand of the image maker who produced the image that they are looking at, but who's existence is now being tacitly denied. This is not to say that the average viewer is not capable of resolving this conceit at some level, but rather that they can never be sure quite how it is supposed to be resolved. Computer graphics are unlike naturalistic paintings or photographs in that the image offers few clues to the technology of production and the role of the image maker. It is not reasonable in this instance to rely upon the culturally specific visual fluency of the viewer, as computer graphics are too epistemologically diverse for this to be an option. Rather, the intention of the creator is concealed within the ambiguous use of aesthetic conventions and technologies.

4.4.2 Realism or Naturalism?

The quest for immersive digital experience within Archaeology and within computer graphics has been paralleled by the development of technologies which allow the rendering of images which have been increasingly realistic in appearance. The need for realism is an implicit feature of the development of immersive computer graphics. Without realism, immersion can never be achieved, we are reminded of Bukatman's "perfect simulacrum" (Bukatman 2007:171). The drive for increasing realism has also been technologically motivated, driven by a computer graphics industry the primary interest of which is to develop increasingly believable computer graphics. However it is questionable as to whether the term *realism* is appropriate when discussing images produced using 3D computer graphics.

Realism requires context; in order to appear to be real an image must reflect the character of human experience. At a very early stage Lansdown criticised the tendency of computer graphics literature to conflate the term *realism* with snapshot images based upon the eyewitness principle (Lansdown 1990:227). Shanks contrasts naturalism and realism through discussions of photography. A photograph of a person may be naturalistic in that it mechanically reproduces a scene but often the image may look unfamiliar, distorted or strange reproducing what Shanks calls a “momentary facet” without the fluidity and context of experience within which that moment made sense (Shanks 1997:79).

This distinction between realism and naturalism is central to understanding the use of images in archaeological applications of 3D computer graphics. Naturalistic visual representations of archaeological subjects have predominated within the body of images produced using these technologies. Generally, they have been described as being real with terms such as *photo-realism* being commonly used (Terras 1999; Moussa and Fritsch 2010). In fact this realism can be much more accurately described as naturalism. Naturalism is an aesthetic definition rather than an experiential one and describes the composition and creation of a simulacrum of reality which is intended to appear real.

The proliferation of naturalistic representations of archaeological subjects produced using 3D computer graphical technologies is emblematic of the disparity between theoretical conceptions of these representational techniques and the practicalities of making images in this way. Between highly theorised conceptions of computer graphics which emphasise immersion and realism, and the practice of making images using these tools, there is a theoretical void; the images which are produced do not fulfil the demands of the theory which is used to justify them. Theorists concerned with the use of 3D computer graphics in Archaeology have acknowledged this disparity and have tended to advocate the modification of technology in order to conform to a theoretical ideal of immersive virtual experience.

4.4.3 Utopianism

The utopian notion that virtual realities can offer an experience through which the user can transcend from the real into the virtual has been a constant feature of archaeological computing literature (Barceló, Forte, and Sanders 2000:3; Forte 2010; Frischer and Dakouri-Hild 2008). Frequently these ideas have been accompanied by statements which implied or stated openly that the image had been (or was about to be) rendered obsolete as a mediational technology by the existence of an interactive surrogate reality (Forte 2010; Frischer and Dakouri-Hild 2008). This has sat at odds to the near total reliance upon images, which in fact has characterised interactions with 3D computer graphics in Archaeology. It is highly significant because it represents a divergence between archaeological thought and practice. It is indicative of a methodology which is primarily top-down and technologically determined, rather than a methodology which is built out of and in response to existing trends in archaeological practice.

In the introduction to *Beyond Illustration*, Frischer presents the case for 3D environments as heuristic devices, rather than as a means of producing images (Frischer and Dakouri-Hild 2008). Frischer differentiates between the illustrative function of 3D computer graphics and the interactive calling for the utilisation of virtual space for sensory engagement and also for empirical hypothesis testing (Frischer and Dakouri-Hild 2008:xvi). A call for diversity in the manner by which 3D computer graphics are employed is entirely positive. However, the implication that these efforts will supersede the illustrative function of 3D computer graphics is problematic assuming as it does that the inherent reductionism involved in image creation precludes this process from also being a valid means of creating new understandings of archaeological subjects.

There is a fundamental disparity between the language and ideas which were developed in response to virtual reality technology and the reality of 3D computer graphics practice within Archaeology. At its most fundamental level this disparity can be seen in technological terms. Archaeological computer graphics never stopped utilising the image as the primary mode of communication and very rarely did they become interactive in any significant sense. Consequently, the mediated (non-immersive) image has been at the heart of almost all examples of archaeological computer graphics. Despite this centrality, the image has not received adequate theoretical attention. Consequently it has remained inhibited, conforming to specific visual tropes which are frequently technologically determined and which reflect this underlying tension (Gillings 2005).

The description above should demonstrate with some force the impact which concepts directly inspired by, or with their roots in virtual reality have had upon archaeological practice and the use of 3D computer graphics. Research agendas and the use of technologies have been formed by prevailing intellectual themes and agendas emanating from the world of virtual reality and computer graphics development. Partly this is down to what Earl describes as: "the consensual exploitation of archaeological data by graphics corporations" (Earl 2005:205). But in addition to this conscious (and often technically productive) relationship there are also more subtle trends at work with predominant aesthetic styles, conceptual language and epistemological assumptions entering archaeological discourse but remaining largely unchallenged. The following section will attempt to demonstrate that a fundamental disparity exists between the treatment of the image within archaeological computer graphics and the treatment which the image has received within Archaeology more broadly. This disparity is indicative of the need for a change in the way in which computer graphical images are seen and used but it also offers the potential for development. Re-engagement with the theory and practice of archaeological image making represents a model for methodological and theoretical re-appropriation of digital image making and the potential for re-engagement with archaeological practice and tradition. Rejuvenation of this relationship has the capacity to offer the theoretical rupture but also to provide a model for the new gaze which Sterne identified as being essential (Sterne 2003:369).

4.5 3D Computer Graphics as Archaeological Practice

The challenge set by Sterne is to find a way of meaningfully appropriating new technology; to develop new conceptions of technology which are shaped by the intellectual themes and methodologies of our discipline(Sterne 2003:370). In order to re-cast the computer generated image as an archaeological tool it is first necessary to begin to understand what contribution these images and the processes surrounding their production might make to archaeological practice. The analysis above has presented the case for theoretical change, for the instigation of Bourdieu's epistemological rupture. However, this can only be achieved through practice. In Shank's study of archaeological photography he identifies that the intellectual diversity and the methodological possibilities of photography are so diverse that to impose formal rules and procedures would be to inevitably close down possible avenues for creative re-appropriation of the technology (Shanks 1997). Instead he proposes that we fulfil our 'obligation to attend to technique and method in a way which recognizes humanistic *possibility'* (Shanks 1997:101). The result of Shanks' analysis then is not a series of instructions but rather, a series of areas for focus. Similar points have been made in relation to 3D computer graphics in Archaeology. Of particular relevance was Gillings' warning that a failure to acknowledge the playful and creative dimension of computer graphics had the capacity to jeopardise the development of these technologies as archaeological tools (Gillings 2000). To these ends, this chapter has identified the following areas which require attention if we are to more fully realise the archaeological potential of computer generated images. It is hoped that if they are addressed with creativity and archaeological purpose they may have the potential to catalyse this kind of activity. They are:

- Identifying a meaningful theoretical framework for computer graphics which moves beyond an implicit or explicit reliance upon concepts of sensory immersion.
- Refining the distinction between realism and naturalism and developing a more nuanced approach towards the aesthetics of computer graphics
- Overcoming aspirational justifications for computer graphics in Archaeology and instead focussing upon the value which existing practice in archaeological computer graphics and related fields of image making brings to Archaeology.

Responses to these areas of interest are likely to be heterogeneous in the extreme and should reflect the methodological diversity which characterises archaeological computer graphics. It is perhaps wrong even to consider computer generated images as a single medium. Methodologies can differ so profoundly that very few, if any, characteristics are common to all computer generated images. Consequently the potentials of each specific methodology differ greatly. The vast epistemic scope of computer generated images is expressed in Figure 4.4.

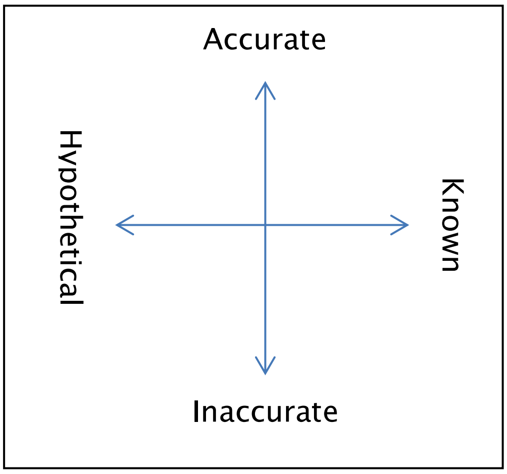

Figure 4.4 As a medium, computer generated images are highly epistemologically unstable. They can highly accurate or entirely inaccurate. They can be entirely hypothetical or entirely based upon experimentally derived data.

It is not viable to attempt to describe the image making process in general terms, nor is it necessary given the focus of this thesis. Instead the following section will deal specifically with the kind of images which are dealt with within this thesis, these could be broadly categorised as Hypothetical-Accurate. The purpose of the remaining part of this chapter is to outline a theoretical response to these issues which help to describe the value of the specific techniques which feature in this thesis.

The discussion will be divided into two parts:

1) Digital Craft: Processes of making in a digital context. The process of image making is highly significant both in terms of the character of the resulting image and in terms of the kind of knowledge which is generated as it is created. If the image making process is inadequately conceptualised then the resulting image is inherently ambiguous in character.
2) Publication and Performance. The tools and processes which can be employed in the production of computer graphics are enormously

diverse and consequently so are the epistemological characteristics of the resulting images. Because of this diversity, the way in which images are mediated acquires a particular significance. Decisions regarding the presentation of images dictate the way in which they are interpreted, understood and used.

4.5.1 Digital Craft: Processes of making in a digital context.

Descriptions of computer graphics often treat images as though they are windows into a virtual world. The fact that these images have been deliberately composed is often overlooked. Emphasis is frequently placed upon the technical processes which are at work with very little attention paid to the subjectivities and creativity of the image making process. The following section will discuss the extent to which theoretical approaches to archaeological image making can help to realise the power and the value of image making processes within 3D computer graphics.

There has been a tendency within archaeological computer graphics literature, but also within theoretical archaeological literature more broadly, to conceptualise the image as something which places distance between the viewer and the subject. These assertions were rooted in a belief that the privileging of the visual, to the exclusion of the other senses, was to risk presenting a skewed and distorted vision of the world. Within archaeological computing this critique often emanated from those seeking to develop research utilising immersive approaches involving multi-sensory human computer interaction. Within archaeological theory these ideas often led to, or were driven by an interest in embodied approaches to the interpretation of the world.

This theoretical agenda had the effect in archaeological computing of directing attention away from the image. Within archaeological literature more broadly a sense of the value of images was generally retained. In fact it could be argued that accusations of occularcentrism led to the image being the subject of a great deal of creative theoretical discourse. In this post-processual theoretical landscape the creative use of images has flourished, driven by an emphasis on image making and the relationship between archaeological images and broader visual culture (Perry 2013; Renfrew et al. 2004).

In the meantime archaeological computing pursued methodological and technological solutions to the perceived inadequacy of images as a form of representation. As mentioned above, this drive towards immersive, multi-sensory digital archaeologies was never really successful and it certainly did not diminish the number of computer generated images being produced. In fact, the period between the 1990s and the present have seen steady increase in the production of computer generated images of archaeology (Gillings 2005).

The importance of the contribution which processes of image making have made to archaeological thought and practice has been increasingly acknowledged through a range of publications, workshops and conferences (Smiles and Moser 2005; Perry, Cooper, and Beale 2013; University of Southampton 2011; Molyneaux 1997; Renfrew, Gosden, and DeMarrais 2004; Renfrew 2003; Rabinowitz 2013). In spite of this, the making of archaeological computer graphics has rarely been the subject of critical attention and the unique contribution which these processes might make to archaeological understandings has been under explored.

Archaeology has a long and extremely rich tradition of image making and of communication using images. These traditions have been the focus of extensive theoretical attention in recent years with attempts having been made to describe the range of interpretive and communicative processes which are involved in the making and dissemination of archaeological images. These intellectual traditions have run in parallel with discourse surrounding the use of archaeological computer graphics but there has very rarely been a great deal of cross pollination between these areas. Image making is integral to conventional archaeological practice. As Molyneaux explains:

"Visualisation is essential in theoretical work, providing a material environment (in the form of models, diagrams and other images) within which intuition can operate and, more subtly, allowing the connection of ideas with natural processes" (Molyneaux 1997:3).

At the heart of Molyneaux's conception of the archaeological image is the figure of the skilled maker who uses intuition and skill and judges the affordances of any given scenario in order to produce images which are insightful and communicative. This is a dynamic conception of the image which can only be understood in terms of practice.

There has been a tendency to see computer graphics approaches as being the domain of technophiles rather than archaeologists (Earl 2005). This perception is apparently borne out in the technical language which characterises the vast majority of publications of this theme. Increasingly however, 3D computer graphics are utilised by archaeologists themselves and as such it becomes increasingly viable to address and conceive of complex research questions which are founded upon advanced understandings of archaeological theory and practice as well as technological skill. Many practitioners of archaeological computer graphics have talked about the process of production as being a creative process through which new understandings of the archaeological material are born (Earl, Keay, and Beale 2008; Earl and Wheatley 2002; Perry 2013) This process of knowledge creation through image making identifies the production of archaeological computer graphics as a craft skill. Bunnell identifies craft as being both process and product and states that craft is a "continuous internal dialogue between maker and technology while being both consciously and subconsciously influenced by the external forces of the cultures of craft, design and beyond." (Bunnell 2004:5)

This definition of craft connects practice, product and culture in a way which is entirely relevant to the use of computer graphics in archaeological image making. As in the case of this research, the process of producing computer graphics is often very drawn out, involving the production of a complex model or simulation in consultation with many experts. Negotiations between archaeologists as well as the intimacy which image makers can acquire with archaeological subjects through an internal dialogue with technology and information ensure that image making is a uniquely productive and distinctive form of archaeological knowledge creation (Molyneaux 1997).

Bradley recognises the skill of the archaeologist and of the image maker and identifies within them common themes which he describes as craft traditions (Bradley 1997). The process of producing images using 3D computer graphics must not be seen as being alien to archaeological research. It should not even be seen as a diversion. Image making using 3D computer graphics has the capacity to be an integral component of archaeological research. The true danger according to Bradley is not that we get it wrong or that we accidentally mislead but that we fail to intellectually engage with the process of envisioning and that we default to an agnostic, normalised position (Bradley 1997).

The identification of archaeological image making as a set of craft traditions is extremely useful in helping us to understand the value of the process of image making. The creation of images in any medium requires a distinct set of practices or skills, affords different benefits and constitutes a unique form archaeological practice. Knowledge is derived and expressed differently according to the medium which is being used. Until now the perceptions of the potential of computer graphics within Archaeology has been driven primarily by technological innovation and the co-option of new technology. However, a reflexive consideration of the role which the technologies have had and might contribute could lead to a far more fulfilling role for computer graphics in Archaeology.

Shanks' discussion of archaeological photography attempts to complicate perceptions of the medium by exposing the range of processes which lay behind the photograph. This analysis provides a model for the way in which we might begin to re-interpret computer graphics. Shanks characterises archaeological photographs as instances of cultural production. In other words the photograph is socially situated and dependent upon social context for much of its meaning. Shanks' observes that: "to make sense, a photograph needs to have established connections and contexts which work within and beyond the image. This may occur in its subject matter and composition"(Shanks 1997:84). The same can be said of the computer generated image although the relationship between the image and the subject which it depicts is far more complex. Unlike the photograph which has been produced through the mechanical capture of energy the computer generated image is borne out of a deliberate constructed simulation.

The contrast between the apparent verisimilitude of the photograph and the synthetic computer generated image is immediately apparent. However, such an analysis does not stand up to scrutiny. Photographs are often treated as unproblematic representations of the subject which they depict but as Shanks points out, photographs are *made* (Shanks 1997:73) There are a range of subjective forces at work in the creation of an image using this technology.

Computer generated images are also *made.* The power of computer graphics lays in the fact that the technology has been developed precisely in order to manipulate and exercise precise control over the process of making.

The digital model, prior to the rendering of images is a dynamic and highly versatile creative space which is rich with interpretive potential. The building of the model affords the image maker a unique intimacy with the subject before images are made and before any characteristic of the model is fixed. Every object must be created and every material property must be defined. It will quickly become apparent to the image maker whether pre-existing interpretations of the subject work when they are subjected to the rigours of being spatially represented according to experimentally derived data. This phase offers the image maker a chance to think about the objects which they are representing and how they relate to each other, this is one forum within which the creative benefits of playfulness and experimentation can truly be felt. Frequently this process is collaborative in nature, with the image maker and the specialist sitting side by side and trying to resolve apparent contradictions in the data or observing correlations or relationships which had not been apparent before the model was made (Earl, Keay, and Beale 2008; Earl and Wheatley 2002). In this sense the model represents an exploratory space within which new understandings of archaeological data can be built. It is this potential which means that it is necessary to conceptualise the modelling process and the model which is created separately from the images which are often seen as the inevitable end point. Image making is one of many activities which can take place within a 3D model.

This diversity has been evidenced during the 3D modelling of the Roman harbour at Portus during the University of Southampton's Portus Project (Earl, Beale, and Keay 2011; Earl, Keay, and Beale 2008). The digital model of Portus has been in constant production for the past nine years and has been developed by a number of researchers. The model has been constantly refined and developed as excavations have continued and has been subject to input from a range of specialists during this time. The Portus Project emphasises the dynamism of the virtual environment but also it's potential to offer a virtual space within which to experiment and test ideas. Within the project the model has been used for a variety of functions including the creation of images for on-site interpretation, spatial calculations regarding the urban layout, structural analysis of particular buildings, lighting analyses and tests relating to the movement of people around specific buildings, the model was even used as a forum for meetings when it was converted into a Second Life model (Earl, Beale, and Keay 2011; Earl, Keay, and Beale 2008; Earl et al. 2013).

A feature of 3D modelling which is highly significant within the context of an archaeological research project is the necessity to consider every component of a simulation as part of a visual ecosystem. The need to reconcile different datasets and to give them a physical coherence means that understandings of objects within the model are contextual and inter-related. The ability to hypothetically represent variables (even very small variables like the turbidity of the atmosphere) means that the building of a simulation and the production of images which results, represents the first step in an exploration of the significance of and physical relationship between data.

The persistent problem of archaeological computer graphics has been the degree of opacity which has surrounded the process of making images in this way. Because these processes are often dismissed as being of incidental benefit they are omitted from research accounts and as such the record which emerges often fails to the reflect the quality of information which has been generated directly through or in response to the modelling process. Where methodologies are described in detail they are rarely expressed in terms which are accessible to an archaeological research community. Nor do they generally convey the complexity, contradictory and serendipitous nature of the research process. It is the job of the craftsperson, the 3D modeller, the image maker or whatever they choose to call themself to narrate this process and to describe the value of modelling both as a form of image making but also as an activity distinct from image making. This can be achieved in a huge variety of ways.

This thesis addresses this challenge by including a methodology which places equal emphasis on every phase of the image making process, from data capture to modelling. It also describes the full range of physical and digital processes which have been involved in generating visualisations. Finally the thesis expresses the subjective and creative elements of the image making process through the publication of the images themselves in Chapter 10 (Results 2).

4.5.2 Publication as Performance

As evidenced within this chapter, the computer generated archaeological image is often treated as being incidental and decisions regarding image making processes are rarely explicit within methodologies or discussions of work. The approach taken within this research to the use of images is to recognise that computer graphics require explicit mediation. The use of computer graphics in Archaeology tend to have been characterised by the assumption that the computer generated image is in some way comparable to a photograph. This constitutes a form of implicit mediation. The fact is that computer graphics have no visual characteristics other than those which they are assigned. Unlike traditional media such as painting or drawing whereby the image is physically constructed from the materials of production, computer graphics in their most basic form, are non-visual entities.

It is worth considering what computer generated images actually are. They are files which have the potential to be visually realised subject to the decision to give them visual form. Mediation represents another link in the image making chain which began with the capture of data and the modelling process and which ends with the creation of an image. This notion of the computer graphics image making process as a chain, or linear narrative is significant. It is useful here to return to the idea of the *distancing gaze* (Thomas 2001:173). The assertion that the image represents an abstraction or distortion of the subject which it depicts relies upon a conception of the image which is purely aesthetic. In fact, computer generated images (and almost certainly other forms of image too) can be seen as not abstract or distorted representations of an original object, but rather as manifestations of the data and most importantly the processes which were involved in their production. The images presented within this thesis are images of painted statues, but only insofar as the underlying data and technical and intellectual processes from which they were formed constitute a complete account of a painted statue. Actually they embody the interplay of inputs, processes, actions and re-actions which have characterised the image making process and the knowledge making process.

However, the process of rendering this complexity meaningfully in visual form is not trivial. Part of the challenge lays in moving beyond the naturalistic conventions which Lansdown termed the normative *snapshot realism* of computer graphics (Lansdown 1990) and towards the production of images which convey the complex, nuanced and dynamic character of archaeological practice. Success in this endeavour lays in the skilful application of the craft of the image maker and their ability to effectively realise this complexity within visual form.

The computer generated image represents an opportunity to compellingly narrate this process but in order for computer generated images to be used in this way it is necessary to confront the issue of mediation and the creation of images from the 3D model. The fact that the digital image has no default form means that the act of manifestation has a performative quality. The image maker is required to mediate the interplay between the image making process and the audience. They are required to say all that they wish to say through the creation of images and their presentation in context. In a play, the performance is the manifestation of a range of processes ranging from the writing of the script to the painting of the stage set all brought to life through the skill of the actor. Similarly, the archaeological image has the power to encapsulate processes, connections and complex narrative. Ingold identifies the performative character of craft when he says: ”the skilled practitioner is like an accomplished storyteller who’s tales are told in the practice of his craft rather than in words” (Ingold 2011).

Devising a method for producing images which embody process and skill and which communicate these dynamic qualities to the audience is by no means a simple task. The dislocation of the mode of production from the medium of representation puts the image maker into a difficult position. Upon what criteria should decisions relating to the mediation of the image be made? The problem brings to mind Benjamin’s fears regarding the loss of authenticity and meaning from art as modes of reproduction entered the mechanical age (Benjamin and Underwood 2008). In this case however, fears over a loss of meaning or value are misplaced. The value of these images does not reside in an unbreakable connection between process and medium but rather in the coherence of the underlying intellectual and physical craft processes.

These craft skills, identified by Bradley, Molyneaux and a range of other archaeological authors, represent the essential methodological and intellectual character of image making as an archaeological pursuit and it is upon these foundations that a distinctly archaeological computer graphics can be built (Bradley 1997; Molyneaux 1997). The enactment of these craft processes within the context of these technologies has the potential to produce any number of creative responses to the potential of the computer generated image and have the power to initiate the epistemological break which Bourdieu and Sterne described (Sterne 2003; Waquant 1989).

4.6 Conclusion

Accusations of ocularcentrism levelled at 3D computer graphics are valid only if we accept that the full value and function of the image resides within the image itself. In addition to being a physical object in its own right images are intimately related to the processes which led to their creation. Consequently, the archaeological image should be understood not only in terms of its value as an illustration of an idea or concept but rather as part of an entire process of skilled mediation between archaeological data, technology and the desire to communicate complex concepts.

In order for 3D computer graphics to more fully realise their potential as archaeological tools it is important that image makers become more adept at exploring and communicating the complexity and significance of the creative process. It is also very important that 3D computer graphics practitioners embrace the image making part of their practice and understand the value of images as a means of engaging creatively with archaeology.

The consumption of images is a creative act and is inherently social. In order to harness this potential, archaeological image makers must begin to consider the unique aesthetic potential implicit in the use of 3D computer graphics and to create images which speak to contemporary viewers. Images fulfil an indescribably diverse range of subtly differing methodological roles within archaeological practice. The potential for innovation is enormous and this thesis will provide a demonstration of one way in which this potential can be fulfilled.

Chapter 5

5 Physically Accurate Computer Graphics: A Guide for Archaeologists

5.1 Introduction

Computer graphical visualisations have become increasingly commonplace within Archaeology. However, many of the techniques used in their production remain obscure and unknown to the majority of archaeologists.

The purpose of this chapter is twofold. Its immediate function is to provide the reader with an understanding of the language and the technological processes which underpin the methodology presented within this thesis. The second function is broader in its scope and is to explain computer graphics in general terms to an archaeological audience. There are two reasons why this is necessary:

1) Without a basic understanding of the concepts and technology which sit behind computer graphics it is not possible to effectively critique or analyse the images or the methodologies which were used in their production.
2) The technologies of 3D computer graphics are increasingly becoming the conventional technologies of archaeological documentation and analysis. Use of techniques such as photogrammetry, laser scanning and reflectance transformation imaging is now widespread within commercial and research Archaeology. An essential knowledge of imaging and 3D computer graphics technologies will enhance the ability of the archaeological researcher to use these tools in innovative ways and to understand the data which result from their use.

The emphasis within this chapter will be upon explaining the techniques which are used within the methodology of this thesis. However, in outlining these technologies and in describing how they fit together into a coherent methodology the chapter will describe every stage necessary to implement a 3D computer graphics workflow.

5.2 Physically Accurate Computer Graphics

Physically accurate computer graphics are computer graphics which are based upon and seek to accurately represent the physical processes of light and reflection. Predictive rendering, a methodological approach rather than a specific technology, describes a computer graphics workflow which is sufficiently physically accurate that it can be used to predict the appearance of a scene in the real world. Predictive rendering methodologies, which invariably incorporate physically accurate computer graphical simulations, are regularly used in fields such as architecture and product design where the need to accurately visualise objects before they are physically realised is essential.

The goal of these techniques is to produce images which are not merely believable but which are demonstrably accurate. Physically accurate computer graphics are technically distinct from conventional computer graphics and have unique methodological requirements. Their potential value as research tools and the unique requirements of implementation will be explored in this chapter (Wilkie et al. 2009).

The purpose of this chapter is to survey techniques which can be incorporated into a physically accurate computer graphics workflow and to begin to consider the potential that they might have for archaeological analysis and interpretation. The chapter will present the reader, particularly the archaeologist, with a summary of the technologies available, and will help to develop an understanding of how the technologies and methodological approaches which characterise physically accurate computer graphics might be combined and meaningfully incorporated into an archaeological methodology.

Physically accurate 3D computer graphics are produced using a suite of hardware and software. These technologies are combined in order to simulate those real world processes which constitute the behaviour of visible light as it interacts with a surface or surfaces. It is up to the image maker to choose which tools are appropriate in any given scenario based upon the character of the task in hand.

Conventional computer graphics have been developed with the aim of producing images which are believable, though not necessarily reliable (See Figure 5.1). Physically accurate computer graphics on the other hand may aim to produce a believable result but, if correctly implemented, will always do so through using reliable, repeatable and accurate simulations of real world processes. The simulations consist of a collection of mathematical descriptions of real world phenomena such as light transport, reflection and refraction. The accuracy of the resultant imagery is, in part, dependent upon the accuracy of these mathematical models. Equally important however are the input data which relate to geometry and reflectance and the means by which the resultant images are displayed.

Figure 5.1 This visualisation of the Anglo-Saxon Witham Bowl was produced using a non-physically accurate rendering technique. While it looks realistic it is not a reliable depiction of reality (Image authors own).

Attempts to refine the simulation of light, and so produce 3D graphics of increasing realism and accuracy, have occupied much of the history of 3D computer graphics research. Very early published research on the subject, although moderating expectations through frequent references to technological limitations, regularly drew upon the vocabulary of accuracy and comparisons with the real world (Phong 1975; Westin, Arvo, and Torrance 1992; Blinn 1977; Blinn and Newell 1976).

Consequently there can be no static (or definite) dividing line between those simulations which can be defined as physically accurate and those which cannot. As with any set of tools, the value of physically accurate computer graphics lays in choosing appropriate tools, in an appropriate combination. All simulations represent a compromise between the apparent realism of the image produced, the complexity of the simulation and the computational cost of the calculation (Strauss 1990). This is as true for cutting edge computer graphics research as it is for simulations carried out on home computers or in small computing labs. Consequently within an archaeological context, implementation of physically accurate computer graphics must balance considerations of requirement (which questions are to be answered?), availability of resources (which data/software/hardware are available?) and appropriateness (which methods and techniques will be most appropriate given the nature of the task?). Only then can it be decided whether physically accurate 3D computer graphics offer an appropriate and achievable solution to the questions which are to be addressed. If it is decided that they do, then a methodology can be designed which contains an appropriate balance between accuracy and computational cost; a methodology which is valid but also efficient.

The purpose of the following chapter will be to describe the range of techniques currently available for the production of physically accurate computer graphics and to assist the archaeological researcher in choosing the correct techniques and methodological approaches. As its basis the chapter will draw upon the 2009 SIGGRAPH Asia course on predictive rendering by Wilkie, Weidlich, Magnor and Chalmers (2009).

This course set out to define a methodology for the production of physically accurate computer graphics of sufficient accuracy that they can predict the physical behaviour of light. Applications which require simulations with this degree of accuracy are relatively few and the possibility of implementing a predictive rendering pipeline containing the hypothetical content necessary for an archaeological reconstruction is problematic. Scenarios within which Wilkie et al. highlight the usefulness of predictive rendering include architectural design, high end product design (automotive design is quoted as an example) and the prototyping of gem cutting (Wilkie et al. 2009:12). Each of these applications demands an extremely high level of accuracy; a level of accuracy which is ultimately ensured through comparison with a physical scene.

A methodology designed to function at this level of accuracy provides a demonstration of the extent to which each of the techniques and processes within a 3D graphics production pipeline are interdependent. A significant compromise at any stage of the methodology would compromise the accuracy of the entire process and, in the case of the above examples, cause the process to be of little benefit. Within archaeological visualisation this compromise is often a necessity but the way in which it is made, and the restrictions which are placed upon the conclusions which can be drawn from the resultant visualisation, must be carefully considered.

The rest of this chapter will be dedicated to a description and evaluation of a range of methods and concepts. It will be divided into three sections; modelling, rendering and display. Each method or concept described here can be incorporated into an image synthesis pipeline which maintains a demonstrable degree of physical accuracy. Each will be described in terms of the role of the technique within the image synthesis pipeline, the merits of each technique and the applicability of each technique to Archaeology.

5.3 Modelling

Modelling refers to the part of the computer graphics creation process during which the 3D model (including all geometry and textures) is created. It is analogous to the creation of an architectural model. As part of the modelling process, variables relating to the geometry in the scene and to the surface properties of these objects are defined. The model is assembled using these data and then when it is complete, light simulations can be conducted within the modelled environment.

5.3.1 Geometry and 3D Data Capture

Geometric data defines the extent and surface of an object within the scene. As we shall see there are many ways of capturing or creating geometry, but regardless of the source from which it is taken, the role of geometric data remains the same. The geometry featured within a scene can be divided into two categories; measured/captured (data captured directly from real world objects) and modelled (that which is created digitally). These data types differ both practically and conceptually although there are areas of cross over.

5.3.1.1 Measured or Captured Geometry

A range of geometric data capture techniques are currently employed within Archaeology. Falling equipment costs mean that the range of 3D data capture solutions available to the archaeologist is expanding rapidly. Archaeological requirements for 3D data capture are subject to enormous variation in terms of the scale of the object being recorded, the conditions under which recording takes place and the requirements for accuracy and precision in the resultant dataset. It should be noted however that all 3D datasets represent only an approximation of the true complexity of the surface geometry and so a subjective decision relating to acceptable levels of accuracy must always be made and justified. Wilkie et al advocate the capture of *exact geometry* which can be assumed to mean the highest resolution and most accurate data technically possible (2009:15). In an archaeological context however, the constraints imposed by recording conditions, the nature and size of the subject and the availability of the equipment are significant. Decisions such as these are familiar to the archaeologist from the use of photography as a means of documentation. The resolution of a photograph is dependent upon a similar process of pragmatic decision making.

Within the context of a physically accurate light simulation, geometry is of central importance. The geometry which is present in a simulated scene dictates a great deal about the way in which light behaves and the levels of light present. Consequently the level of accuracy which the simulation is able to achieve is dependent upon two factors, the accuracy and the resolution of the geometry. It is worth noting that this accuracy can be compromised at any point through the use of mesh smoothing or other surface manipulation algorithms, it cannot however be improved upon without the addition of more experimentally derived spatial data. This is again analogous to photography. Data can be lost from a photograph as it is manipulated, made smaller and cropped. Data cannot be added to a photograph once it has been taken. It is important then to consider the data capture process before the data are gathered.

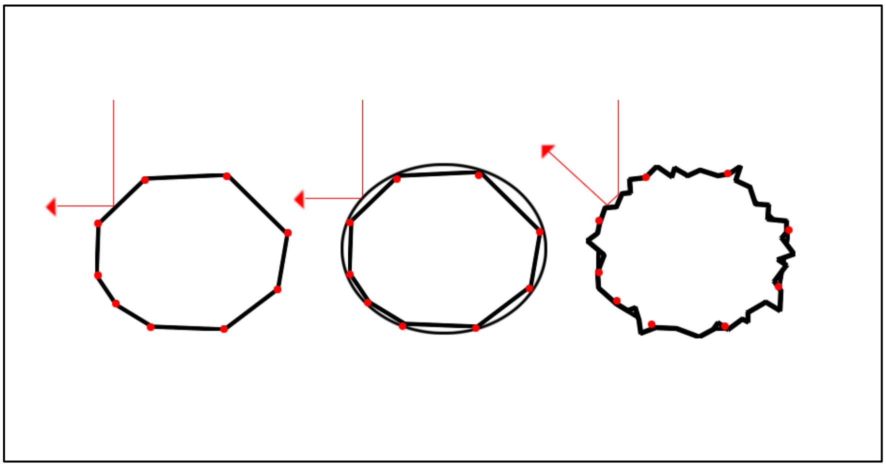

Figure 5.2. This image shows how different representations of the same object can behave differently within a simulation. The shape on the left is a low resolution object. The shape in the middle has been smoothed. It now looks different and reflects light differently despite the fact that no additional data is available. The shape on the left was captured at a higher resolution and so the surface geometry reflects light differently and in a more physically accurate way.

Accuracy is paramount. Inaccurate records of objects severely compromise claims of physical accuracy providing, as they do, an uncertain relationship between the geometry of the virtual object and the real object which was recorded. Whichever data capture method or device is employed the highest possible levels of accuracy should be ensured. In reality of course, accuracy is inevitably compromised to some degree, due to imperfect recording conditions and the nature of the device used. Accuracy is particularly important due to the lack of a means of 'ground-truthing' geometric data.

Secondary to accuracy is resolution. The higher resolution a geometric record of an object is, the more accurately it can be assumed to behave. Simulations of reflective surfaces in 3D graphics can be compartmentalised into three levels, the micro-, meso- and the macro- geometric. Due to the fact that they describe the same phenomenon at different levels of detail the dividing line between the categories is relative. However, micro-geometry can broadly be defined as geometry, the form of which is not clearly visible to the naked eye, but which defines the reflective characteristics of a surface, such as apparent colour or texture (Glencross et al. 2008). Meso-geometry can be defined as those geometric features which are visible and which comprise the visible texture of the surface, for example the wrinkles in skin or leather, meso-geometry is responsible for creating effects such as self-shadowing and is often captured along with macro geometry (Müller, Bendels, and Klein 2005). Macro-geometry (generally described simply as geometry) describes the form of an object; its shape and apparent physical limits.

In theory, the ultimate goal of physically accurate 3D computer graphics is to capture and represent all of these levels perfectly. The consequence of this would be a simulation of surface which did not differentiate between geometric and surface properties but which simulated the reflection of light entirely as a unified physical process (there would in this case be no need to define discrete colour, reflectance or scattering values). In reality both light simulation and the ability to accurately capture fine surface geometry prevent this goal from being realised. While a simulation of this type is still some way off it should be noted that the simulation of reflection is increasingly being calculated physically and as a unified process. Significant innovations in this area have been the development of spectral rendering (Devlin et al. 2002), the development of devices which capture geometric and surface detail as part of a unified process (Schwartz, Weinmann et al. 2011) and the capture of geometry and texture from photographic data (Glencross et al. 2008). All of these examples will be dealt with at length later in this chapter.

Consequently however, geometric capture (which has typically been concerned with the capture of macro level geometry) should be as high resolution as possible. High resolution, highly accurate datasets reduce the extent to which simulations rely upon estimates of surface behaviour and maximise the extent to which these behaviours can be physically calculated. High levels of surface detail have been shown to be highly important within archaeological settings. Examples of archaeological computer graphics which have relied upon high levels of geometric detail include the use of laser scans of rock art for identification and analysis of detail invisible to the naked eye (Schaefer and Inkpen 2010), the use of scan data to analyse and to study stone tools (Grosman, Smikt, and Smilansky 2008) and the use of laser scanned artefacts for online virtual study (Scopigno et al. 2011:49).

The technique of which most use will be made in this research is triangulated laser scanning (see figure 5.3). This technique uses a process of triangulation between the point at which a laser is emitted, the point at which it makes contact with an object and a camera, to establish the location of a point. Through repetition of this process a high density three dimensional record of a surface can be acquired. This technique has the benefit of speed and accuracy but most implementations of the technology allow only relatively small areas to be scanned. The characteristics of different systems vary considerably, however capture of data in this way is frequently time consuming, involves the use of specialist recording devices and generally speaking must be conducted under controlled conditions. The primary benefit of triangulated laser scanning is the level of accuracy and complexity which can be achieved (Cignoni and Scopigno 2008). The precise nature and characteristics of the systems used in this thesis will be described at greater length in Chapter 6 (Methodology I).

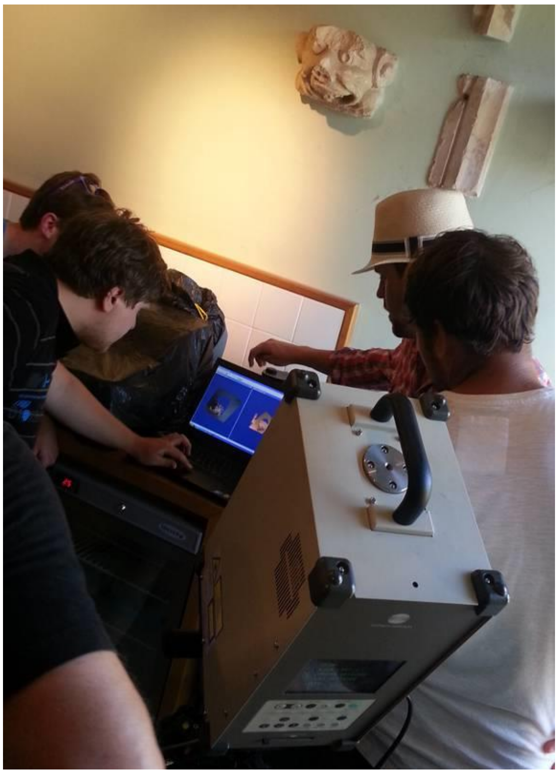

Figure 5.3 Using a Konica Minolta triangulation laser scanner to record a corbel at the Basing House project 2013 (CC-BY-SA-3.0 Nicole Beale).

Conversely, time of flight laser scanning uses the direction of emission coupled with a measurement of the time taken by the laser to reach the surface being scanned and be reflected back to the laser scanner to establish direction and distance. This approach has the benefit of being functional over very large distances. The accuracy of this technique is limited by the fact that it relies upon extremely precise measurements of time (the time taken for a laser travelling at the speed of light to reach the object being scanned and be reflected back again). This technique is inappropriate for the high resolution precision scanning of objects but is entirely appropriate for the recording of structures or larger objects where accuracy is less significant (Boehler, Bordas Vicent, and Marbs 2003; Fontana et al. 2003; Al-Kheder, Al-Shawabkeh, and Haala 2009).

Figure 5.4 Using a time of flight laser to record the interior of a corridor at the Portus Project (Image author's own).

Photogrammetry is commonly employed within Archaeology as a means of 3D data capture. Generally, for the purposes of physically accurate computer graphics, this will entail close range rather than aerial photogrammetry. The process involves calculating estimated 3D geometry from images of a subject which are taken at an offset and so consequently offer different views. A range of algorithms are available which enable this process and the precise requirements of each vary. The accuracy of the technique is dependent upon the quality, quantity and resolution of the images which form the input dataset as well as the use of an appropriate and efficient algorithm. Consequently, geometric data produced in this way vary considerably in terms of accuracy, precision and resolution. The number of variables inherent to the process means that estimates of accuracy relating to specific datasets are difficult to make (Cignoni and Scopigno 2008; Lambers et al. 2007; Lerma et al. 2010).

The final technique in common use is structured light scanning. A pattern of light is projected onto the object being scanned. Distortions in this pattern are observed by a camera. An algorithm then allows these distortions to be interpolated into a three dimensional surface. This technique uses similar algorithms to triangulated laser scanning and is capable of achieving similarly accurate results (McPherron, Gernat, and Hublin 2009; Cignoni and Scopigno 2008; Sansoni, Trebeschi, and Docchio 2009; Roman, Inglis, and Rutter 2010).

5.3.1.2 Modelled Geometry

Modelled geometry may also be featured within a simulation. Modelled geometry is not captured directly from a physical object but is created digitally. Modelled geometry can be entirely hypothetical or can be based upon a range of supporting data (see Figure 5.5 overleaf). Non-continuous 3D point data such as 3D survey or sparsely sampled 3D point clouds captured using photogrammetry can be used as a basis for comparison to ensure a relatively high level of geometric accuracy in modelled geometry. Even where modelled geometry does not incorporate supplementary 3D data it can often be based upon a very detailed, non-3D, record of the original object such as architectural plans and elevations.

However, regardless of the integrity of the data used to produce the modelled geometry, within a simulation intended to be physically accurate it represents an inherently hypothetical component.

Modelled geometry has an important role to play in the application of a physically accurate rendering pipeline within an archaeological methodology. The fragmentary nature of the archaeological record frequently makes it impossible to capture a geometric record of an object using any of the techniques outlined above. Examples may include the need to hypothetically reconstruct partially destroyed buildings, hypothetically replace missing parts of statues or 'virtually reconstruct' badly weathered or eroded surfaces (Gutierrez et al. 2007; Happa et al. 2010).

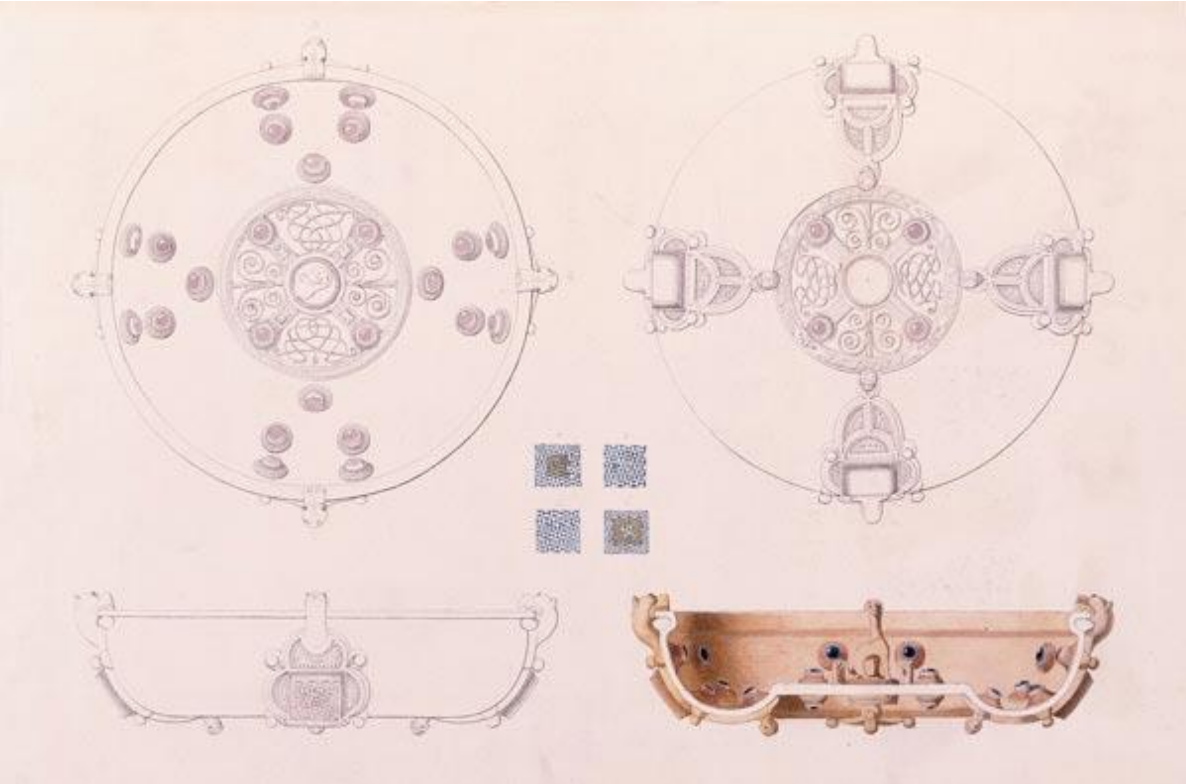

Figure 5.5 Illustrations of the Witham Bowl were used to produce a 3D model (shown in Figure 5.1). While this was not as accurate as using data captured directly from the object it allowed measurements to be taken. The nature of these underlying data define the epistemic character of the resulting 3D computer graphics (image courtesy of the Society of Antiquaries).

5.3.2 Materials

Materials define the reflective characteristics of objects within the modelled environment. The reflective characteristics of surfaces within the simulation can be defined in a number of ways and can be based upon a range of different data. Materials simulations are primarily concerned with the representation of micro-geometric features of a surface, those characteristics which affect the texture, colour and reflective properties. The simulation techniques employed, as well as the input data, define the physical accuracy of the reflectance simulation and dictate the reliability of the result. The precise manner by which materials are defined is dependent upon the nature of the renderer used. Rendering will be dealt with in detail below in section 5.4. The following section will describe the various concepts and processes from through which material properties are generally expressed in computer graphics.

5.3.3 Reflectance

Bidirectional Reflectance Distribution Function (BRDF) (see figure 5.6) is the most elementary description of reflective characteristics used within 3D computer graphics. BRDFs sit at the heart of virtually all current techniques for representing surface properties in 3D computer graphics. The function describes the ratio of incoming to outgoing light at a given point on a surface, defined in relationship to the angle of irradiant (incoming) light and radiant (reflected) light. To clarify, the BRDF allows the level of visible light to be specified for any point on a surface according to the position of the light source and the position of the viewer (Glassner 1995). BRDF's have been implemented since the very early stages of 3D computer graphics research and have been continually developed and supplemented since their introduction (Phong 1975; Westin, Arvo, and Torrance 1992).

BRDF calculations are still frequently employed within 3D computer graphics however the use of BRDF as a solution for physically accurate surface description is limited in several respects. Firstly, the hemispherical nature of the calculation requires that all light is reflected away from the surface, it is not possible for light to penetrate the surface. Consequently BRDF is unable to account for translucent materials which allow light to penetrate their outer surface. This simplification is compounded by the fact that BRDF assumes that light is reflected from the same point at which incident light makes contact with the surface. The consequence of this is that BRDF cannot describe a material which allows light to enter at one point and leave at another, a characteristic of the majority of translucent materials.

Increasingly complex mathematical descriptions of surface properties have enabled these simplifications to be addressed. Bidirectional Transmittance Distribution Function (BTDF) takes account of light reflected into, the surface, rather than away from it. When combined with BRDF the composite calculation (known as Bidirectional Scattering Distribution Function or BSDF) allows a spherical rather than a hemispherical model of reflection, consequently light can be transmitted through an object. Bidirectional Surface Scattering

Reflectance Distribution Function (BSSRDF) adds a further level of complexity by allowing light to be reflected from a different point on the surface than that at which it enters the object, enabling the possibility of subsurface light transport. This is the truest representation of reflectance as it allows for the reflection and refraction of light within an object.

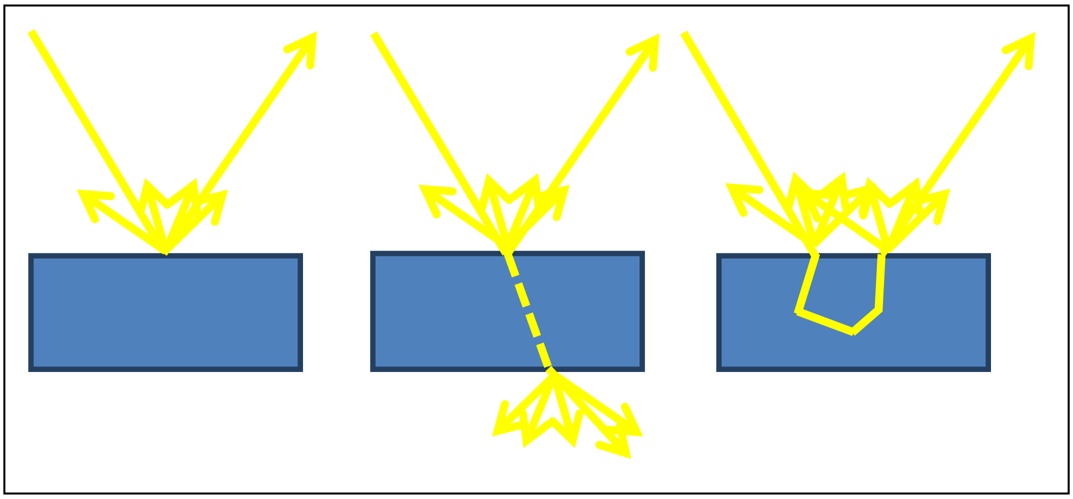

Figure 5.6 (Left) BRDF (Middle) BSDF (Right) BSSRDF.

In order for a BRDF to be implemented within a simulation, the reflective characteristics must first be defined. There are two, conceptually quite separate methods of doing this. In the first instance, a BRDF can be defined based upon an analytical model, in the second it can be based upon experimentally derived data. (Wilkie et al. 2009)

A BRDF based upon an analytical model is not based upon observation of a real world phenomenon but represents an approximation of physical reflective behaviour. These techniques are highly efficient but represent a compromise in terms of accuracy. These approaches are generally unsuitable where an extremely high degree of accuracy is required but are frequently used to produce highly believable and moderately accurate (though approximated) results. BRDFs can also be based upon observations of reflective characteristics of real materials. This approach tends to lead to less efficient rendering but has the benefit of greater accuracy. Datasets are time consuming to collect and require specialist recording equipment; either a multi-view light dome, as described below in the section relating to BTF measurements (Müller, Bendels, and Klein 2005; Schwartz, Weinmann et al. 2011), or a gonioreflectometer (Westin, Arvo, and Torrance 1992; Ghosh et al. 2007). Both of these techniques have the potential to be extremely accurate and have received a great deal of attention from archaeologists and those working in cultural heritage. Attempts have been made recently to create systems which offer an intermediate step, by enabling high-speed capture of estimated BRDF data based upon photographic data (Paterson, Claus, and Fitzgibbon 2005; Hawkins, Cohen, and Debevec 2001; Glencross et al. 2008; Goldman et al. 2010).

Despite these developments, BRDF capture remains time consuming, resource intensive and relatively complex and will not be possible in many archaeological research scenarios. However, several collections of experimentally derived BRDF data are available, placing this approach within the capability of non-specialist users (Matusik 2003). Furthermore, generic BRDFs packaged with rendering and 3D modelling software are becoming increasingly complex, offering a more accurate estimate of a range of surface types. Clearly, neither of these approaches represents a truly physically accurate solution, a compromise is either made by using a generic, approximated analytical model of BRDF, or by using an experimentally derived dataset, not collected from an object with identical material properties to that being represented.

The final technique which will be discussed in this section is the Bidirectional Texture Function (BTF). The BTF is a comparatively recent development having only been implemented within 3D rendering in the late 1990s (Dischler 1998). BTF uses the same parameterisation as BRDF, as described above. It is spatially varying, similarly to the Spatially Varying BRDF (SVBRDF) function, but crucially it also includes the capacity to represent meso-level (as opposed to micro- or macro-level) geometry. This is achieved using an apparent BRDF (ABRDF) value for each cell of the texture. The result of this is that the technique is able to provide a highly realistic rendering of surface appearance including meso-geometric effects such as self-shadowing, masking and inter-reflection (Müller, Bendels, and Klein 2005).

Data needed to implement this technique are captured using a multi-view/multi-light dome or gonioreflectometer. The multi-view/multi-light dome allows the subject to be recorded with many incident light directions from many different angles of view. The resultant data are then compiled into a single texture description. The device needed for this capture process is described in Müller et al's paper mentioned above (ibid). The technique has been developed recently to incorporate the simulaneous capture using structured light scanning of geometry (Schwartz, Weinmann et al. 2011). The devices needed to capture these data are purpose built, non-portable and very expensive to manufacture. This will limit their use in Archaeology, however, a wide range of materials are now being made available through online data bases which may allow the application of BTFs which approximate the intended surface appearance.

A goniospectrometer is a device which is capable of recording the wavelength and direction of reflected light from a surface under controlled conditions. Consequently it is possible also to assemble a BTF using this technology which contains not only tistimulus (RGB) values but a true representation of the wavelength of refected light. This solution has proven successful but has not been as widely applied as the method described previously largely due to the measurement time of more than 72 hours (Lyssi 2009).

The technique has, until very recently, been reliant upon the use of unaltered experimentally derived data and it has been very dificult to manipulate BTFs to represent anything other than that which has been recorded in the source object. Clearly this would limit the application of the technique in a scenario where virtual reconstruction is necessary. Attempts have been made to address this shortcoming, although modification is still non-trivial (Müller, Sarlette, and Klein 2007; Menzel and Guthe 2009). It should be stressed that the experimental use of BTF as a means of capturing archaeological material has been extremely successful, with several projects having been completed (Schwartz, Weinmann et al. 2011; Schwartz, Ruiters et al. 2011; Müller, Bendels, and Klein 2005).

5.3.4 Subsurface Scattering

Subsurface scattering has been at the forefront of computer graphics for the past decade. Initial developments focussed upon the representation of homogeneous materials such as milk, skin or simplified representations of marble (Jensen et al. 2001; Jensen and Buhler 2002). Early attempts to simulate subsurface scattering were limited by the assumption of homogeneity with materials and also by reliance upon a semi-infinite plane approximation which did not take account of arbitrary geometry (Carter 2007).

Recent research has focussed on the measurement and representation of heterogeneous materials, the subsurface scattering properties of which differ spatially throughout the object (Peers et al. 2006; Goesele et al. 2004; Arbree 2009). Clearly the developments offer a significant expansion in the potential use of subsurface scattering in the representation of archaeological material. The main reason for this increase in usefulness is that archaeological materials which exhibit a significant degree of subsurface scattering are frequently heterogeneous in nature and consequently can be more accurately visualised if subsurface scattering calculations are able to account for this. Examples include marble and other stones such as flint, jade and obsidian, glass, precious stones and layered paint (see figures 5.7, 5.9 and 5.10) (Peers et al. 2006; Loriot et al. 2007).

The most common method of mathematically describing subsurface scattering has been the Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF) developed by Nicodemus et al. and implemented by Jensen at al. (Jensen et al. 2001; Nicodemus et al. 1977). The BSSRDF is derived from, and represents a development of, the standard BRDF model. As well as allowing the movement of light through the outer surface of the object it also permits the light to leave the object at a different point to that at which it entered.

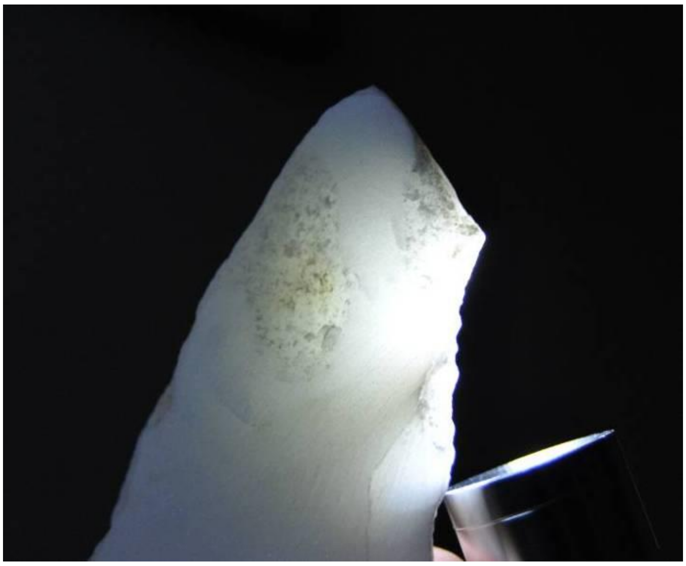

Figure 5.7 A piece of white marble illuminated by a torch emphasises the translucent properties of the material. Documentation and representation of these properties great potential as a means of improving understandings of the use of these materials (photograph author's own).

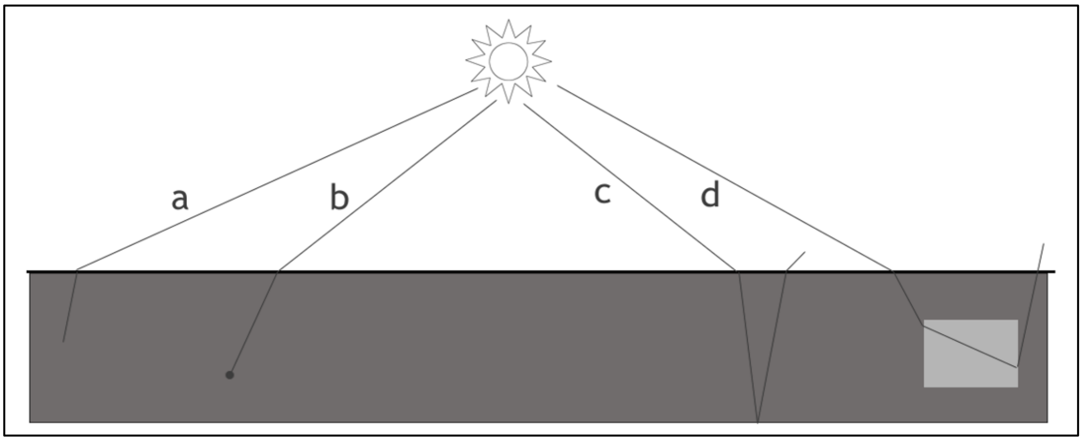

Figure 5.8 Examples of the four different types of scattering which can occur when a light ray intersects with a surface: a) single scatter b) diffusion c) multiple scatter d) multiple scatter through non-homogenous material.

As with standard BRDFs, BSSRDFs can be based either upon experimentally derived data (Weyrich et al. 2006; Donner et al. 2008) or upon analytical models (Donner et al. 2009). The collection of data necessary in order to produce a BSSRDF based upon observed physical phenomena is time consuming and involves using either a gonioreflectometer or a specialist photographic and lighting rig largely unavailable within an archaeological research context (Weyrich et al. 2005; Weyrich et al. 2006). Successful attempts have also been made to produce estimated BSSRDF values based upon photographic datasets. At present, this approach has been confined to simple homogeneous materials (Munoz et al. 2011). Consequently, within an archaeological context the most practicable solution is either to use estimated values, or to rely upon published data relating to measured samples.

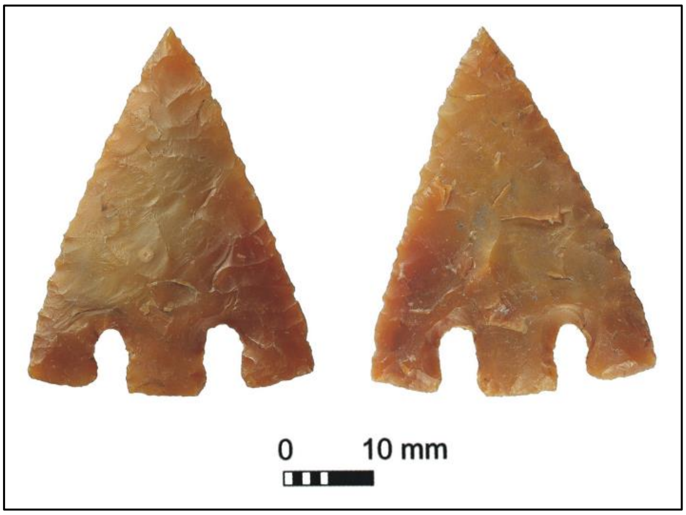

Figure 5.9 Early Bronze Age barbed & tanged arrowhead from the excavations at Heathrow Terminal 5. Subsurface scattering is often evident in stone tools (CC-BY-SA-3.0 Wessex Archaeology).

Figure 5.10 Copper alloy ring with an intaglio (a carved or engraved gem) in the form of a human figure, made from translucent, dark blue glass. It probably dates from the early 1st or 2nd century AD. Glass may have been used to emulate the translucency of intaglio rings using carved gems (CC-BY-SA-3.0 Wessex Archaeology).

The importance of subsurface scattering for the representation of archaeological materials is significant. A variety of objects including stone tools, glass, precious stones, sculpture, bone and some fabrics exhibit subsurface scattering (see figures 5.9-10). Whether or not these qualities were central to the decision to use these materials, the fact that they have a translucent character is integral to their appearance. Where possible it is important to incorporate subsurface scattering into any subsequent visualisation.

5.3.5 Reflectance Transformation Imaging

An imaging technique closely related to BRDF is Reflectance Transformation Imaging (RTI). Originally intended as a means of simulating material properties which altered according to the angle of light, RTI has since been widely adopted as a 2D imaging technique, particularly within cultural heritage (Mudge et al. 2005; Malzbender, Gelb, and Wolters 2001; Happa et al. 2010). The technique cannot be straight forwardly implemented within a 3D computer graphics pipeline

Figure 5.11-12 (Left) A photograph of an inscription from the entrance to the old church in Holcombe Somerset. (Right) The same image but enhanced using specular enhancement, a feature of RTI (photographs author's own).

RTI's are created from a series of digital photographs taken from a fixed position. Within each image the direction and angle of illumination is altered; the ultimate goal being to provide even coverage of lighting across a range of images. The resulting photographic data set provides a record of the highlights and shadows across the surface of the object being captured.

It is important that the direction from which the object is illuminated in each image is known. This can be achieved in two different ways, either a fixed lighting rig with known light positions is used or a reflective sphere is included within each image. The highlight on the surface of the sphere allows the angle of illumination to be reliably calculated.

Once the capture process is complete all data from the images are mathematically compiled and an approximated per-pixel reflectance function is generated. The result is what appears to be a single image, within which the user can interactively relight the object.

RTI data can also be mathematically enhanced. Techniques such as specular enhancement (a technique which boosts the specular highlights in order to produce an apparently glossy surface) enable the identification of surface details which might have been invisible under normal lighting conditions. The user is also able to control the intensity, colour and number of illumination points (Rabinowitz, Schroer, and Mudge 2009; Mudge et al. 2006; Earl, Basford et al. 2011).

RTI files can be used to produce normal maps (see Figure 5.13) which can be used to enhance the apparent surface detail of 3D data captured using other techniques. This technique is not widely used within physically accurate computer graphics due to the fact that the data have no depth information associated with them and so do not constitute a source of accurate data.

However, within a conversation on physically accurate computer graphics the relevance of RTI is primarily in its unprocessed data. Methods developed at the Archaeological Computing Research Group at the University of Southampton allow a laser scan of an archaeological object to be virtually re-lit with the same parameters that existed during the RTI capture of the original object. These twin datasets, one photographic and one rendered, can be straightforwardly compared on a pixel by pixel basis, enabling a quantitative comparison of experimentally derived photographic data and rendered counterparts (Earl, Beale et al. 2011). One of the most compelling arguments for the use of RTI in this way is the large and growing body of available data. Unlike BTF and other surface capture techniques, many archaeological and cultural heritage projects are currently underway or have been completed which have generated large quantities of RTI data (Mudge et al. 2006; Earl, Basford et al. 2011; Earl, Beale et al. 2011; Mudge et al. 2005).

Figure 5.13 A normal map of the statue of a young woman derived from an RTI. The different colours in the image indicate the direction in which each pixel is sloping. This can be observed in the fact that the pixels on the left of the image are green while those on the right are cyan.(image author's own).

5.3.6 Spectral Reflectance Data

While dealing with the modelling of material properties it is important to consider spectral reflectance data. Most renderers, as we shall go on to see, perform all calculations within a standard colour space such as RGB. Spectral renderers use wavelength descriptions of light, the colour of reflected light is calculated based upon the absorptive properties defined for the reflecting surface.

The RGB value (which defines a level of red green and blue) can be used to express the vast majority of colours perceptible to humans. The expression of colour in this way is known as tristimulus representation and is based upon the human body's capacity to perceive colour. Colour space descriptions were designed in order to describe colours which could be represented on a screen. Spectral reflectance data on the other hand describe colour in terms of wavelength, a description of colour as a physical phenomenon.

The main benefit of spectral (wavelength based) expressions of colour within computer graphics, is the ability to properly express metameric colours (Wilkie et al. 2009:17). Metameric colours are those colours which appear to the human perceptual system to be the same, but which are composed of differently combined wavelengths of light. As a consequence, as the nature of the light source changes, the apparently similar colours may diverge.

Spectral descriptions of colour are capable (constituting as they do a physical description of reflectance) of describing this change. RGB descriptions however cannot express this change, their sole function being the ability to communicate a single colour value to the human perceptual system. Where the physical accuracy of a simulation of light is paramount, as in the examples from the beginning of this chapter, this improvement in the accuracy of the expression of light can be highly important (Johnson and Fairchild 1999).

The result of this complex calculation is that visual phenomena such as dispersive refraction, scattering, interference and diffraction which involve the decomposition of light into discrete wavelengths across the visual spectra can be physically simulated.

The reflectance data required in order to perform spectral rendering calculations are more complex than conventional methods of representing reflective behaviour. The material must be able to describe the reflective characteristics of a surface at multiple points throughout the visual spectrum of light. The majority of materials can be quite simply expressed in terms of standard distribution curves dictating what proportion of irradiant light is reflected at a specific point in the visual spectrum. Certain materials however contain irregular spikes or changes in reflectance and pose more of a challenge, these include butterfly wings and shot silk type fabrics (Dorsey, Rushmeier, and Sillion 2008). These measurements can be captured using a gonioreflectometer, an instrument capable of observing the index of refraction at regular iterations across the light spectrum.

The representation of colour as a physical phenomenon rather than a visual phenomenon has significant implications for archaeology and for archaeological image making. Calculating colour in this way allows the simulation of light to be treated as an observable phenomenon within a physically accurate simulation. This opens up a raft of possibilities for archaeology in the development of methodologies (like the one presented within this thesis) which use light simulation as an analytical tool. However, the treatment of light as a physical phenomenon, rather than a visual one, complicates the process of image making and requires the image maker to decide how to transpose a wide range of spectral data into the limited spectrum which can be represented using conventional print or screen media. These issues are dealt with respectively in sections 5.4 and 5.5 of this chapter. Chapter 8 (Methodology II: Modelling, Rendering and Display) also deals with the role which these issues have had in defining the methodological approach taken within this thesis. The theoretical issues raised by the separation of the technical processes of simulation and image making are discussed in the previous chapter.

5.4 Rendering

At the heart of all 3D computer graphics we find the renderer. The renderer consists of one or multiple pieces of software, the purpose of which is to translate a scene file (containing geometry and materials) into an image based upon all of the specified variables relating to geometry, materials, light sources and viewer position. In order to do this the renderer has to simulate a range of processes all of which contribute to an approximated model of the behaviour of light in a given environment. The way in which light behaviours are compartmentalised into individual processes and the algorithms used to simulate these processes vary considerably between renderers.

5.4.1 Light and Accuracy

Physically accurate renderers can loosely be defined as those renderers which seek to model the behaviour of light in a realistic way. In order then to assess the relative merit of different rendering approaches it is first necessary to consider the processes which are being simulated.

In the natural world light sources emit energy, the visibly perceptible portion of which is known as light, once emitted the light continues on a straight path until it encounters a surface. At this point the light is subject to one of four processes, it can be absorbed, reflected or refracted. The fourth process is fluorescence but this process is sufficiently unusual that it will not be addressed here. Generally speaking the light will be subject to more than one of these processes simultaneously. The reflected and refracted light will continue to be reflected or refracted around the space until all of the energy has been absorbed. Every reflective, refractive or partial absorptive event has the potential to alter the wavelength of the light causing its perceptible colour to alter. As a consequence of these changes we are able to perceive the colour of objects and in the case of refractive dispersal to see light separated into its component wavelengths. The precise nature of the surface encountered defines the nature of the subsequent reflection/refraction/absorption and defines the visual appearance of a surface.

The challenge of rendering is to break this very complex process (far more complex than the description above allows) down into discreet calculations which will mimic real world phenomena. Renderers compartmentalise and perform these calculations in a number of different ways and have been developed for a range of purposes prioritising accuracy, speed or flexibility.

5.4.2 Approaches to Rendering

Approaches to rendering differ in many respects. As mentioned above, all computer graphics can be seen as a compromise between the realism of the output image, the complexity of the simulation and the computational cost of the calculation. Depending upon the desired result and the resources available a balance of the above factors must be reached. As we shall see, different approaches to rendering manage these factors in different ways (see figures 5.14).

Figure 5.14. Different rendering techniques create different results both in terms of believability and accuracy. From left, a ray traced image without global illumination, a ray traced image using photon mapping to calculate global illumination, a path traced image using a spectral calculation (images author's own).

5.4.3 Spectral and Colour Space Rendering

Perhaps the most significant differentiation in physically accurate rendering, lays between spectral and colour space renderers. In reality the appearance, (including the colour) of a surface is dictated by the extent to which, and manner by which, different wavelengths of light are reflected away from it. Spectral renderers attempt to attempt to mimic this manipulation of light wavelengths in order accurately simulate colour as a physical phenomenon.

The elementary principles of spectral rendering have already been outlined in the *5.3.6. Spectral Reflectance Data* section above. However, it is sensible here to expand slightly upon this definition.

The majority of renderers are non-spectral, meaning that they attempt to simulate the appearance of a surface through simplified colour space descriptions which mimic human visual perception. Consequently, descriptions of colour within these systems (usually expressed in terms of RGB values) are static. This means that regardless of changes in illumination any surface to which a specific RGB value has been assigned will behave in the same way (in terms of colour). In the physical world however this is not the case. Colours composed of different combined wavelengths of light can appear to be the same; these are known as metameric colours. However, as the illumination varies (and so as a consequence do the combinations of wavelengths of light) these colours can appear to diverge. A spectral renderer is able to accurately represent this phenomenon.

Spectral rendering however relies upon a description of the reflective characteristics of a surface taking into account reflections and refractions at many points across the light spectrum. As a result, spectral renderers are capable of reproducing this complex reflective phenomenon to a degree of accuracy which has been impossible using conventional colour space rendering (Johnson and Fairchild 1999; Devlin et al. 2002; Wilkie et al. 2009).

It should be noted that many of the phenomena which spectral rendering is able to simulate accurately are actually comparatively unusual (Dorsey, Rushmeier, and Sillion 2008). Often, colour space rendering techniques will produce a result indistinguishable from that produced using spectral rendering. However, the true value of spectral rendering is not in its ability to produce images which are necessarily more realistic, but in the increased probability that the result will be correct. A simulation conducted in colour space may deviate in unpredictable ways from an equivalent real world scene. While they still offer only an approximation of reality, a spectral render will produce a reliable and consistent result. Consequently, in order to implement a predictive rendering pipeline, spectral rendering is essential.

Spectral rendering is often implemented in conjunction with an unbiased rendering algorithm (see section 5.4.4) in order to produce the most accurate possible result in terms of both colour and the behaviour of light in the scene. It should be noted however, that the additional accuracy which comes from spectral rendering can be drawn upon without the additional computational cost implicit in the use of a path tracing renderer. An example of this is the spectral ray tracing renderer developed by Johnson and Fairchild, the specific purpose of which was to produce high speed, highly accurate colour calculations without the additional accuracy which would have come from the use of a path tracing renderer (Johnson and Fairchild 1999). This represents a good example of a physically accurate technology being appropriately employed outside of a predictive rendering pipeline in order to address specific research questions.

5.4.4 Biased and Unbiased Rendering

The introduction of systematic bias is the primary means by which rendering calculations can be made to be more efficient. Bias can be summarised as being the introduction of assumptions which simplify the rendering calculation, thus lessening the time needed to resolve the calculation. The cost of this efficiency is a potential lack of reliability. It can be assumed that an unbiased rendering algorithm will eventually calculate the correct solution. The same cannot be said of a biased calculation. However, as we shall go onto see, this does not mean that a render produced using an unbiased rendering algorithm will be correct, nor does it mean that one produced using a biased calculation will always be incorrect.

Unbiased Rendering: Path Tracing

Path tracing is one of the most commonly employed techniques of unbiased (see figure 5.15) rendering and is the technique favoured by many spectral renderers (Next-Limit 2011; LuxRender 2011c; Dumazet 2011; Chaos-Software 2011), however it should be noted that not all spectral renderers use unbiased calculations (Johnson and Fairchild 1999).

Figure 5.15 A rendered image of the Amazon statue produced using LuxRender; a spectral path tracing renderer (image author's own).

Instinctively it would make sense for renderers to trace light from the light source and assess its effect upon objects in the scene. However to do so would be enormously inefficient as the vast majority of light radiating from a light source is likely not to come into contact with objects in the scene. Instead, several rendering techniques take the opposite approach and trace light rays from the viewing plane of the rendered image into the scene. The consequence of this reversal is a huge increase in the efficiency of the rendering algorithm.

Path tracing is one of the most physically accurate, and simplest rendering techniques in the sense that it very closely emulates the physical processes to which light is subject (Kajiya 1986). Consequently, images produced using path tracing are capable of a very high degree of physical accuracy and realism. The consequence of this is that path tracing is extremely computationally expensive and has only very recently begun to be used on conventional GPUs (Huwe and Hemmerling 2010).

Path tracing emulates the ‘real world’ process outlined above but instead of tracing light from the light source to the viewer it tracks the light in the opposite direction. Light is traced from a pixel in the viewing plane to its first intersection with an object in the scene. At this point a new ray is randomly created according to the properties defined for the surface at the point of intersection. Rays are traced in this way until they intersect with a light source. Those rays which do not intersect with a light source are omitted from the final calculation. Consequently path tracing represents a very inefficient but highly accurate means of resolving the rendering equation and ensures an accurate distribution of light throughout the scene (Shirley and Morley 2003; Huwe and Hemmerling 2010). The physical accuracy of path tracing means that many of the visual effects which have had to be engineered into other rendering solutions occur naturally.

Biased Rendering: Ray Tracing

The vast majority of renderers under development or in use today, which claim to incorporate ‘physically correct’ or ‘physically accurate’ simulations of real world lighting phenomena, rely upon ray-tracing solutions see figure 5.16, in some instances supplemented with photon mapping (Jensen and Christensen 2007; Ward, Rubinstein, and Clear 2007; Jarosz, Jensen, and Donner 2008; mental-images 2011; Chadwell 1997).

Figure 5.16 An image produced using mental ray; a raytracing renderer. Global illumination has not been applied (image author's own).

Ray tracing is one of the most efficient methods of calculating the lighting in a scene in an accurate way. It was developed at a very early stage of 3D computer graphics (Phong 1975; Westin, Arvo, and Torrance 1992) and continues to be widely employed. In its most simple implementation ray tracing calculates a path from each pixel in the visual plain, to a point of intersection with an object in the scene. At this point the ray may be reflected absorbed or refracted. Reflected rays may 'bounce' a predefined number of times between surfaces in the scene before the calculation ends. It is this truncation which makes ray-tracing more efficient than other techniques which continue to calculate the movement of light indefinitely. At every point of intersection with an object the relationship between the point in question and the light source is calculated, the influence of the material settings taken into account, and the colour value of the pixel set. Refracted rays behave similarly to reflected rays but are able to enter and exit the surface of an object at different points (Glassner 1989).

Ray tracing has been widely adopted as the basis for subsequent developments in physically accurate 3D computer graphics because, despite being computationally expensive compared to other techniques such as scan line rendering, it is an efficient way of accurately approximating the path of light within a scene without resorting to extremely computationally expensive methods such as path tracing. The accuracy of ray tracing has been enhanced through the addition of numerous supplementary technologies which seek to address some of the inherent shortfalls of the ray tracing process.

Global Illumination: Photon mapping

Perhaps the most significant development in this area has been photon mapping (see figure 5.17) (Jensen 1996; Jensen and Christensen 2007). Photon mapping supplements the backwards ray tracing technique by emitting photons (nominal particles of light) from light sources into the scene. These particles are reflected around the scene allowing the renderer to ascertain a light value at each point of contact. These data are stored in photon maps. Rather than relying upon extremely high sample density, photon mapping makes use of density estimation, allowing an estimate of values between samples to be made based upon nearby values. Photon mapping makes this process even more efficient by using a *Russian roulette* sampling strategy meaning that the proportion of photons reflected is adjusted to represent diminishing energy levels of photons, rather than the energy of each photon (Jensen 1996). Consequently the number of calculations made is reduced significantly.

Figure 5.17 A rendered image of the Amazon statue produced using mental ray with photon mapping enabled (image author's own).

When the rendering phase of the image synthesis process takes place, values from the photon map are used to supplement the light values ascertained through ray tracing to provide a more accurate impression of the impact of indirect illumination within the scene. The accuracy of the indirect illumination estimated through photon mapping is dependent upon the number of photons which enter the scene; this can be thought of as the density of samples in the resulting photon map. Theoretically speaking, if the number of photons were sufficiently high, then a level of accuracy akin to that possible through path tracing could be achieved (Hachisuka, Ogaki, and Jensen 2008).

5.5 Display

The least fully explored area of digital image synthesis both in Archaeology, and in the field of computer graphics more generally, has been display. The display of an image represents the interface between the simulation and the human perceptual system. Consequently the physics at this stage of the pipeline are extremely complex and are closely related to the psycho-physical capacities of the viewer (Seetzen, Whitehead, and Ward 2003; Kuang, Heckaman, and Fairchild 2010; Hatada, Sakata, and Kusaka 1980).

Due to these challenges and the associated costs of solving them, display is the stage of the predictive rendering pipeline which is most problematic to implement. As part of a predictive rendering pipeline, a display should be capable of reproducing the field of visibility and reproducing the physical effects to which a viewer would be subject if they were to encounter the scene in the physical world. The former constitutes ensuring that all which would be visible to a human viewer in a real environment is visible within the presented image. This includes the maintaining of visible detail in the darkest and lightest areas of the image. The latter involves the reproduction of appropriate levels of brightness, contrast and colour, allowing the perceptual system of the viewer of the simulation to react in the same way that the viewer would when encountering this scene in the real world (Wilkie et al. 2009).

High Dynamic Range (HDR) displays have been developed which allow a much larger dynamic range to be represented than has been possible using conventional display devices. HDR displays developed by Seetzen et al were found to be capable of representing a dynamic range of 50,000:1 in comparison to the 100:1 achievable with a standard CRT screen, the 1000:1 possible with high quality printing and the 30:1 possible for printing on paper (Seetzen et al. 2004; Gutierrez et al. 2004). These displays are commercially available but remain highly specialist and expensive and, it should be noted, do not allow a reproduction of dynamic range equivalent to the real world (Happa et al. 2010). They do however allow some simulation of the physical effects of exposure to extremes of light and dark to be achieved. For example, the slow increase in visibility upon entering a dark space from a very light space.

As we have seen throughout this chapter, choices made during the image production process dictate the use to which images can ultimately be put. Consequently it is important when designing a methodology which incorporates physically accurate computer graphics to consider every stage of the process.

The decision of whether or not to compromise at any stage of the methodology becomes particularly pertinent when considering display, for not only are appropriate devices relatively inaccessible they are also restricted in nature, dictating the use to which images represented in this way might be appropriately used (Happa et al. 2009). Cultural heritage projects which have made use of HDR displays have tended to be analytical in focus, requiring only small audiences and limited contact time with the virtual reconstruction (Chalmers and Zányi 2010; Gonçalves et al. 2009; Happa et al. 2009). Significantly these papers tend not to have originated from cultural heritage research centres, perhaps due to limitations in the availability of this technology.

The alternative to HDR devices is tone mapping to displays with a more limited dynamic range (Cadik et al. 2008; Drago et al. 2003; Yoshida et al. 2005). Because the dynamic range of the image produced may be much larger than that which the available device can display, the image must be tone mapped into a colour space which the device is capable of displaying and which, to as great an extent as possible, provides the viewer with an accurate representation of the scene. This process can be controlled through the use of tone mapping operators which each take a different approach to the calculation and which consequently yield very different results.

This problem can be further intensified when images are printed. This is due to the fact that most printers use a subtractive, rather than an additive, colour model. Consequently it becomes necessary to translate the additive colour model used to describe images (generally RGB) into a subtractive colour model (often CMYK).

In order to ensure that the visual output remains consistent, all equipment used to display or reproduce the rendered images must be calibrated in order to produce the most faithful representation possible. The need for this level of accuracy is dependent entirely upon the use to which the images are to be put. This is not to say that the use of display technologies inappropriate for a predictive rendering pipeline causes the use of other elements of such a methodology to be invalid.

Crucially, the use of tone mapping and calibration to maximise the effectiveness of a non-HDR display, whilst certainly introducing error, can be highly consistent. So, despite the fact that these modes of display do not offer the same psychophysical approximation of physical stimuli that might be achieved using an HDR display, they can be capable of communicating a lot of the additional image content which comes from the implementation of a predictive rendering pipeline. The current state of technology makes this compromise almost inevitable as part of an archaeological application with conventional methods of publication ensuring that at some point images will be displayed not only on a non-HDR device but also on a device for which images had not been calibrated.

5.6 Conclusions

The goal of the preceding chapter has been to provide a summary of the techniques and processes currently available for the production of computer graphics with a degree of physical accuracy. The paper has drawn upon Wilkie, Weidlich, Magnor and Chalmers' 2009 SIGGRAPH ASIA course on predictive rendering as a bench mark for achievable physical accuracy (Wilkie et al. 2009) and has found that in many cases the technologies required to implement these are not widely available to archaeology. However, as Wilkie comments;

"The key advantage of spectral renderers – the capability to properly handle metameric colours – is rarely needed, and for most general users the disadvantages of having to obtain spectral reflectance values for all surfaces in a scene outweigh any increased realism that such renderers offer" (Wilkie et al. 2009:17).

This statement should serve to remind archaeological researchers, or indeed any other group of researchers, that the adoption of these technologies should be driven by a perceived usefulness and not by an ill-defined desire to pursue something better, more accurate or more believable.

It is important at this stage also to consider the use to which the images resulting from a 3D computer graphics methodology will be put. The medium of reproduction has significant theoretical and aesthetic implications upon the way in which images will be seen. Many of these issues are discussed in Chapter 4 (3D Computer Graphics: Image Making and Contemporary Archaeological Practice). The need to consider medium is particularly acute in a field in archaeology where the production of images should be driven by the requirements of the research process, rather than the potentials of new (often largely inaccessible) technology.

There have been many excellent implementations of predictive or highly physically accurate rendering being applied to archaeological subjects. Notable examples relate to the work of Chalmers and associated researchers on the implementation of complex light simulations within archaeological contexts as a means of producing perceptually reliable visualisations of archaeological subjects (Devlin and Chalmers 2001; Gutierrez et al. 2004; Sundstedt et al. 2005; Happa et al. 2010). Other recent examples have included attempts to virtually reconstruct and visualise the original colours of medieval architectural and sculptural polychromy under natural and artificial lighting conditions (Callet et al. 2010; Dumazet, Callet, and Genty 2008). These examples are pioneering and are representative of some of the possibilities which these technologies might have for the study of Archaeology and Cultural Heritage. There can be little doubt that these fields would benefit from greater integration with archaeological research communities and processes. It would seem that while technologies required for predictive rendering remain highly specialist collaborations between Computer Science and Archaeology represent the most fruitful avenue for development.

As well as collaboration there is also room for innovation. The realities of dissemination and publication in an academic and public sphere are such that HDR display is not always possible. All projects incorporating physically accurate computer graphics will have to compromise methodologically at some point, if only at the publication stage; in the production of non-HDR images for conventional digital or print media. As Devlin has noted, this represents a persistent obstacle in the implementation of predictive rendering methodologies for Archaeology (Devlin 2012).

Referring back to the industrial implementations of predictive rendering we find that the successful cases have been those which do not exceed the limits of the available technologies and which are not inhibited by the need to view images under controlled conditions on a very limited number of display devices (Wilkie et al. 2009). Archaeological methodologies are, at least in part, characterised by the need to communicate and to disseminate results and interpretation and so the use of media inappropriate for a predictive rendering pipeline is inevitable.

However, this need not signal a rejection of these techniques, or of predictive rendering methodologies by archaeologists. The strength of any methodology lays in the choice of methods and the degree to which they offer an appropriate means of addressing the goals of the project. Generally speaking the goals of the project and the associated requirements which these bring are many, and so consequently a range of technologies are required. This is certainly the case for this research.

Chapter 6

6 Methodology I: Data Capture

6.1 Introduction

This chapter, the first of the two-part methodology, will deal with strategies for and techniques of data collection. The second part of the methodology (Chapter 8 – Methodology II) will deal with issues of modelling, rendering and display. This chapter is built upon previous chapters in that it relies upon the conceptions of statuary, colour and context described in Chapter 2 (The Statue and Architecture) and Chapter 3 (The Colours of Statuary) and the description of physically accurate computer graphics techniques for Cultural Heritage in Chapter 5 (Physically Accurate Computer Graphics).

Leading on from Chapter 2 and Chapter 3 in which the nature of the subject and variables were introduced and explored, this chapter will describe how data relevant to the simulation are to be captured and quantified. A coherent strategy for data capture will be outlined, including a detailed description of all techniques, capture devices and experimental processes.

The following chapter is structured by subject and by data type. Capture methods differ according to the kind of data being captured and according to the subject which is being recorded. The chapter will begin by describing data capture strategies for the statue itself.

6.2 The Statue

6.2.1 Geometric Data

Laser scanning was employed as the primary means of creating a 3D record of the surviving elements of the statue and of other examples of statuary which were used to hypothetically reconstruct areas which were absent.

An initial phase of recording was undertaken using an arm mounted Metris triangulation laser scanner which was able to record at up to 80,000 points per second at a resolution of approximately 0.05mm. Consequently the resulting mesh is extremely accurate and very fine. Supplementary laser scanning both of the statue head and of examples of other statues were conducted with a

Konica Minolta Vivid 910 triangulation laser scanner the resolution of which is between 0.1 and 0.22mm and can record up to 307,000 points per scan.

The Metris system is theoretically superior in terms of density of points recorded and in terms of the accuracy of the results. Consequently data recorded in this way have greater potential for future re-use in situations where high point density might be required. However the quantity of data recorded in this way was limited by the fact that the Metris system is difficult to transport and time consuming to set up and use. Furthermore, the recording environment must be stable and controlled, physical contact with the arm or base during recording can compromise the calibration of the instrument and cause inaccuracies to occur. In contrast, the Konica Minolta system is designed to be portable and can be set up and used almost immediately by a single operator, the Konica Minolta system can be moved and individual scans discarded if they are compromised by physical movement or interference of other kinds. Consequently the Konica Minolta is a more robust solution to the recording problem. Ultimately, the resolution of data produced by the Konica Minolta scanner proved to be higher and is likely to be more accurate than those captured with the Metris system. It is likely that the data from the Metris system were compromised by movement in the base and subsequent inaccuracies.

6.2.2 Surface Recording

As well as capturing a geometric record of the statue it was also important to capture a record of the other surface properties, particularly those variables relating to the reflectance of light which dictate the visual appearance of an object. Laser scanning produces only a geometric record of an object and captures no data relating to the material composition, colour or reflective properties of the surface.

In some cases, data captured relating to the surface of the statue were to feed directly into the virtual reconstruction process. This was particularly true where the subject being measured was well preserved and straightforwardly quantified. In other cases however, data was able to impart, or to help develop, understandings of complex variables which in turn led to the development of more focussed, more accurate hypothetical alternatives.

6.2.2.1 Identification of Pigments and Surface Treatments

The treatments and pigments used on the surfaces of the statues and the manner by which they were applied are both extremely important factors if we are to consider the current appearance of the statue and how the statue was intended to have appeared in the past.

Despite the fact that the pigments are (compared to other surviving examples of Roman statuary) very well preserved a great deal of information is missing. While we are clearly able to see where the pigments were applied and are able to guess at their colour, we are able to make very few definitive statements regarding the nature of the pigments or the manner by which they were applied, particularly if we rely solely upon visual inspection.

With the assistance of X-Ray Fluorescence (XRF), Enzyme-linked Immunosorbent Assay (ELISA), Antibody Testing and Fourier Transform Infrared Spectroscopy (FTIR) carried out prior to the commencement of this thesis it has been possible to ascertain the nature of some of the chemical compounds and elements which were used in the creation of the pigments. The results of these tests will be relayed in Chapter 7 (Experimentally Derived Data).

X-Ray fluorescence

X-Ray fluorescence (XRF) is a technique widely employed in Archaeology in order to identify the presence of specific elements within a sample. The technique works by monitoring the florescence (secondary radiation) characteristics of a sample which has been bombarded with gamma radiation. The wavelength of photons emitted from a sample treated in this way allows a picture to be built up of the varying quantities of different elements present. This analytical technique is extremely useful in the sense that it allows the chemical composition of a sample to be characterised (Shackley 2011).

Enzyme-linked Immunosorbent Assay Antibody Testing

Enzyme-linked Immunosorbent Assay (ELISA) Antibody Testing is a relatively recent addition to the range of analytical tools available within Cultural Heritage. The technique is designed to detect antibodies present within specific biological materials and thus allow their presence within a sample to be confirmed or rejected. A reaction is instigated which causes the presence of a specific antibody to create a colour change within the sample. This colour change can then be measured very precisely using a spectrometer to measure the degree of colour change. In this way the presence of specific biological materials can be confirmed. The value of this technique for Cultural Heritage and Art History especially has been in allowing the identification of binding agents used in the production of pigments. These agents are very often biological in nature with wax, egg and various oils being used throughout history (Getty Conservation Institute 2010).

Fourier Transform Infrared Spectroscopy

As a form of spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy relies upon the capacity of materials to absorb different wavelengths of light in order to identify their presence within a sample. FTIR takes many measurements of a sample while exposed to a light source with known characteristics. Rather than using a monochrome (single wavelength) light source a light is used which contains a wide spectrum of wavelengths. This is known as a broad band light source. The characteristics of this light source are repeatedly altered by small amounts and measurements of the reflected light from the sample are taken. These data are then compiled in order to produce a very precise measurement of the absorptive character of the sample. This signature may then be used to identify the material or materials present.

These techniques have produced very insightful results which will be outlined in detail in Chapter 7 (Experimentally Derived Data). They have allowed the identification of individual elements which were present within the pigments used on the statue. However, their nature dictates they have been unable to enable to identify how these elements were combined into different compounds or how these compounds were combined in different recipes to produce pigments dyes or paints. This residual uncertainty was compounded by limited understandings relating to the manner by which these pigments were applied to the surface of the statue (Brinkmann, Wünsche et al. 2007:188; Torraca 2006).

It became clear that the results of these tests represented only one element of the reconstruction process and that in order to proceed, data would need to be captured which could augment these findings. The strategies and processes which were adopted are described below in section 6.3 and the results of these experiments are presented in Chapter 7 (Experimentally Derived Data). A broader discussion relating to the physical complexity of the painting process can be found in Chapter 3 (The Colours of Statuary).

6.2.2.2 Photography

Extensive photographic representations of the statue head have been captured. An X-rite Colour Rendition Chart (often generally known as a Macbeth Colour Chart) was included within images in order to allow colour calibration to take place and absolute colour values to be acquired. This process was of particular importance during the recording of the statue head as it was not possible to capture colour data using a spectroradiometer.

The photographic record of the statue head has formed a central reference point during the reconstruction process. Images were captured at high resolution with a 12.1 mega pixel Nikon D3 DSLR camera. A high resolution photographic record will ensure that any details which are not observed at the time of recording but which are of interest later will be likely to have been recorded.

6.3 Supplementary Data Capture

Where insufficient data were directly available from the statue to formulate accurate hypotheses relating to key variables, such as the original form of the statue or the appearance of areas of marble which had been painted, physical experiments were conducted. The purpose of these tests was to refine and to inform the development of hypotheses which would be tested through the final process of image production. The capture of these supplementary data helped to avoid the development of unaccountable or speculative hypothetical visualisations. Instead, they ensured that the images produced contained hypotheses grounded in a process of physical testing and which allowed the accurate visualisation of a range of plausible alternatives.

The following section will describe each of the sources of supplementary data, the reasons for consulting them and the techniques used to capture data from them.

6.3.1 Geometric Data

Because the statue is fragmentary it has been necessary to hypothetically reconstruct the missing parts of the body and face. This was achieved by laser scanning statues which were deemed to have similar characteristics.

The identification of the statue of a young woman remains uncertain. Similarities have been noted between the statue and the *Sciarra* type Amazon, however discreet differences in the hair at the nape of the neck and the angle of the head have called this into question and raised doubt as to the possibility of a straightforward attribution (Borriello, Guidobaldi, and Guzzo 2008:249). Parallels have also been drawn to the *Sosikles* type Amazon (Guidobaldi and Moesch 2009:3; Borriello, Guidobaldi, and Guzzo 2008:115, 249). It has been proposed by Moesch that the statue does not represent one of the five typical Amazon types but may in fact represent a Roman innovation, the only comparator for which was found at the Villa of the Papyri (Guidobaldi and Moesch 2009:4; Ridgway 1974).

Because of this ambiguity several alternative statues were laser scanned in order to allow hypothetical reconstruction of the absent parts of the face and body. Typical examples of *Sciarra* and *Sosikles* Amazons were scanned from the collection of plaster casts at the Museum of Classical Archaeology at Cambridge. An original and largely physically preserved example of a *Sciarra* Amazon housed at the Ny Carlsberg Glyptotek in Copenhagen was also scanned. For a further discussion of statue types and of the identification of this statue please refer to Chapter 2 (The Statue and Architecture). The scanning of alternative body parts all made use of the Konica Minolta laser scanner described at the start of this chapter. For more information about laser scanning solutions consult Chapter 5 (Physically Accurate Computer Graphics).

6.3.2 Surface Recording

Supplementary surface data for the statue were derived primarily from a sample of marble which was experimentally reconstructed with various pigments. The surface of the statue as it has been preserved does not retain sufficient data to allow meaningful hypotheses to be developed relating to the intended or original appearance of the surface. A proxy object provided a means of conducting small scale physical reconstructions without causing any damage to the original object and provided a basis for hypothetical reconstructions within which variables could be meaningfully adjusted according to real world data.

The methods by which quantitative and qualitative data were acquired are described below. The results of these analyses are presented in Chapter 7 (Experimentally Derived Data).

Marble Proxy Object

The marble sample was selected based upon a range of criteria. It is of similar petrographic content and structure to the stone used to create the Amazon statue. The stone exhibits similar crystalline structure being close grained and smooth with few reflective highlights in the fabric. The colour of the stone is very close to the stone of the statue. The stone used to produce the statue has been identified visually as being Pentelic and the sample was acquired from the modern quarries in the Pentéli Mountains.

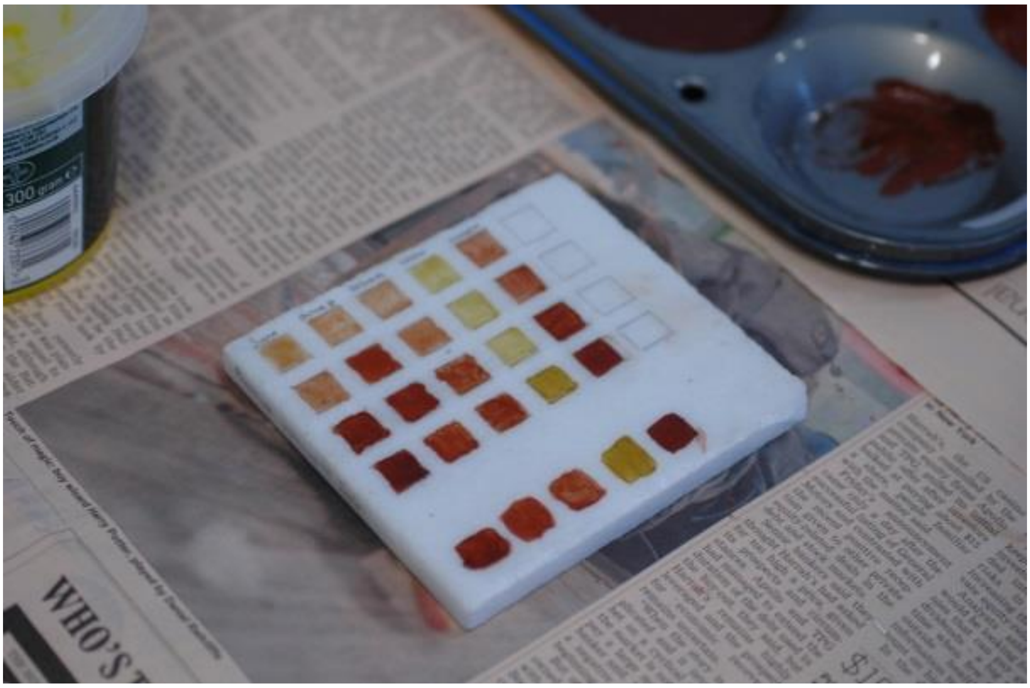

Figure 6.1 Stone sample used as a means of acquiring supplementary data (photograph author's own).

The sample was used in order to acquire the following types of data:

Spectral Reflectance Data

The marble sample was a source of spectral reflectance data. Colour data were captured from the marble sample using a spectroradiometer. The index of refraction (IOR) of the marble sample was measured at defined points which were marked on the surface of the stone or painted surface. The index of refraction of the surface was measured at iterations of 5nm from 340 nm to 830nm this spectrum incorporates normal human visual range of 390-750nm. This resulted in 490 wavelength measurements per sample. These measurements were then employed in order to replicate the reflective properties of the surface of the object with an extremely high degree of accuracy.

Subsurface Scattering

Subsurface scattering, the nature of which is dealt with in some depth in Chapter 5 (Physically Accurate Computer Graphics) is an essential component of any physically accurate material which features, as marble does, a degree of translucency. Subsurface scattering data consists of a record of absorption and scattering co-efficients as well as records of colour.

Subsurface scattering data for the marble was based upon data collected by Jensen et al. in their analysis of the subsurface reflectance characteristics of a range of materials (Jensen et al. 2001). However, these data will be modified as necessary following a process of verification in relation to the marble sample. The nature of this process is described below in section *8.4 Verification of Results* of Chapter 8 (Methodology II).

This approach will be used for those areas which are painted and those areas which are unpainted. Further discussion of the implementation of subsurface scattering data can be found below in section *8.2 Data Visualisation* of Chapter 8 (Methodology II). More information relating to the validation process can be found in section *8.4 Verification of Results* of Chapter 8 (Methodology II).

Reflectance Transformation Imaging

Reflectance Transformation Imaging (RTI) has already been dealt with at some length in Chapter 5 (Physically Accurate Computer Graphics). It will suffice here to outline the specific ways in which this technique and specifically the implementation known as Polynomial Texture Mapping (PTM) can help us to create a meaningful record of the marble sample. The ability to view the surface of the marble sample subject with controlled lighting from multiple directions can reveal a great deal about the materials which contribute to its visual appearance. Multiple PTMs were captured from 90˚ (face on to the marble sample), 60˚ and 120˚ this was done in order to monitor the impact of angle of view upon the apparent colour of the surface.

Although PTM is not able to provide a full visualisation of the phenomena described by the Bi-Directional Reflectance Distribution Function (BRDF) (see below and Chapter 5 – Physically Accurate Computer Graphics), it does allow us to observe one component of this equation; the differing appearance of a surface according to the angle from which it is lit. These observations allow the variation of colour to be observed according to light position. Similarly the PTM imagery also allows us to observe the varying luminance and apparent colour of a given area according to the light position.

Comparisons were made between PTM imagery and computer generated virtual reconstruction imagery in order to ensure the precision and accuracy of the simulation process. These verification processes are dealt with at length in section *8.5 Visualisation and Analytical Techniques* of Chapter 8 (Methodology II).

Pigments and Surface Treatments

The marble sample was extremely useful as a means of testing hypotheses relating to the construction and application of pigments and surface treatments. Clearly it would not have been possible to apply hypothetically reconstructed pigments to the original statue. Given the limited data available relating to the original appearance of pigments and surface treatments it was imperative that additional data building upon and related to these variables be captured. Consequently the use of a proxy object was highly advantageous.

As detailed above, the statue head alone has yielded insufficient information to enable the meaningful formulation of hypotheses regarding the original appearance of pigments. If all pigment elements are unambiguously identified, the problem remains that there can be little certainty with regards to the way in which pigments were mixed into paints or the way in which they were applied (Edwards and Chalmers 2005:59; Brinkmann, Wünsche et al. 2007:188). To address this uncertainty and to refine understandings in this area will be central goals of the research.

A number of variables have been identified by practitioners of tempera painting as being highly significant in defining the appearance of paint applied to stone (Brinkmann, Kellner et al. 2007; Penny 1993; Rockwell 1993; Harland 2010 pers. comm, Nov 2010; Breeze 2010 pers. comm, Nov 2010; Mayer and Sheehan 1991:264), they include:

- different ratios of pigment to binding medium
- the nature of the surface being coloured
- the use of different binding media
- the length of time between washes of pigment
- the number of washes of pigment
- the number of different colour layers applied
- surface treatments added over the paint layers

In order to assess the impact of these variables upon the visual appearance of painted stone the following experiments were conducted. All experiments were conducted under the direct supervision of Dr. Beth Harland, a specialist in tempera painting and pigment construction at the Winchester School of Art. The process and results of these experiments will be reported in Chapter 7 (Experimentally Derived Data).

A series of samples of sculptural marble of the following types were acquired, Carrara (Fanti Scritti), Seravezza (Pollo), Seravezza (Trambi), Penteliko (White Sculptural, quarry unknown). The latter stone is very similar to the marble from which the statue head is carved and is believed to have come from the same geographical location although the precise source of the stone used for the statue head is unknown (Guidobaldi and Moesch 2009). The stones all fall within the broad category of white sculptural marbles although they vary considerably in colour and constitution. The latter stone will be used as the main source of colour information.

The following pigments were sourced; burnt sienna, medium red ochre, dark red ochre, haematite, madder and umber, consult Table 6.1 for more detail. These pigments have been chosen in part because in the case of the ochre pigments, the burnt sienna and the haematite, they are iron based as the pigments present on the statue head are known to have been (refer to Chapter 7 – Experimentally Derived Data for more on these results) (Torraca 2006). They were also chosen based upon the fact that they are known to have been available and in use during the 1st Century in Italy and represent a selection of colours similar to those which have been used extensively during this period (Stege, Fiedler, and Baumer 2007:184) and on statues of this type (Østergaard and Copenhagen Polychromy Network 2010). Particularly in the case of ochre there are considerable variations in colour depending on the source and preparation of the pigment as a result a light and a darker red ochre were sourced.

Pigment	**Details**	**Origin**	**C.I.**	**Particle Size**
Burnt Sienna	Kremer Pigments ID: 40430	Italian	N/A	0-120µm
Red Ochre (Medium)	Kremer Pigments ID: 11575	France (Burgundy)	N/A	0-120µm
Red Ochre (Dark)	Kremer Pigments ID: 11577	France (Burgundy)	N/A	0-120µm
Haematite	Kremer Pigments ID: 48600	N/A	Fe2 O3	
Umber	Kremer Pigments ID: 40611	Italian	PBr7	

Table 6.1 Details of the pigments used in the physical reconstruction of paints.

Preliminary results from the hair of the statue suggest that pigments were likely to have used egg as a binding medium. This result is not definitive but it will be considered to be the primary hypothesis (Thompson 2007). Experimental results from other projects have confirmed that egg tempera was in use as a technique for statue painting in both ancient Greece and Rome (Chiavari et al. 1993; Colombini et al. 2004; Stege, Fiedler, and Baumer 2007). The experiment will also test linseed oil and will experiment with wax as alternative binding media commonly used in contemporary practice and with some studies suggesting its use in the ancient world (Mayer and Sheehan 1991:266; Østergaard 2007).

The range of pigments tested within this experiment was limited by time. The subject of pigment composition, use and reconstruction has been the subject of dedicated research and a great deal of work remains to be done (Freccero 2011; Brinkmann and Koch-Brinkmann 2010; Brinkmann 2004). However, forming as it does only a single discreet aspect of this thesis, the number of experiments which could be conducted was limited. The number of variables explored in the construction and application of paint also dictate that a full exploration of the physical possibilities of all paints will not be possible. The experiment was undertaken not as an exhaustive study of the visual/physical properties of pigments and paints but rather as a means of grounding the virtual reconstruction which followed upon reliable physical observations.

The following tests were conducted for each alternative binding media and pigments in combination (see figure 6.2):

1) A paint (Paint A) was mixed at the minimum ratio of pigment to binding medium which represents a functional paint. For more information regarding the mixing of paints refer to section 3.2. Paint of Chapter 3 (The Colours of Statuary) on statue painting and Chapter 7 (Experimentally Derived Data) which will document the results of the statue painting experiment.
2) A sample of this paint was applied to the surface of each marble sample.

3) A sample of paint was mixed at the maximum ratio of pigment to binding medium at which the paint was still practically applicable (Paint E).
4) Two more paints were mixed at equal iterations between Paint A and Paint E based upon pigment volume used.
5) The five pigments were applied to the surface of each marble sample in equally sized squares (see Figure 6.2.).
6) The different quantities of pigment present as well as the ratio of pigment to binding agent were marked in pencil above the sample (pigments were named, different ratios marked I-V).
7) An additional sample of each pigment mixed at the median concentration was added to the edge of the stone in order that it may be 'over painted' after fully drying.

Recording:

8) Measurements of the pigmented areas were taken with an Analytical Spectral Devices Hand Held Portable Spectroradiometer in order to acquire a series of absolute colour values from specific locations.
9) The marble sample was then photographed under varying lighting conditions always with a Colour Rendition Chart in shot so that the effects of the light could be monitored.
10) PTMs of each of the samples were also recorded in order to assess the effect of the direction of light upon the appearance of the surface. PTM records were taken from several angles in order that the influence of angle of view might also be observed.
11) As outlined above, quantitative results were extracted from the PTM relating to colour variance according to angle of view. These were compared with the results of the simulation in order to demonstrate the accuracy of the simulation process. The results of these measurements are presented in Chapter 7 (Experimentally Derived Data)

Surface Treatments:

12) A beeswax coating was added to the surface of the marble in order to observe the impact of a polished wax coating. This was done six months after the initial experiment. The wax was melted and brushed onto the

surface before being polished off. It was not possible to record the wax layer with the Spectroradiometer but steps 8-11 above were repeated.

These tests laid the foundations for the ensuing virtual pigment reconstruction. Hypotheses relating to the appearance of painting were developed according to these data, based upon the degree of variation between samples and based upon the viability of each hypothetical pigment reconstruction. The experiment clarified many of the uncertainties surrounding the practice of statue painting and will at least allow certain hypotheses to be excluded from the process of visualisation.

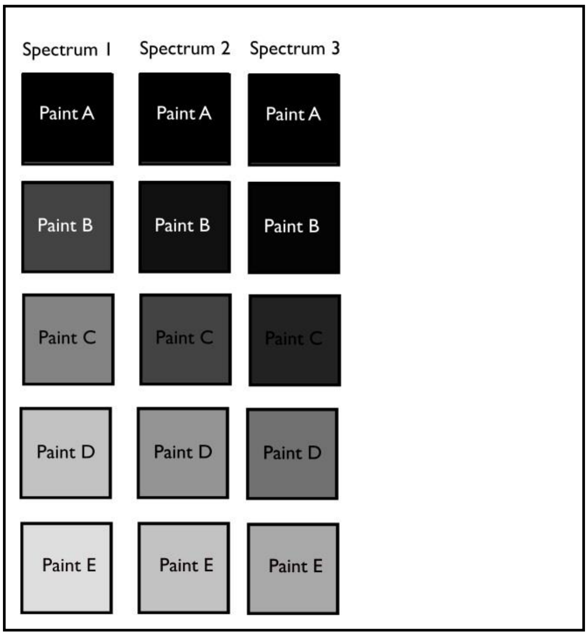

Figure 6.2 A diagram showing the format for the application of paint to a marble sample.

6.4 Architectural Reconstruction

Visualisations of the statue take place primarily within architectural scenarios which are based upon data captured from, or relating to, the House of the Stags and the House of the Mosaic Atrium at Herculaneum. As will be described in section *8.5 Visualisation and Analytical Techniques* of Chapter 8 (Methodology II), the objective of the visualisation process has not been to totally virtually reconstruct the entire buildings but to model specific areas which will feature in visualisations. Consequently the reconstructions take the form of a number of discrete 'stage sets', rather than a typical 'total' architectural visualisation of the house. It is important however to consider that these reconstructed areas necessarily extended beyond the architectural elements which were visible within the resultant images and were required also to include those elements which were not visible but which affected the behaviour of the light in the scene. Consequently large areas of the structure were reconstructed for each suite of images.

The high levels of preservation at the House of the Stags and the House of the Mosaic Atrium mean that these buildings constitute an extraordinarily complete record. However, the sheer volume of relevant data present required that decisions were made relating to which data were captured and which were not. The following section will describe which data were captured from the houses and how these data were acquired. The reasons for choosing the House of the Stags and the House of the Mosaic Atrium as the primary sources are described at length in Chapter 2 (The Statue and Architecture).

6.4.1 Building Recording

6.4.1.1 Geometric Data

Very few geometric data were captured directly from the site. This is due primarily to the extensive recording which has been undertaken of the building and its surrounding environment. These data and their use will be described at length in section *6.4.2 Supplementary Data* below.

6.4.1.2 Surface Data

Whilst geometrically speaking the House of the Stags has been extensively documented there remained a need to capture a large amount of surface data which were unrecorded. Surface data were collected extensively from the site, which despite having been heavily restored, represents the most extensive and reliable source of information available. These surface data related to the reflective properties of surfaces within the building however as mentioned below the capture of these data directly from surviving architectural components was not reliable. The function of these surface data was to ensure that the reflection of light around the interior of the building could be accurately simulated.

Walls

Wall paintings were documented throughout the houses using high resolution colour calibrated photography and RTI. High resolution photographs of each wall painting to be included within the reconstruction were taken. These images will all contain an X-rite colour chart in order to allow colour correction to take place. Spectral reflectance data were also collected in order to assist in calibration of colour values. RTI records were also taken of a sample of wall paintings. These data provide a means of judging the influence of light position upon the appearance of wall paintings. There is uncertainty relating to the extent to which restoration might have affected the reflective properties of the wall paintings (Freccero 2011; Mills and Smith 1990; Mora, Mora, and Philippot 1984). If the wall paintings were found to have been restored in such a way that they cannot be relied upon to yield useful reflectance data, parallels from elsewhere within the same building were sought and reflectance data captured accordingly. RTI data also allowed for normal maps to be derived which provide detailed surface topography of wall paintings to supplement the geometric model of the building.

Subsurface scattering may play a role in defining the visual characteristics of wall painting but its influence upon the movement of light around a room is likely to be negligible. It has not been possible to capture any data from the buildings themselves owing to the fact that data capture would require a degree of surface contact. Even if it were possible to capture these data at Herculaneum the same concerns outlined above regarding the influence of conservation upon the reflective character of wall paintings would be relevant. The capture of supplementary subsurface scattering data from alternative sources may be possible and should form part of any further research in this area. The matter of ongoing work is discussed at greater length in Chapter 11 (Conclusions).

Floors

Examples of all flooring present in the House of the Stags and the House of the Mosaic Atrium have been recorded using high resolution photography with x-rite colour charts and scales included. These records constitute a record of colour and also a detailed document relating to the use, arrangement and distribution of materials including the sizes of individual pieces of stone (e.g.

tesserae, stone tiles). Floors were cleaned prior to recording in order to remove dust and to expose the colour of the underlying materials.

RTI data were captured relating to each floor type. These data allow (as described above in the *RTI* part of section *6.3 Supplementary Data Capture*) an estimate of the influence of the direction of light upon surface appearance to be made. These data were used to verify BRDF models as described in Chapter 8 (Methodology II) in section *8.2 Verification of Results*.

6.4.2 Supplementary Data

Supplementary data have played a central role in the reconstruction of the different areas of the House of the Stags. The reasons for this are twofold:

a) The nature of reconstruction is such that all of the data needed in order to hypothetically reconstruct a building are not available on-site. Elements of the building which have been lost or which have been damaged to the point that they contain little relevant physical or colour data have been reconstructed using appropriate data from elsewhere.

b) The building has been hypothetically altered in order to illustrate the impact that subtle changes in architectural detail may have had on the appearance of the statue. These changes are representative of known trends or practices in Roman architecture and decoration but the necessary data may be captured elsewhere.

6.4.2.1 Geometric Data

The primary sources of geometric data have been plans and elevations of the House of the Stags and the House of the Mosaic Atrium which have been created by the Herculaneum Conservation Project.

6.4.2.2 Surface Data

There is considerable uncertainty relating to the extent to which the reflective characteristics of the wall paintings at Herculaneum and Pompeii have been altered through efforts to conserve them. Consequently onsite inspection and consultation with the conservation team has been necessary in order to ensure the capture of high quality, meaningful data. Wall paintings data from the

House of the Stags and the House of the Mosaic Atrium were recorded and were re-used throughout the simulation.

6.5 Light Reconstruction

The simulation of light is as important as the simulation of any of the physical objects or reflective surfaces in the virtual reconstruction. The volume and nature of data required in order to accurately simulate lighting varies depending upon the type of virtual light used and the requirements of the renderer being used to resolve the rendering calculation.

6.5.1 Natural Light

Natural light was simulated using a physically accurate lighting model built into LuxRender (see Chapter 8 – Methodology II) (LuxRender 2011b).

6.5.2 Artificial Light

The physically accurate reconstruction of artificial light is essential in order to construct meaningful visualisations of painted statuary in context. The precise nature of the use or composition of sources of artificial light in the Roman domestic setting remains uncertain. However considerable documentary evidence exists which would appear to suggest that the lighting by night of interior spaces through the use of torches and lamps would not have been uncommon at Herculaneum or in the Roman world more generally (Eckardt 2002; Devlin and Chalmers 2001; Gonçalves et al. 2008).

Artificial lighting was produced using a method similar to that proposed by Devlin et al. for the virtual relighting of Pompeian frescos, and outlined again by Happa et al. (Devlin and Chalmers 2001; Happa, Mudge et al. 2010). Spectral emission data which were captured using a spectrophotometer were used in order to define the colour and luminance values of a flame based light source (Hughes and Gale 2007). Initially (whilst using a ray tracing renderer with photon mapping) these data were converted into RGB colour space for rendering. These data were also used in order to create spectral light sources for use in spectral rendering.

Where flames are included within the field of view HDR captures of appropriate luminaires were used in order to accurately simulate the appearance and distribution of light within the scene (Happa, Mudge et al. 2010; Happa, Artusi et al. 2010).

Chapter 7

7 Experimentally Derived Data

The methodology for this thesis has been divided into two parts. It is structured in this way due to the fact that many of the decisions which influenced the design of the latter part of the methodology were based upon data which were collected as a result of processes outlined in the first part of the methodology. The purpose of this chapter is to act as a bridge between these parts. This chapter will present experimentally derived data which have been captured as a result of the processes outlined in Chapter 6 Methodology I: Data Capture). These data were instrumental in conducting the processes outlined in Chapter 8 (Methodology II: Modelling, Rendering & Display). They must be presented before this chapter can be understood.

Experimentally derived data were captured in order to inform the hypothetical reconstruction of different aspects of the statue. Due to the fact that they were captured specifically for the purposes of this thesis they have not been published elsewhere and so they will be presented here. This will include all data which were captured specifically for this thesis with the exception of imaging data which will be presented in digital form in Appendix A (Images Used in the Modelling Process). Descriptions of other datasets and the manner by which they were incorporated into the simulation will be described in part two of the methodology. Some data, specifically the spectral measurements of hypothetical pigments are summarised here in graph form. The full tabular version of the data is presented in Appendix A (Tabulated Spectral Data).

7.1.1 The Statue

7.1.1.1 Geometric Data

Geometric data captured from a number of sources were used in the virtual reconstruction of the statue. The methods and technologies used to capture these data are presented in Chapter 6 (Methodology I). The hypothetical reconstruction of the absent parts of the statue is described in Chapter 8 (Methodology II).

Source 1. Herculaneum

The most important source of geometric data was the original statue from Herculaneum (inv. 4433/87021). The statue was captured with a Metris arm mounted laser scanner as described in Chapter 6 (Methodology I). As they were taken directly from the statue which forms the subject of this research these data were used in each of the hypothetical reconstructions of the statue.

Source 2. Ny Carlsberg Glyptotek, Copenhagen

The statue of what has been identified as a Sciarra Amazon (inv.1568) from the Ny Carlsberg Glyptotek was laser scanned with a Konica Minolta laser scanner (this system is described in Chapter 6 – Methodology I). These data were used in order to act as a proxy for the absent body of the painted statue head which forms the subject of this study.

Source 3. Museum of Classical Archaeology, Cambridge

Data were required to replace the absent facial areas of the statue. In order to acquire several alternative datasets for this purpose, five casts of different Amazon statues from the Museum of Classical Archaeology, Faculty of Classics, University of Cambridge were laser scanned.

7.1.1.2 Surface Recording

The collection of surface data to be used in the simulation of the statue occurred in several phases. These are outlined in detail in the previous chapter. The first phase of data collection occurred in 2006, prior to the initiation of research for this thesis. Several analyses were conducted by Toracca on the surface of the statue in order to identify the chemical composition of pigments/surface treatments present on the surface of the statue (2006). The results of these tests are unpublished at present but findings relevant to this research are summarised below. These tests were able to offer a great deal of insight into the composition of the pigments. However, the picture which they gave was not sufficiently complete to allow the development of hypotheses relating to intended appearance to be based upon this data source alone. In order to augment these findings, a process of experimental reconstruction was initiated. Pigments were produced using ingredients with the same chemical characteristics that were identified through chemical analysis. These pigments were applied to a marble tablet with the same provenance as the stone which is believed to have been used to produce the statue (Moesch 2008). Through this process different variables were explored, including differences in pigment to binder ratio and the possibility of over-painting. This experimental process provided a hypothetical dataset upon which the simulation could be based. These samples, once dry, were measured with an Analytical Spectral Devices Hand Held Portable Spectroradiometer. The results of these tests are summarised below in figures 7.1-6 and are included in Appendix A in tabular form.

Pigment ID

Before research for this thesis began several tests were carried out by Torraca on the surface of the statue with the purpose of identifying substances or elements which formed ingredients in the pigments used to colour the surface (Torraca 2006). Each of the tests conducted (X-Ray Fluorescence, Fourier Transform Infra-Red Spectroscopy and Enzyme-linked Immunosorbent Assay Antibody Testing) was suited to the detection of different substances and so the results of the tests differed greatly.

X-Ray Fluorescence (XRF): XRF testing was carried out on a range of samples taken from the surface of the statue. The results of these tests were not able to conclusively describe the chemical make-up of pigments in full but did identify a series of elements. The elements with the most substantial presence were in each case calcium and Iron. It can be assumed that the high presence of calcium occurred due to the calcitic composition of marble. The presence of iron seems to indicate that pigments used were iron based. This is not surprising given the nature of the colours present; oranges, reds and browns were very often derived from iron oxides (for more information on the composition of pigments please refer to Chapter 3 – The Colours of Statuary). The trace presence of manganese, potassium, titanium and sodium is likely to be due to the occurrence of these elements in the natural environment or in the debris and soil within which the statue was preserved. The results are included below in Table 1.2.

Sample Area	Pigment Description	Chemical Elements Present
Right Pupil	Black	Substantial Presence: Ca (Calcium) Fe (Iron) Trace Presence: S (Sodium) K (Potassium) Ti (Titanium) Mn (Manganese)
Forehead	Bare Marble	Substantial Presence: Ca (Calcium) Fe (Iron) Trace Presence: K (Potassium) Ti (Titanium) Mn (Manganese)
Left Eyebrow	Brown	Ca (Calcium) Fe (Iron) Trace Presence: S (Sodium) K (Potassium) Ti (Titanium) Mn (Manganese)
Front Hair	Red	Ca (Calcium) Fe (Iron) Trace Presence: S (Sodium) K (Potassium) Ti (Titanium) Mn (Manganese)

Table 7.1 Breakdown of chemical elements present in each sample area.

Fourier Transform Infra-Red (FTIR) Spectroscopy: Ten samples were measured using FTIR Spectroscopy. They were distributed across the front of the statue with three samples being taken from the areas of painted hair at the back. The results of these tests were inconclusive with each measurement giving a result similar to that which would be expected from measuring marble. The presence of pigments seems not to have been influential upon any of the results. The only deviations occurred in a sample taken from the hair immediately to the left of the left eye of the statue and a sample taken from the left side of the rear of the head at the point at which the hair appears to be secured. These results suggested the presence of other elements which are likely to be present in residues of volcanic soil. As these tests were conducted prior to the cleaning of the statue, it is extremely likely that these are anomalous results caused by the presence of residual soil (Torraca 2006).

Enzyme-linked Immunosorbent Assay (ELISA) Antibody Testing: ELISA Antibody Tests were conducted in an attempt to identify biological substances which may have been used as binding media for the pigmented areas of the statue. The results of these tests were conclusive indicating the presence of egg, a common binding medium used in tempera painting. The tests did not indicate the presence of antibodies which should be present had other organic binding media been used.

The results of the experiments outlined above provided a sound foundation upon which to base hypothetical reconstructions of the intended appearance of the statue. The presence of iron in the pigmented areas of the statue confirmed that iron based pigments had been used. Consequently the pigment reconstructions (the results of which are described immediately below) would focus upon iron based pigments. The ELISA Antibody Test results were highly significant, confirming that the binding medium used was egg-based. This provides not only a sound basis for hypothetical pigment reconstruction but also gives an indication of the nature of the visual appearance which might have been achieved, tempera painting having distinctive visual and physical qualities. The implications of these results will be described in the next section.

7.1.1.3 Experimental Pigment Reconstruction

The manner by which the experimental reconstruction of pigments was conducted is described in detail in Chapter 6 (Methodology I). The results of these reconstruction experiments are summarised here. For a full presentation of the data in tabular form refer to Appendix A (Tabulated Spectral Data). In addition to the quantitative data, the experiment provided new insights into the painting process and the experience of using these materials. A qualitative understanding of the use of the materials and of the practice of painting is highly significant and is discussed here.

Qualitative Results

The qualitative observations which were made during the pigment reconstruction will be presented before the quantitative results. The reason for this is that the qualitative observations are concerned primarily with the process of painting while the quantitative results are concerned with the resultant data. Consequently, an understanding of the qualitative observations may give the reader some insight into the quantitative data presented below.

Experimental reconstruction of paints and their application to a sample of marble yielded insights regarding not only the appearance of paint once applied but also of the limits and affordances of the materials used. This was particularly true as the experimental process was conducted with the assistance of Prof. Beth Harland, an experienced tempera painter and expert in pigment and painting processes used in fine art.

The experiment began with the mixing, under the advice of Prof. Harland, a paint considered to be the minimum ratio of binder to medium which would result in a viable pigment. In order to demonstrate this point pigment was mixed at a lower ratio than this. The result was a clear paint with coloured particles suspended within it. This sample was then discarded. Once a paint had been made from each of the pigments, these were applied to the surface of the marble. The appearance of these pigments was translucent and the underlying colour of the marble remained partially visible. The next stage was to mix paints at the maximum concentration which was considered viable. These were noticeably thicker and when applied to the surface of the marble they completely obscured the underlying surface. These paints were sufficiently thick that they added a visible layer to the surface of the marble. These paints completely obscured the underlying marble. A paint was mixed which Prof. Harland judged to be over-concentrated. This was pastey and unworkable and upon drying was brittle and easily brushed from the surface of the stone.

The application of the wax coating to the surface of the stone revealed the complexity of using wax based varnishes. The application was straight forward but the polishing of the coating was far more complex. The quantity of wax removed affected the appearance of the surface and a number of effects could have been achieved. We decided to use the wax as a polish and removed most of the wax from the surface. This caused the surface to take on a more uniform appearance and seemed to mask the matte texture left by some of the pigments. The variety of effects which might have been achieved using wax coatings means that further work in this area is necessary. This issue is dealt with at greater length in Chapter 11 (Conclusions).

These observations were highly significant in developing meaningful hypotheses relating to the appearance of the statue. They demonstrated the physical limits of painting in this way and placed constraints on the range of visual effects which might be achieved when using this method.

Quantitative Results

Quantitative measurements of the reconstructed pigment samples were measured with a spectroradiometer in the Geography & Environment Field Spectroscopy laboratory at the University of Southampton. The paint with the middle ratio of pigment to binding medium was measured in each case. Due to time constraints it was not possible to record every sample. The tabulated results describing these measurements can be seen in Appendix A (Tabulated Spectral Data). As described in Chapter 6 (Methodology I), each measurement was taken three times in order to detect anomalous readings and ensure a reliable result. Mean results of the reflectance properties of each material across the visible spectrum are presented below in Figures 7.1 to 7.7. As detailed in Chapter 6 (Methodology I), five densities of paint were mixed for each pigment.

7.1.1.4 Marble Surface Data

As well as measuring the spectral reflectance characteristics of painted areas of marble, unpainted areas were also measured. Three readings were taken of the sample and the mean values are presented in Tables 7.1 and 7.2.

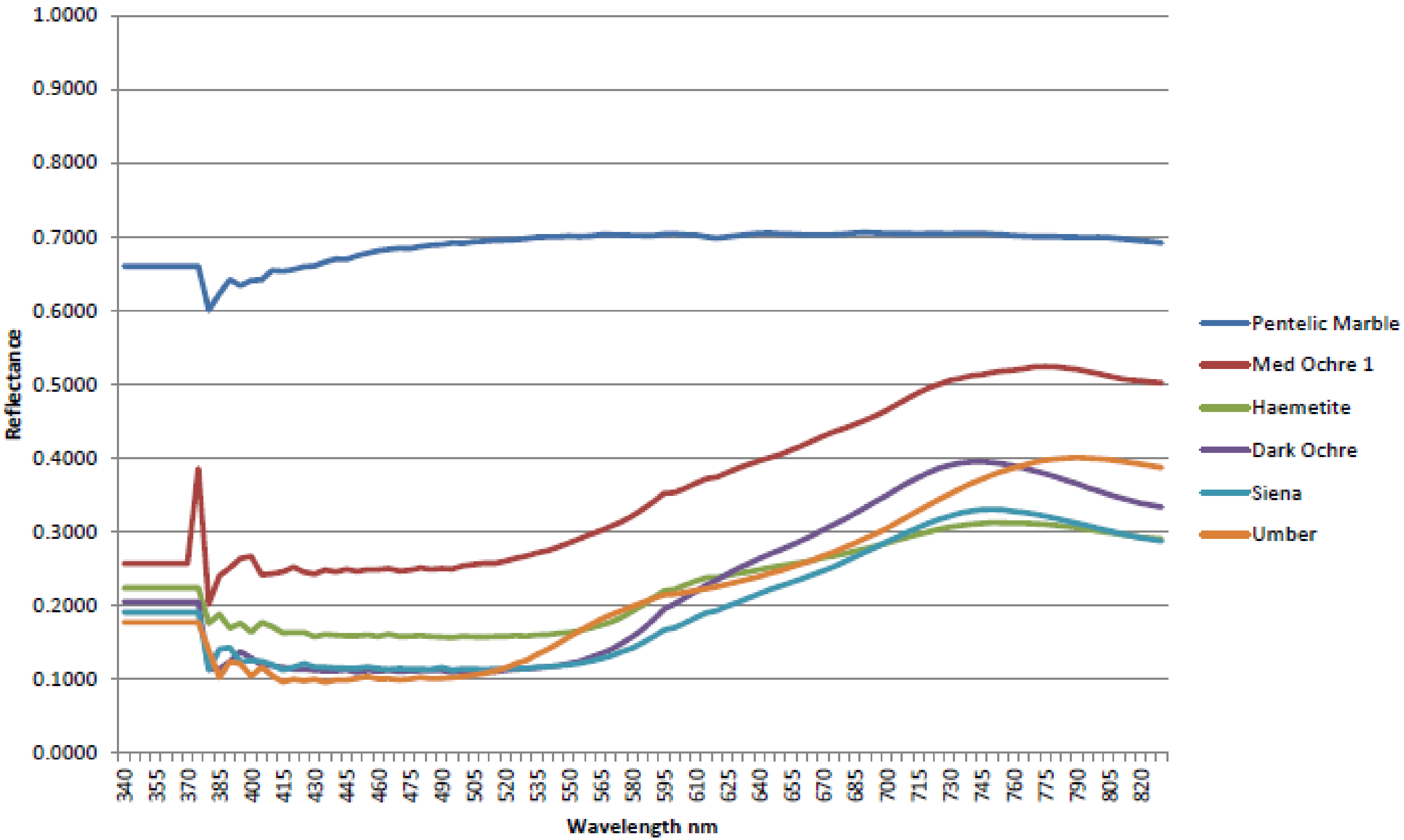

Figure 7.1 The graph shows the index of refraction of each pigment at every wavelength from 340-815. It is interesting to note the difference the between the lighter unpainted marble and the painted samples.

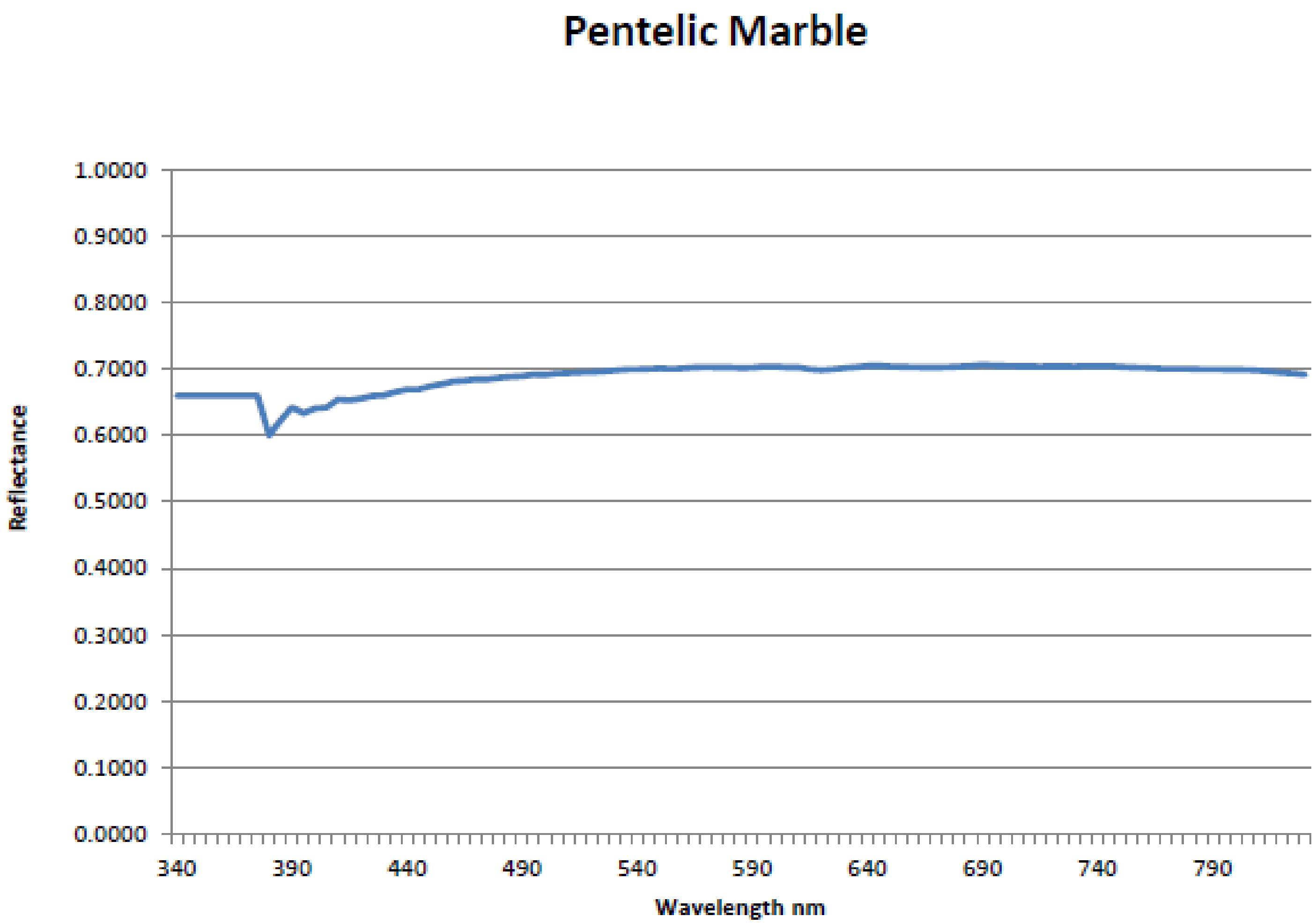

Figure 7.2 Reflectance characteristics of paint made with pentelic marble.

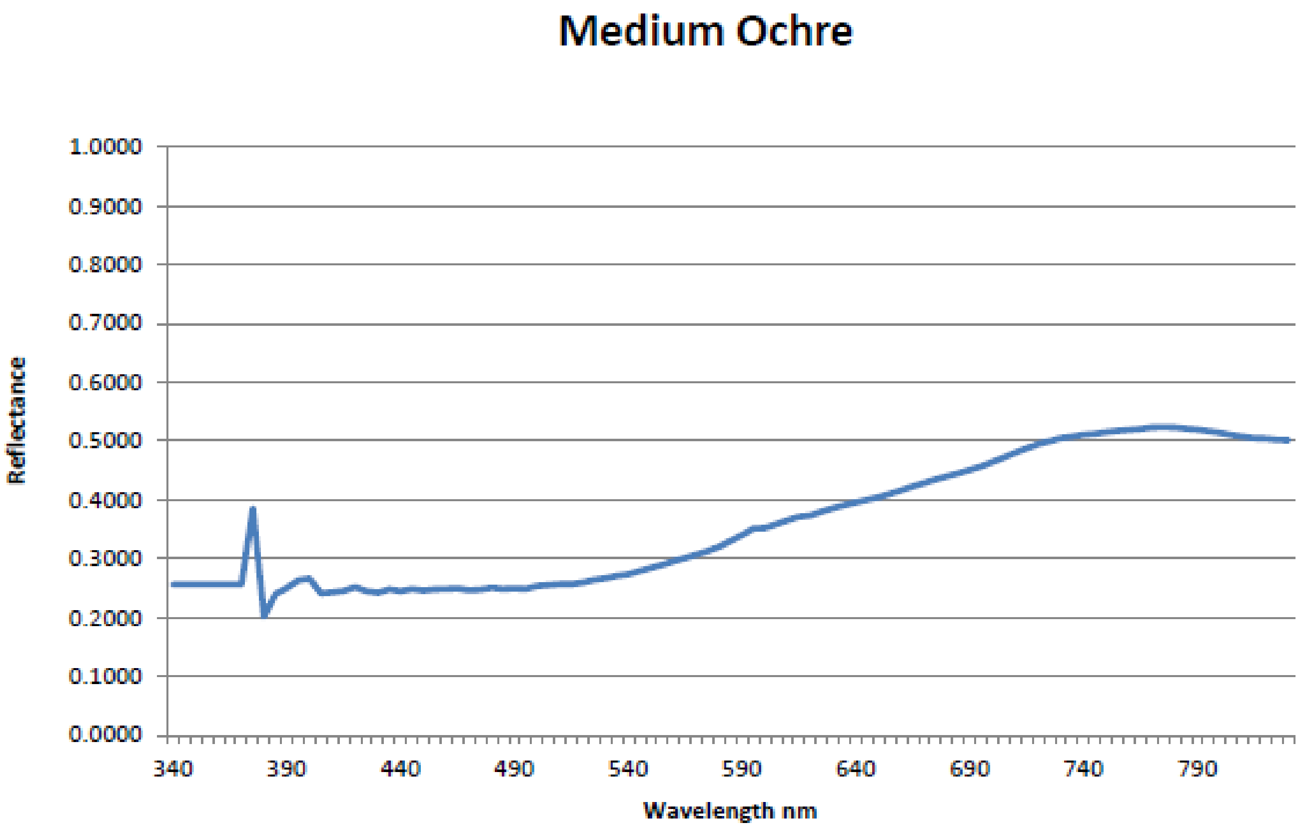

Figure 7.3 Reflectance characteristics of paint made with medium ochre.

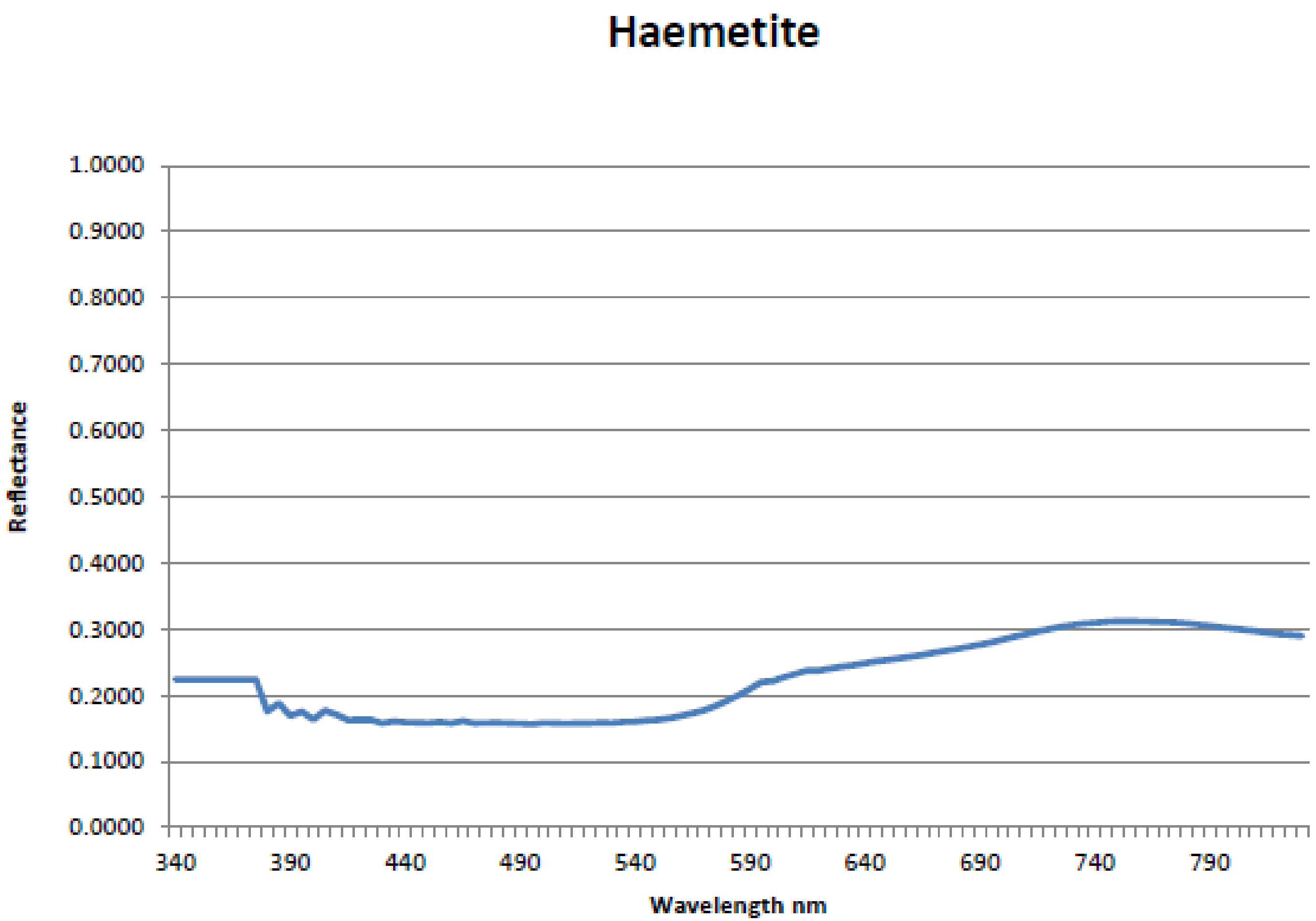

Figure 7.4 Reflectance characteristics of paint made with haemetite.

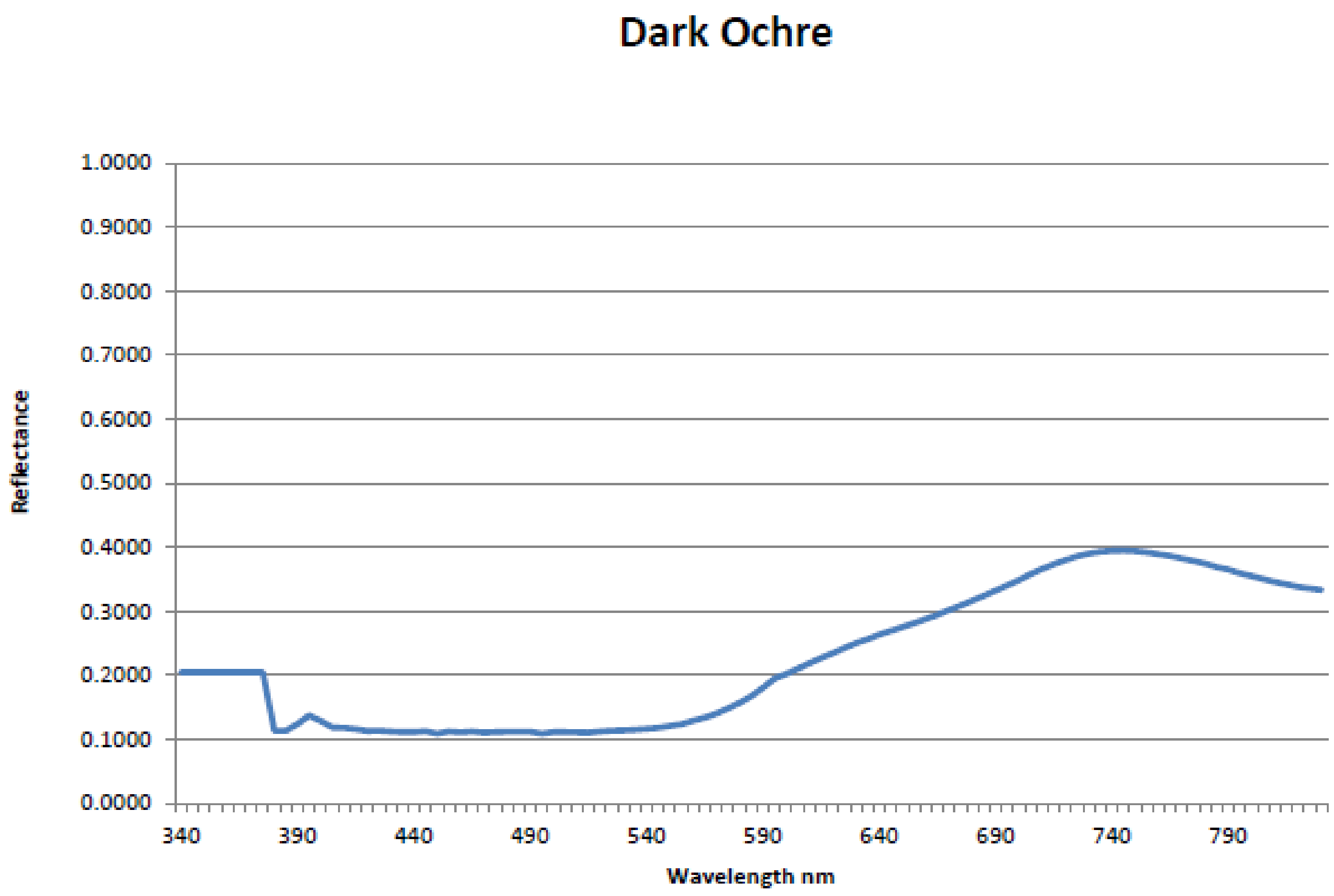

Figure 7.5 Reflectance characteristics of paint made with dark ochre.

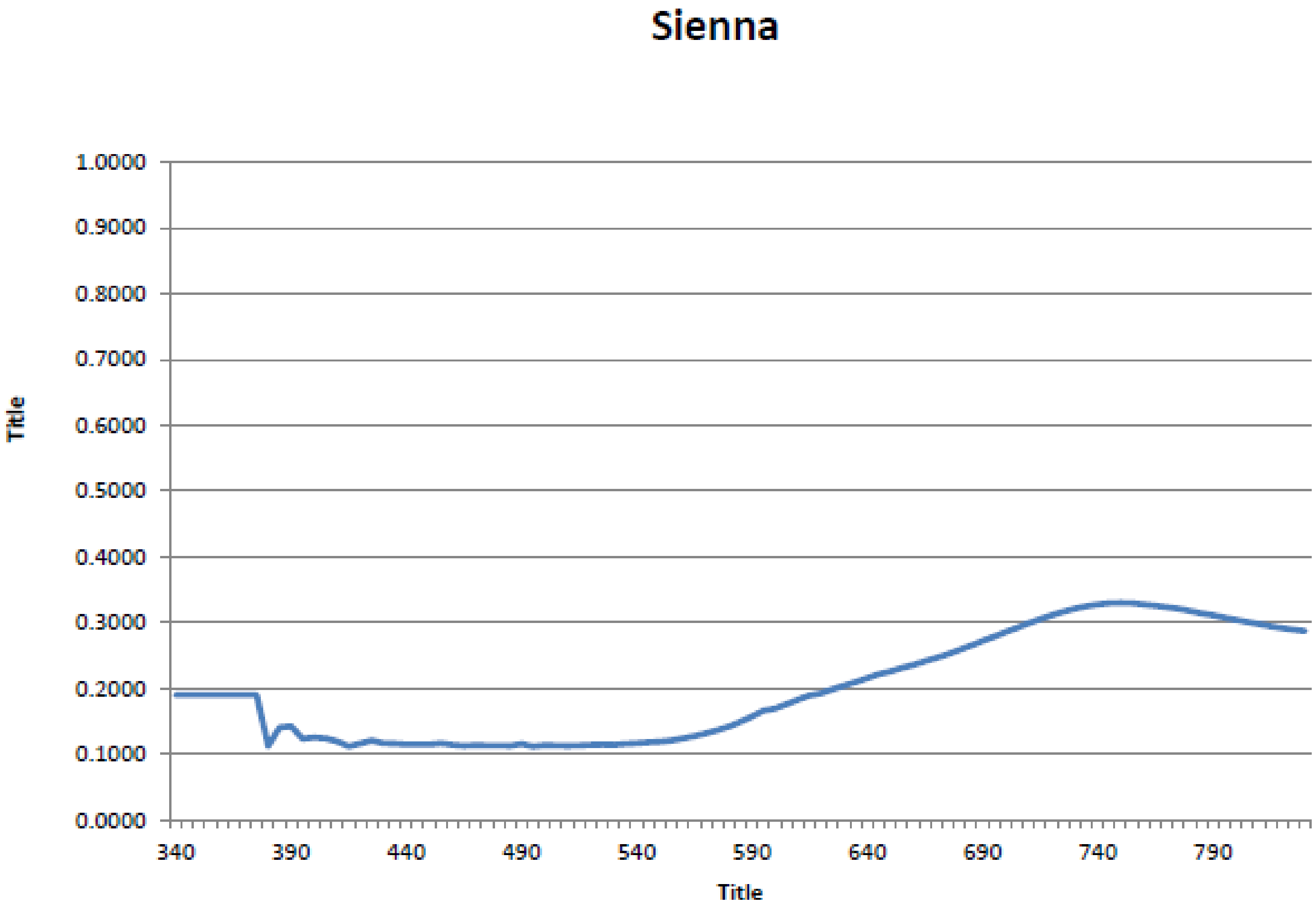

Figure 7.6 Reflectance characteristics of paint made with sienna.

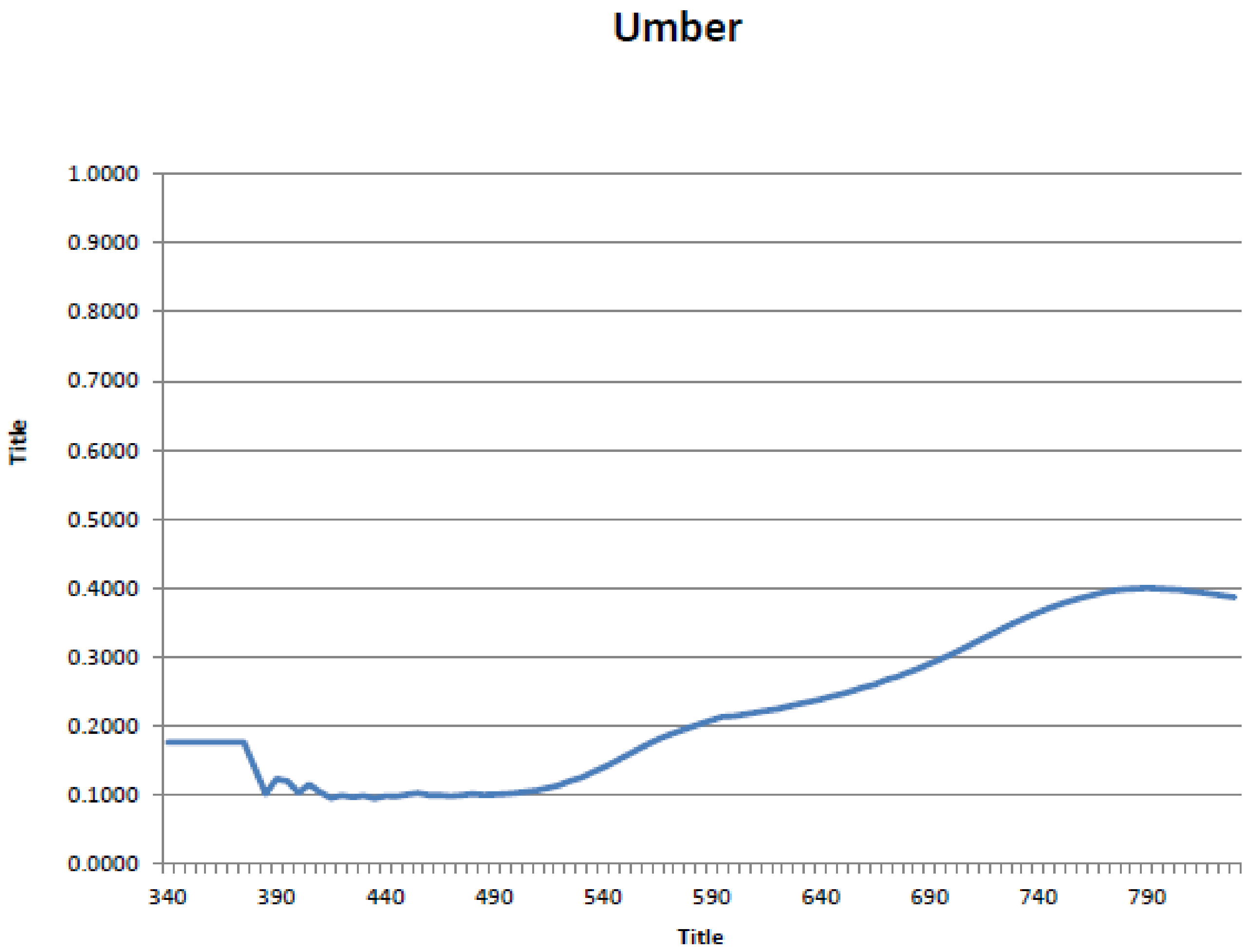

Figure 7.7 Reflectance characteristics of paint made with Umber

Chapter 8

8 Methodology II: Modelling, Rendering and Display

This chapter constitutes the second part of the methodology. Part one, presented in Chapter 6 (Methodology I), dealt primarily with data capture techniques, while in Chapter 7 (Experimentally Derived Data), all data were presented and all processing described. This chapter will deal with the latter stages of the image production pipeline namely; modelling, rendering and display. This chapter will also describe the manner by which these images will be employed as tools for interpretation and hypothesis building.

8.1 Structuring Uncertainty

Despite the fact that the statue which is the object of study in this thesis is comparatively well preserved, there remain fundamental uncertainties relating to those areas which are poorly preserved or have been damaged. Uncertainties also exist regarding the context within which the statue would have been seen and the environmental circumstances in which it would have been encountered. Exploration of these variables is the central purpose of this thesis and is essential in order to develop a meaningful, contextually informed, interpretation of the phenomenon of statue painting.

For this reason it was necessary to structure and to make explicit the way in which variables were navigated. It is not viable to exhaustively represent the statue according to every possible interpretation, nor is it desirable. The purpose of the thesis is to develop improved understandings of the phenomenon of statue painting, to demonstrate the variety of interpretation which can be justified by the data which we have available. In order to further these goals a series of variables were identified which would influence the appearance of the painted statue presented within context. For each of these variables, a number of alternative hypotheses were developed and these were then implemented within the simulation and rendered. Different combinations of hypothetical variables were combined in alternative hypothetical configurations in order to produce a set of images which reflect a wide variety of visual hypotheses.

The combination of hypotheses used in any given image can be easily understood using the flowcharts contained within this chapter. These flowcharts can be connected to provide a structured map of variables for each image. In addition to providing an explanation of variables within the context of the methodology, these flowcharts will also be used to provide metadata for the published images in a concise visual form and are included in Chapter 10 (Results II). Descriptions of each of these variables and the different combinations of variables which were rendered are outlined below.

8.2 Modelling

The chapter will begin by describing the modelling process. It will begin with the modelling of the statue and will then present the modelling of the buildings. Finally the chapter will deal with the modelling of the lighting and environmental elements.

The accurate translation of experimentally derived data and data collected directly from archaeological material into a format compatible with the modelling process represents one of the greatest challenges of the thesis. The visualisation must, insofar as is possible, recreate all of the data collected from the physical world with a high degree of accuracy and precision in virtual space. The reliable, precise and accurate translation of real world data into digital visualisation was achieved using a twofold approach. Primarily it was important that data were accurately converted into forms which could be represented and that any changes made to the data were carefully documented so as to ensure the repeatability of the modelling process. The second stage of the visualisation process has been verification. It is important not only that data are accurately visualised but that this accuracy can be demonstrated through quantitative comparisons between photographic and virtual data. The verification process is dealt with at length below in the *8.4 Verification of Results* section of this chapter.

The primary tool for reconstruction has been 3ds Max. 3ds Max is a 3D modelling, rendering and animation package which can be used in conjunction with third party rendering applications in order to carry out physically accurate light and surface reflectance simulation. Several rendering applications were trialled in order to select the most appropriate solution. Following these trials two renderers were selected; LuxRender and mental ray. As a consequence there will be points during the following methodology where two methods of implementation of a specific dataset will be described. Where this occurs an explanation will be given. Details relating to the physically accurate simulation of light are discussed in Chapter 5 (Physically Accurate Computer Graphics).

8.2.1 The Statue

Several variables related to the statue were studied. These can be broken down into two groups, those relating to geometry or form and those related to colour and reflectance. Within 3D computer graphics these categories correspond to geometry and materials. These two groups are presented below.

8.2.1.1 Geometry

The translation of geometrical data into digital space is relatively straightforward. The laser scanner outputs high resolution data at real world scale which can be imported directly into 3ds Max.

Geometric data were combined using an open source 3D data processing program called Meshlab. The purpose of combining the data was to ensure that the mesh had a coherent exterior surface without holes or overlapping faces. An algorithm known as Poisson Reconstruction was used to produce a single mesh for the statue. The statue parts which were used to build the hypothetical statue are detailed in chapter 6 (Methodology I). For the final visualisations two alternative facial reconstructions were developed, one based upon the Sciarra amazon from the Ny Carlsberg Glyptotek and the other from a Sosikles Amazon from the collection of the Museum of the Faculty of Classics at the University of Cambridge (see section *8.2.1.4 Hypothetical Reconstruction* for more detail). The resolution of the final dataset was higher than in any of the source meshes ensuring that no detail was lost from the original data.

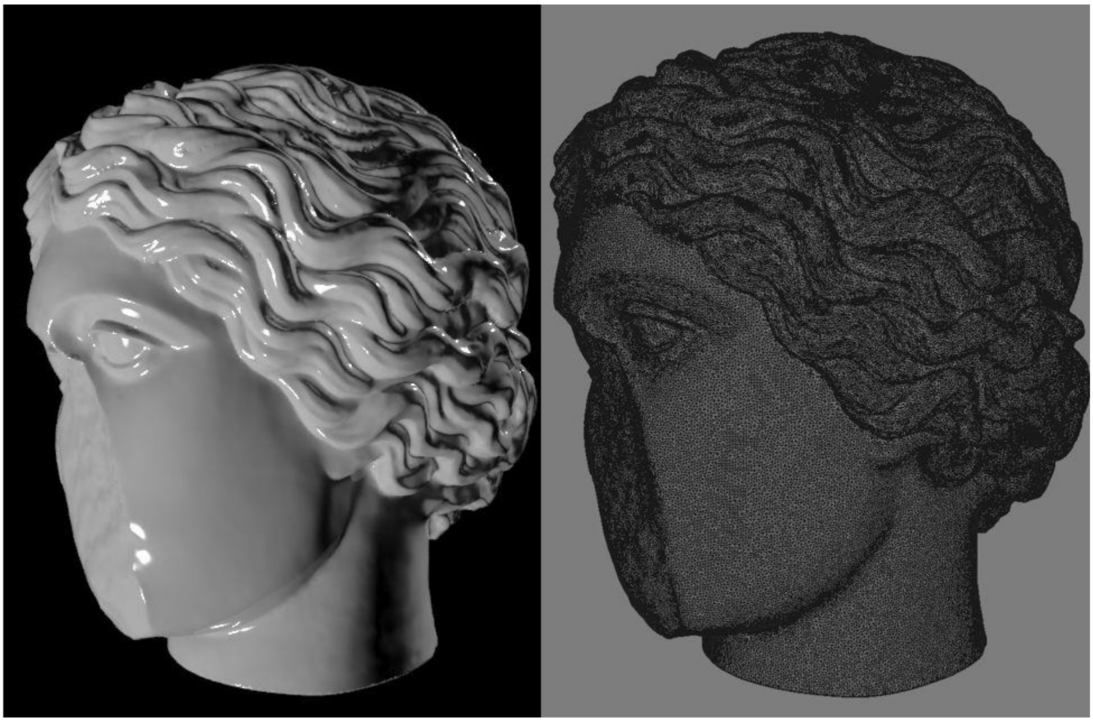

Figure 8.1 (Left) Processed laser scan data (Right) rendered in viewport window (images author's own).

8.2.1.2 Materials: Stone

There are several considerations which have been taken into account when reproducing the stone from which the statue head has been carved. Firstly, this material, as with all of the other materials in the virtual reconstruction works procedurally. That is to say that the appearance of the materials are not image-based (e.g. from photographs of the original object) but are dictated by a series of mathematical formulae which dictate in a physical way the reflective behaviour of the surface.

Colour

Colour data for stone materials were derived from the marble sample. They take the form of a record of spectral reflectance captured with a spectroradiometer. For more information about these data sets refer to the summary of experimentally derived data presented in Chapter 7 (Experimentally Derived Data). For more information on the capturing of these data refer to the first part of the methodology, Chapter 6 (Methodology I).

The statue head itself is not sufficiently reliable as a source of colour information: the colour of the head might have altered due to a number of factors including aging, exposure to the intense heat of the eruption and the chemical effects of the subsequent burial which caused its preservation.

The sample used to derive colour information for the stone was the same sample used in the pigmentation experiments explained in the *6.3.2. Surface Recording* section of Chapter 6 (Methodology I), specifically the sub-section on *Pigments and Surface Treatments.* For more information on the nature of the preservation of the head and the potential changes in appearance wrought by this process please refer to Chapter 2 (The Statue and the Architecture).

The spectral data captured from the marble sample were implemented as a LuxRender material file and combined with other material properties (BRDF and subsurface scattering) which were implemented according to the methods outlined immediately below. For compatibility with a renderer working within RGB colour space the values can be averaged to generate a single RGB value, this technique was used when using mental ray to compose the scene and produce draft images. Colour variation was approximated using smoke and noise maps. It was not be possible to collect sufficient spectral data within the time constraints of this research to simulate this variation based upon dense sampling with a spectroradiometer.

Colour derived from a calibrated photographic record of the statue itself was not implemented for use with a spectral renderer as this would have offered no improvement in accuracy.

Reflectance

The influences of viewer position and light position upon the appearance of a surface are of increasing interest in computer graphics. As discussed in Chapter 5 (Physically Accurate Computer Graphics), descriptions of surface reflectance (BRDF, BSDF and BTF) are the subject of active development. Within the context of this thesis, pre-written shaders designed to represent lightly polished stone were used. This decision was taken owing to the difficulty of acquiring reflectance data directly from the original statue. It would have been possible to record a sample of similar stone but under these circumstances the data gathered would be insufficiently reliable as a representation of the marble of the statue head to justify the difficulty and expense of capturing the data where generic data could be used instead.

A process of verification was essential in order to ensure that the shading algorithm used represented a sufficiently physically accurate representation of the stone surface. This verification was of particular importance where experimentally derived data could not be collected. The process of verifying the accurate procedural simulation of these aspects of the material followed the established method of PTM verification outlined below in the *8.4 Verification of Results* section. The stone surface has been verified against PTMs of the statue head and of marble samples. Where the results differed too greatly according to a series of sampled quantitative measurements the simulation was revised.

These functions can be straightforwardly implemented within any material for use in either mental ray or LuxRender.

Subsurface Scattering

Subsurface scattering has contributed greatly to the physical accuracy of the virtual reconstruction of the stone material. The phenomenon of subsurface scattering is detailed more thoroughly in Chapter 5 (Physically Accurate Computer Graphics). The ability to describe and to visualise the way in which light penetrates a surface and is reflected from within an object is extremely desirable if we are to visualise materials such as marble for which this is such a defining characteristic.

It was not possible to capture information relating to the specific subsurface scattering characteristics of the statue head. The equipment necessary to take these measurements is not readily available (see Chapter 5 – Physically Accurate Computer Graphics, for more information on this equipment) and in the event that this data could be acquired it would be an enterprise beyond the scope of this research to translate these data into a form which relates to the variables used to describe subsurface scattering within mental ray or LuxRender.

Subsurface scattering played a central role in reconstructing the stone material. Several typical subsurface scattering models exist which are based upon recordings of marble (Jensen, Marschner et al. 2001). These have been implemented and tested. The accuracy of the subsurface scattering simulation was tested by creating an object of identical shape and dimensions to a sample of pentelic marble. The physical sample was photographed under controlled lighting conditions whereby a light was shone through the surface of the marble. The sample was photographed from all sides. These conditions were then replicated using 3D graphics. The rendered outputs were compared both qualitatively and quantitatively by noting the luminance value of each cell within the two corresponding images. This process of validation is described in greater detail in the *8.4 Verification of Results* section described below.

8.2.1.3 Materials: Painted Surfaces

The representation of painted surfaces follows all of the same processes outlined above. However, in some cases the means of capturing data and methods of reproducing data differ slightly. The most significant difference is in the implementation of the layering required to accurately simulate the addition of paint layers to the surface of the marble.

In the reproduction of colour, consultation of the statue head is of use only in terms of defining the areas in which the paint is likely to have been applied and also in offering hints relating to the way in which it would have been applied. These, as noted by Østergaard, often prove to be the most enigmatic aspects of statue painting often causing hypotheses relating to the original appearance of the statue to remain highly speculative (2007). A great deal of detail survives on the statue head and it is likely that close inspection will offer many insights into the manner of painting. For more information relating to the precise details of the painted head please refer to Chapter 2 (The Statue and Architecture).

Structure

The layering of layers of paint on top of the underlying marble surface required the use of layered subsurface scattering materials. Unlike the other materials implementations mentioned in this chapter which have only involved settings shared between LuxRender and mental ray, the implementation of subsurface scattering is renderer specific.

In mental ray, a physical subsurface scattering material was used within which outer layers of the material can be defined using settings different to the underlying material (LAmrUG 2006).

Within LuxRender the strata of paint will be defined physically using a layered material (LuxRender 2012a). The layered material is a composite material which allows several materials to be layered. Each material has entirely autonomous settings meaning that bump maps derived from RTI data can be used to define the apparent surface geometry of the outer layers. The scattering effect is defined by specifying the opacity of each material combined with the other material settings.

Colour

Colour values for painted areas were not taken from the statue itself. It is quite clear that the preserved colours do not offer a precise record of the original colours. As described in Chapter 2 (The Statue and Architecture), while the palette of colours is likely to be similar to those originally present, there are obvious signs of degradation and the possible loss of exterior layers of paint. Consequently, colour values were derived from the pigment reconstruction experiment detailed in Chapter 6 (Methodology I). The spectral data from the marble sample were used to dictate the reflective characteristics of the paints in the simulation. The spectral renderer, LuxRender, was used to produce the simulation. This program allows the input of tabular data as a means of dictating the reflective characteristics of a material and so the data collected could be used without any additional data processing. These data are presented in Chapter 7 (Experimentally Derived Data).

Reflectance

Standard shading algorithms were used to simulate the reflective characteristics of the painted areas of the statue. In order to ensure that these generic shading algorithms created an adequate description of the reflective characteristics of the surface they were compared to RTI data which were captured according to the technique outlined below in the *8.4 Verification of Results* section. Data captured in order to validate BRDF or BTF descriptions was taken from a painted marble sample. However the number of painted areas created by the pigment reconstruction experiment was so large that a sub-set was used to generalise according to pigment type.

Subsurface Scattering

Subsurface scattering for the painted areas of the statue was based upon subsurface scattering data collected by Jensen, Marschner et al. (2001). This model was augmented through the use of the layered material within LuxRender which allows light to be reflected between layers. The accuracy of this model was ensured using the process for verifying the accuracy of subsurface scattering outlined below in the *8.4 Verification of Results* section.

8.2.1.4 Hypothetical Reconstruction

The production of coherent models of the statue in context necessitates the inclusion of hypothetical content. The buildings and the statue itself, while being remarkably well preserved, are only partially preserved. The value of physically accurate virtual reconstruction lays in the ability to hypothesise as to that content which is absent within a reliable and controlled virtual environment. In the case of this research the absent data range from entirely absent portions of the statue or building through to data which are only slightly compromised, for example the reflective properties of the marble floors.

In order to produce meaningful hypotheses for the replacement of these missing data it was crucial that supplementary data were appropriate and meaningful; that a range of alternatives were chosen appropriate to the nature and the level of uncertainty. These data and the techniques used to capture them are described in Chapter 6 (Methodology I) and Chapter 7 (Experimentally Derived Data) respectively. Here the discussion will focus upon how these hypothetical alternatives were implemented. As discussed in the introduction to this chapter, flowcharts will be used to demonstrate the navigation of these alternative configurations of hypotheses.

Geometric Reconstruction

The statue which forms the focus of the simulation is, as we have seen in Chapter 2 (The Statue and Architecture), physically incomplete. Due to the violent effects of the eruption, the body of the statue has been lost as have the nose and mouth of the head. Uncertainty surrounds the original form of both of these components of the statue. As discussed in Chapter 6 (Methodology I); supplementary data which would allow two alternative reconstructions of the statue to be created were scanned from a Sosikles Amazon from the collection of plaster casts at the Museum of Classical Archaeology at the University Cambridge Faculty of Classics and an original and a physically well preserved example of a Sciarra Amazon housed at the Ny Carlsberg Glyptotek in Copenhagen (see Figure 8.2).

Figure 8.2 The face of the statue from Herculaneum was reconstructed using laser scan data taken from (left) a Sosikles Amazon from the cast gallery at the Faculty of Classics Museum, Cambridge and (right) a Sciarra Amazon from the Ny Carlsberg Glyptotek, Copenhagen (images author's own).

The missing facial components were reconstructed according to two different hypotheses, one using data from the Ny Carlsberg Glyptotek Sciarra Amazon and the other using data from the Sosikles Amazon held at the Museum of Classical Archaeology (see Figure 8.2-3). The data were straightforwardly fitted to the existing data from the statue head, in both cases the fit was extremely close and required very little manipulation in order to connect seamlessly with the existing geometry. Other data were not used as they were deemed to be too similar to the two datasets which were used to offer any improvement in insight.

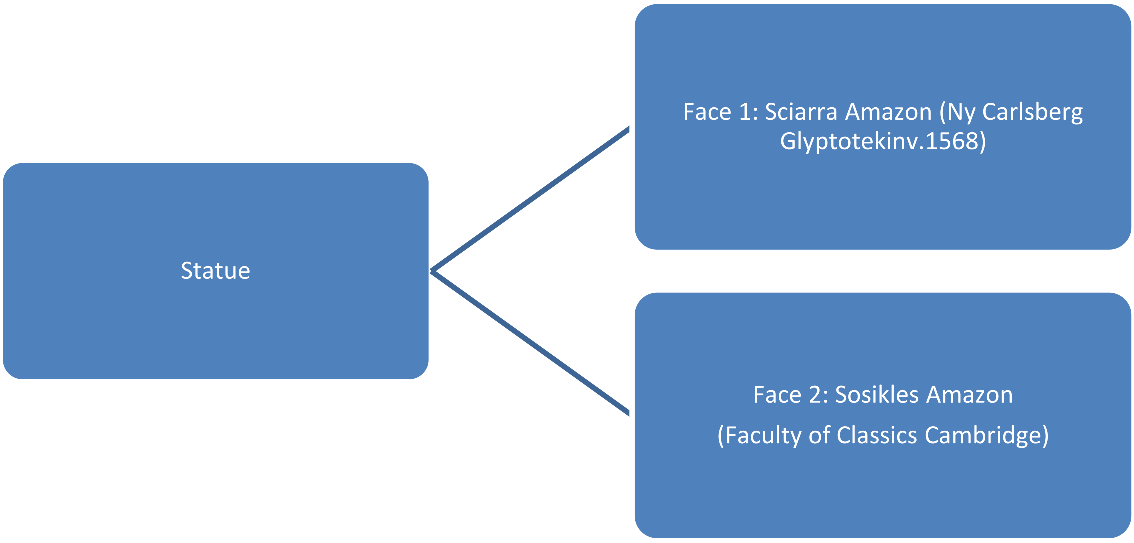

Figure 8.3 Flowchart illustrating the process of reconstructing the statue face.

The body was reconstructed using the laser scanned record of the Sciarra Amazon from the Ny Carlsberg Glyptotek in Copenhagen and a Sosikles Amazon statue captured at Museum of Classical Archaeology (see Figure 8.4 below). The fitting of the head to the bodies was straightforward with location and alignment being dictated by the existing heads on these two statues.

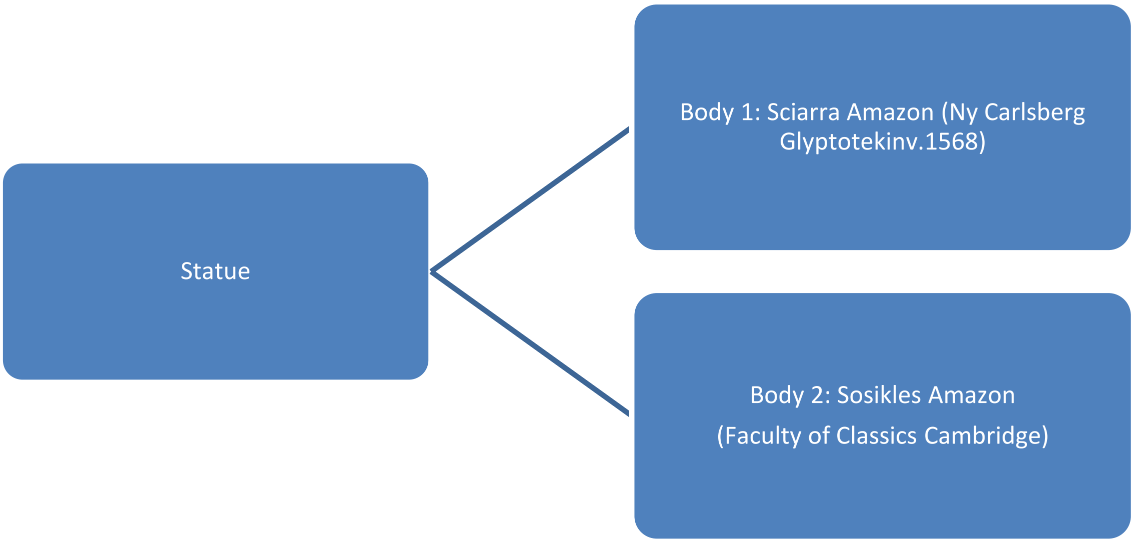

Figure 8.4 Flowchart illustrating the process of reconstructing the statue body.

Surface Reconstruction

The main variables which needed to be considered when hypothetically reconstructing the statue, related to the different painted parts of the surface. The painted areas of the statue can be broken down into: the brow, the lashes, the iris, the pupils and the hair. It is possible that each of these areas will have a different paint applied to it and each paint used has five potential variables; four gradiations of pigment and the possibility of a double layer. It is also possible for one pigment to be layered over another. The diagram below (Figure 8.5) illustrates the variables which are available once an area of the statue (in this case the brow) and a pigment (in this case umber) have been chosen.

Physically preserved areas of the statue head indicate quite clearly the areas in which the statue has been painted, coupled with the results of pigment analysis sufficient data exist to hypothesise as to the location and shape of the painted areas. The hypothetical distribution of paint in the areas of the statue which are not preserved were based primarily upon pigment location and identification data captured from the Sciarra Amazon at Ny Carlsberg Glyptotek in Copenhagen (Østergaard and Copenhagen Polychromy Network 2010).

The manner by which pigment data were generated and reproduced has been outlined above. Pigments of variable intensity and of the types identified were added to areas of the statue as per the results acquired by Torracca (2006) and by Østergaard and the Copenhagen Polychromy Network (2010). The influence of the wax varnish upon the reflective characteristics of the surface appeared negligible and so the varnish was represented as a different colour (see Chapter 9: Results II for more information).

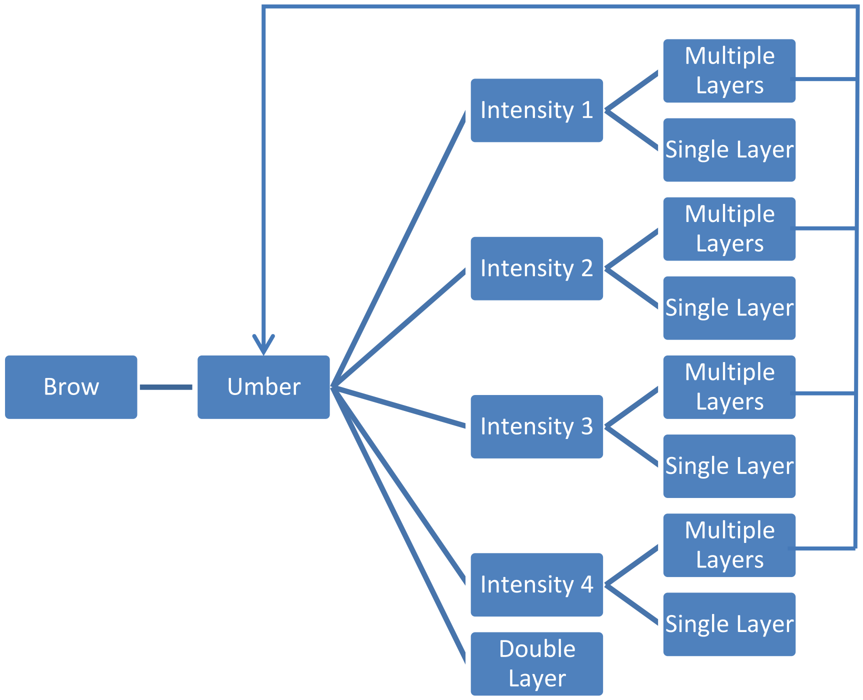

Figure 8.5 Flowchart showing the possible combinations of variables associated with painting a specific area of the statue with a particular paint.

8.2.2 Architecture

Three different architectural scenarios were modelled. Two of these were based upon areas of the House of the Stags at Herculaneum, one was based upon the House of the Mosaic atrium. The first part of this section will describe each of the areas. The following sections will then detail which data were used in the modelling process and how they were incorporated.

8.2.2.1 Cryptoporticus: House of the Stags

The cryptoporticus of the House of the Stags is a narrow corridor lit by large windows which links different parts of the house together. See Figure 8.6 below for a plan of the location of the cryptoporticus.

Figure 8.6 The cryptoporticus of the House of the Stags is marked in red. The location of the statue in the simulation is marked as a blue circle (image author's own).

8.2.2.2 Large Dining Room: House of the Stags

A large dining room at the Southern end of the House of the Stags with views of the Pergola and the sea beyond. See Figure 8.7 for a plan of the location of the dining room.

Figure 8.7 The large dining room of the House of the Stags is shown here in green. The location of the statue in the simulation is marked as a blue circle (image author's own).

8.2.2.3 Peristyle: House of the Mosaic Atrium

The interior of the peristyle which surrounds the internal garden of the House of the Mosaic Atrium. See Figure 8.8 for a plan of the location of the peristyle.

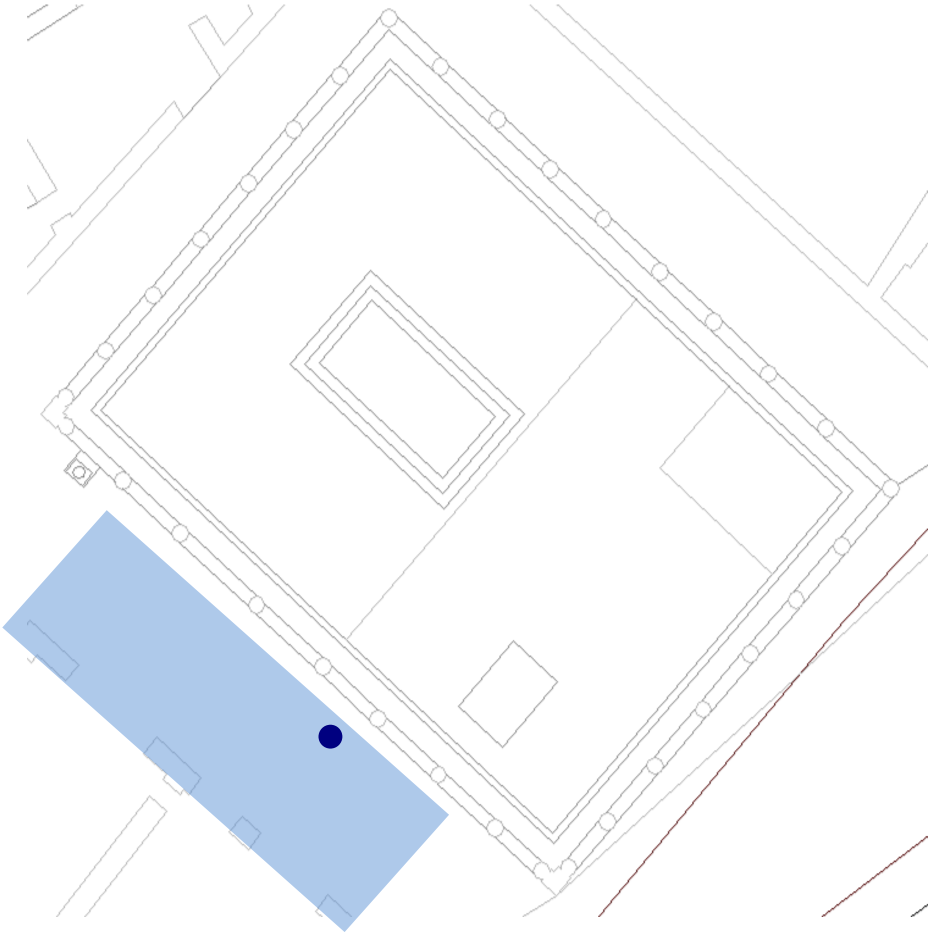

Figure 8.8 The area of the peristyle garden of the House of the Mosaic Atrium in which the statue was visualised. The point of the statue within the simulation is marked with a blue circle (image author's own).

It is important however to recognise that these architectural scenarios are not accurate visualisations of these buildings. The intention of the models was not to propose definitive reconstructions of these particular areas, but rather to present a variety of alternative scenarios within which to conduct lighting simulations. The areas were chosen because they represented a diverse range of architectural settings and lighting conditions. The reasons for having chosen these specific locations are outlined in Chapter 2 (The Statue and Architecture).

The modelling of architecture involved the integration of several different data types as well as the hypothetical reconstruction of both geometric and surface data. The hypothetical reconstruction of the architecture incorporated a level of uncertainty far beyond that which characterised the reconstruction of the statue. The reason for this uncertainty can be attributed to the extraordinary range of materials, to uncertainty surrounding the influence of conservation techniques upon appearance and to the limited resolution of available geometric data.

8.2.2.4 Geometry

The bulk of the geometry for the architectural component of the simulation was based upon survey data captured from the house and from elevations and ground plans already created by the Herculaneum Conservation Project. Consequently the resultant model did not represent a physically accurate record of the building as it stands but rather a hypothetical interpretation of the available data. This loss of accuracy has not been detrimental to the accuracy of the simulation owing to the fact that regardless of the resolution of geometric data available, the simulation incorporates a virtual reconstruction of the building and not a representation of it in its current state. Consequently the modification or modelling of geometry is an unavoidable part of the production process.

Plans and elevations were digitised and imported into 3ds Max in order to provide a geometric basis for the modelling process. Survey data were also imported where necessary.

8.2.2.5 Materials: Walls

Colour data for walls were acquired directly from the site using calibrated photographs. In the visualisations produced using spectral rendering with LuxRender; photographically derived colour values were used to manipulate pre-written material properties. Uneven distributions of colour across panels of wall were generated procedurally using a composite of a noise map and an image based map. The distribution of colour in areas where detailed multi-colour wall paintings exist were defined according to photographically derived maps generated from photographs taken on site.

All photographs were colour corrected before being used. An X-Rite colour rendition chart was included in all photographs for this reason. The images presented below were manipulated so that they could be included within the simulation as architectural components. The process of manipulating them for inclusion within the simulation was carried out using Adobe Photoshop. The wall and marble pavement images were altered so that they would seamlessly tile and could be used as repeating textures on floors or walls respectively (see Figure 8.9 – 8.12).

Figure 8.9 (Left) A photograph of a wall painting captured in the peristyle of the House of the Stags at Herculaneum (photograph author's own) (Right) A modified and colour corrected version of the file which was used as a texture map in the simulation (image author's own).

Figure 8.10 (Left) A photograph of a red painted wall from the House of the Mosaic Atrium at Herculaneum (photograph author's own) (Right) A modified and colour corrected version of the file which was used as a texture map in the simulation (image author's own).

Estimated BRDF representations were generated and refined according to comparisons between the simulated and RTI data. The reflective properties of wall paintings were more uniformly distributed than on the statue due to the application of varnish and surface treatments across the entire surface. These results are described in Chapter 7 (Experimentally Derived Data).

Absorption and scattering coefficients of wall paintings, have been estimated and validated according to the technique outlined below in the *8.4 Verification of Results* section. This process has been repeated in order to refine the effect until a satisfactorily accurate result is achieved.

8.2.2.6 Materials: Floors

Floors in the House of the Stags are composed primarily of simple two tone mosaics or marble pavements, the latter being constructed through the arrangements of differently coloured marbles.

Figure 8.11 A photograph of a marble pavement floor from the House of the Mosaic Atrium at Herculaneum (photograph author's own).

Figure 8.12 Modified and colour corrected images derived from Figure 8.11. These images were used as texture maps in the simulation (images author's own).

Mosaics in the House of the Stags are constructed of mid-size white marble tesserae which measure approximately 1cmx1cm on their exposed surface. The mosaics are irregular in size and alignment and are arranged into geometric patterns. The white marble material used for the tesserae were based upon a white marble physical subsurface scattering mental ray material incorporating the reflection and absorption coefficients gathered by Jensen, Marschner et al. for marble (2001). Colour values were based upon colour calibrated images as described above in Chapter 6 (Methodology I) in the *6.4.1 Building Recording* section. Because geometric data were not collected from floors, displacement maps were produced from the RTI data which provided a good estimate of the surface geometry of the floor.

The material reconstruction of the marble pavements was similarly executed. Colour and subsurface scattering components were defined in the same way as for the mosaic floors.

8.2.2.7 Hypothetical Reconstruction

The hypothetical reconstructions of the fabric of the buildings were conducted using the techniques described above. The specific variables which were incorporated into the simulation are described here. The most significant variable relates to the context within which the simulation took place. Three architectural scenarios were modelled and featured within the simulation. They were based upon three different architectural environments from Herculaneum, as described above:

1. The cryptoporticus of the House of the Stags at Herculaneum
2. The southern large dining room of the House of the Stags in Herculaneum
3. The peristyle of the House of the Mosaic Atrium

Within each of these architectural scenarios specific variables were altered in order to control the movement of light around the scene. Each of the scenes was modelled with a plain red painted wall (see Figure 8.10) and with a decorated blue wall (see Figure 8. 9). Figure 8.13 illustrates this part of the map of variables.

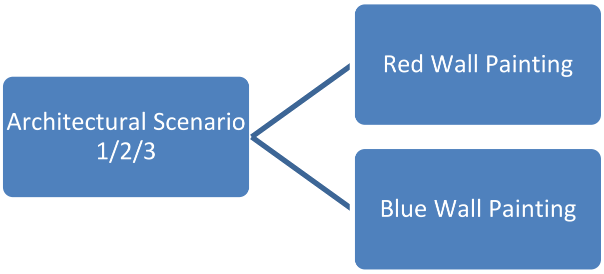

Figure 8.13 Flowchart showing the architectural scenarios within which the statue was visualised.

8.2.3 Lighting and Environment

Lights were implemented differently within the different renderers. The reasons for using multiple rendering solutions and for having chosen specific rendering solutions are outlined in section *8.2 Rendering*.

8.2.3.1 mental ray

Daylight was simulated using a mental ray physical sky/sun lighting environment. Luminance and colour settings were approximated based upon the HDR lighting environments, the recording of which was outlined in Chapter 6 (Methodology I) in the *6.5 Light Reconstruction* section. Artificial lights were produced using mental ray area lights. Calibrated colour values captured using a spectroradiometer were converted into RGB values. For more information about mental ray light types refer to the mental ray support website (Mental-images 2011).

8.2.3.2 LuxRender

Daylight was simulated using the LuxRender physically accurate sun and skylight. Artificial lights were produced using mesh lights. Mesh lights are luminaires; objects which emit light in the direction of their surface normals. These were used to approximate the shape of a flame. Spectral lighting information derived from research conducted by Hughes and Gale (2007) was implemented in order to inform the colour and luminance of the light source. For more information about LuxRender lighting refer to the *LuxRender Lighting* pages of the LuxRender wiki (LuxRender 2011b).

8.2.3.3 Hypothetical Reconstruction

Variables relating to lighting and the environment dictate the luminosity of a scene as well as the colour of the light. Consequently, these variables are highly significant in dictating the appearance of the scene. The following section will explicitly describe LuxRender settings because they differ significantly from those within mental ray. LuxRender was used to produce all of the visualisations which feature in the results chapter.

Two light sources have been simulated as part of this work; the sun and an oil lamp. Both lights are implemented within LuxRender according to physically accurate lighting data. Specific aspects of the light sources can be controlled. In the case of the sun the major variables are the time of day which dictates the position of the sun, the time of year which also dictates the position of the sun and the turbidity of the atmosphere caused by the presence of suspended particles.

All of these variables affect the colour and luminance of the light source. The time of day and time of year are expressed in conventional terms, i.e. hours and months/days. Simulations were run hourly at midsummer and midwinter. Turbidity is a much more complex phenomenon to quantify and is expressed within LuxRender on an arbitrary scale varying between 1 and 10. The arbitrary terms in which the variable is expressed prevents it from being meaningfully explored. However simulations were run at intervals of 1, between the values of 1 (lowest turbidity) and 8 (moderate turbidity) in order to observe the effects of different levels of atmospheric pollution upon the scene.

The variables relating to the implementation of the artificial light were fewer and were based on physically modelled light-sources (Hughes and Gale 2007). As a result, only the location of the light source could be reliably altered (see Figures 8.14 and 8.15).

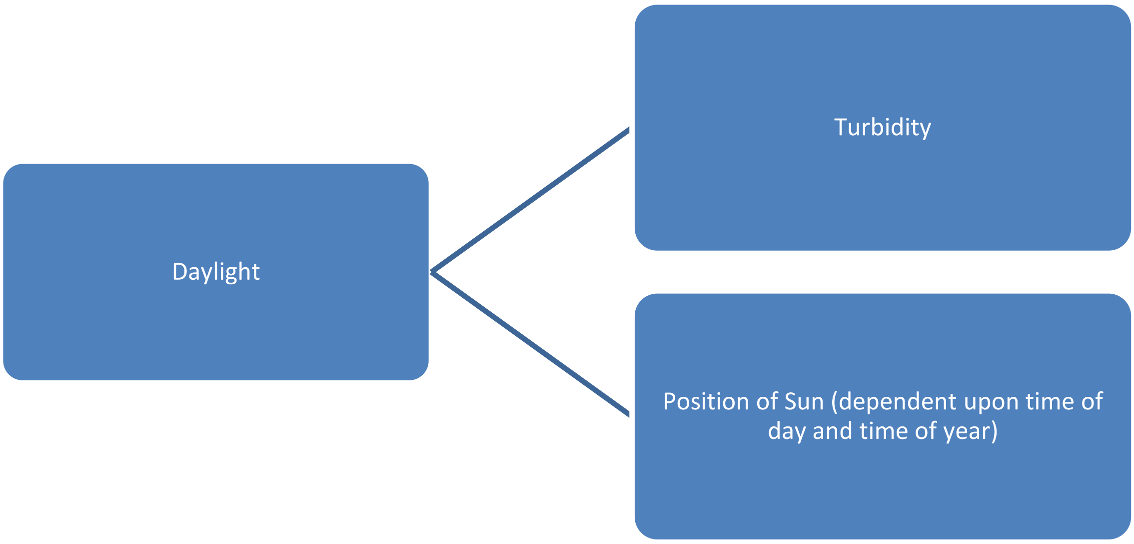

Figure 8.14 Flowchart showing the variables associated with the use of LuxRender daylight simulation.

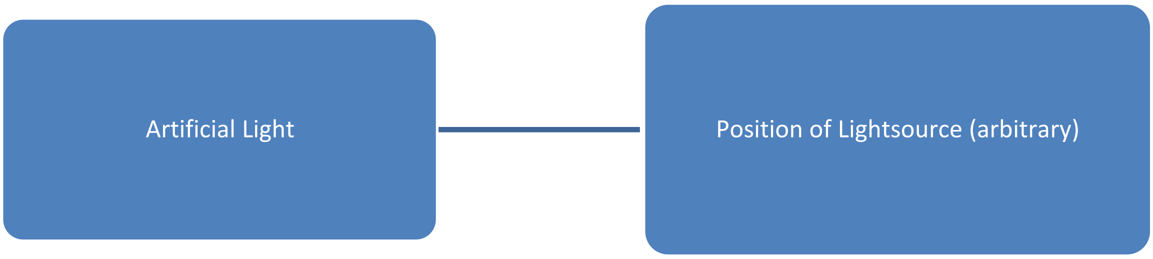

Figure 8.15 Flowchart showing the variables associated with the use of a simulated oil lamp.

8.3 Rendering

8.3.1 Renderers

A combination of renderers was used throughout the rendering process. As will be described in the *8.5 Visualisation and Analytical Techniques* section below, images played several roles in the interpretive and analytical stages of the research. The need to choose appropriate rendering solutions based upon the specific task has been dealt with in detail in Chapter 5 (Physically Accurate Computer Graphics). A description of rendering technologies can also be found in Chapter 5.

The modelling process within mental ray was utilised. mental ray is a ray tracing colourspace renderer with photon mapping implemented as a plugin within 3Ds Max. The benefits of choosing mental ray lay in its efficiency. Images could be quickly rendered during the modelling process and provided an acceptable approximation of the final output image which would be produced with LuxRender. The high rendering speeds were an essential consideration at this stage test renders were made following and change to objects within the model. The number of test renders made it imperative that times were kept low. The average rendering time for an image using mental ray was approximately 2 minutes.

All production renders were produced using LuxRender; a physically correct, path tracing spectral renderer implemented as a plugin within 3Ds Max. LuxRender was chosen for production rendering because it is a spectral renderer with a wide variety of appropriate shaders built in which can be adapted in order to represent the materials required within the scene. It was not feasible to use LuxRender to produce all of the test renders due to the fact that the average rendering time was approximately 1440 minutes.

8.4 Verification of Results

The verification of the simulation is of central importance to this methodology. Many of the methods used to reproduce the surface properties of materials within the scene were based upon estimated values and consequently it is essential that these approximated results were compared to reliable experimentally derived data in order to ensure the accuracy of the simulation process and the resulting images. The results of all verification experiments are presented in Chapter 9 (Results I).

8.4.1 Verification of Colour

The verification of rendered images against photographic counterparts constitutes one of the most important elements of the research in terms of ensuring the reliability of the simulation process and of the enterprise more generally. This process, as has been mentioned, has taken place at every stage of the reconstruction process in order to ensure the reliability of each material to be reconstructed.

In order to ensure accurate colour reproduction, corresponding renders and colour calibrated photographic images were produced. The rendered image resembled the photograph in terms of camera position, field of view, light position and light level. In order to simplify this process the photographic images used were, where possible, taken from unprocessed RTI datasets. The benefit of using photographic data from this source is that the camera position, light position and light characteristics are all known, additional ambient light is excluded from the scene.

A method for the production of images which correspond precisely to RTI captures of the original object has been developed by the author and colleagues at the Archaeological Computing Research Group at the University of Southampton and will be employed here (Earl, Beale et al. 2010).

Following this process of image production, specific sampled colour values from within each image were compared directly, allowing for a quantitative comparison of colour values between a photographic and rendered image. The resulting data are presented in tabular form in Table 9.1 in order to provide an objective comparison of the correspondence between the physical behaviour of the original surface compared to the simulated surface. This technique of verification is applicable to any object which can be recorded using RTI recording methods.

8.4.2 Verification of Reflectance

The verification process outlined above can be extended to include the photographic capture/rendering of the object from several different angles.

The addition of multiple directions of view as well as multiple light positions to the process provides sufficient data to assess the accuracy of the BRDF as a record of the behaviour of a surface.

As well as the quantitative comparison of single sample values, results can also be compiled into PTM visualisations, allowing an interactive, though subjective comparison of the photographic record to the rendered reproduction. Assuming that the setup is exactly the same in terms of light type, light positions, dome size, and also relative position of object and PTM rig, the results should be indistinguishable. Any differences between these results must be attributed to inaccuracies in the simulation process.

This approach was used to observe the reflective characteristics of the painted and unpainted areas of the marble sample. These measurements are presented in Table 9.2. It was not possible to measure every pixel and so pixels were chosen at random across the surface of the sample. The locations of these samples are illustrated in Figure 9.2.

It should be noted that while the PTM process is repeatable (and reliable) it is a process of interpolation. Consequently the comparison of PTMs should not be considered as entirely equivalent to the comparison of still (non-interpolated) images (Malzbender, Gelb et al. 2001). Nonetheless, if treated appropriately, PTM imagery may be used for both observational and statistical comparison.

8.4.3 Verification of Subsurface Scattering

The simulations were reliant upon subsurface scattering data captured as part of other research projects. As discussed in Chapter 5 (Physically Accurate Computer Graphics), the resource requirements of capturing the necessary absorption and scattering coefficients required to accurately specify the subsurface scattering characteristics of a material were beyond the scope of this research. However, an abundance of relevant data relating to marble allowed accurate estimates of the subsurface scattering of materials to be made.

In order for these results to be considered accurate though it was imperative that the rendered outputs were ground-truthed against photographically derived data. The verification method proposed here was a contact technique and so consequently could only be applied to those surfaces deemed sufficiently durable (physically and in terms of exposure to light) that such an analysis can be justified. Consequently, for the statue itself a sample of stone (described above in section *8.2.1.2 Material: Stone*, sub-section *Subsurface Scattering*) was used in place of the actual statue. Proxy objects were also used for wall paintings while marble floors were captured on site.

A controlled light source of known luminance characteristics, in this case a white LED, as recommended by Weyrich, Matusik et al. for use in a similar context, was applied to a surface (2006). The light source was sealed against the surface so as to ensure that all visible light emitted from the light source has travelled through the object. No additional light was admitted to the scene. The object was then photographed with a single lens reflex camera from a known camera position immediately above the object. The object could also be photographed from other known positions if appropriate (depending on the nature of the geometry).

The photographic results could then be compared to rendered images equivalent in terms of camera position, exposure settings, light position, geometry and luminance of light source, resolution and aspect ratio. This allows a direct comparison of falloff and intensity. The photographic image could be subtracted from the render providing a representation of difference which constitutes an accurate indicator of the extent to which the subsurface scattering algorithm is effectively simulating the physical process.

The mode of visual inspection which this method affords limits the extent to which this method can be used to quantify difference (in anything other than relative terms) and limits the use of this technique as a means of refining the settings of the subsurface scattering shader. However, it provides an accurate means of ensuring that estimated values are close to those exhibited by the actual material and provides an accurate method of assessing the relative accuracy of different approximations

8.5 Visualisation and Analytical Techniques

Previous sections of the methodology have dealt with the construction and execution of the simulation and rendering process. The following section will describe the production of the results of the research. There are two parts to the results section. The first part demonstrates that a simulation of a statue which incorporates all available data can function as an accurate and reliable means of testing hypotheses. The success of the simulation in empirical terms is demonstrated through the use of tests which are outlined in detail in the *8.4 Verification of Results* section above. The results of these tests are presented in the first part of the section *9.1 Verification of Results* in Chapter 9 (Results I).

The accuracy of the simulation having been demonstrated, the second part of the results (Chapter 10 – Results II) is the visual communication of the results of the simulation.

The following section describes the way in which these images were compiled into a glossy book and explains how this volume was produced. A more thorough theoretical account of the book and its content is provided in the place holder for Chapter 10 within this thesis.

Having decided upon a visual approach to the communication of the observations made from the simulation it was necessary to decide what form these images would take and how they would be presented. It is important to recognise that the production of images is not a passive process. It was necessary to take broad spectrum numerical descriptions of light and to transpose these data into a visual form. While advanced screen media (as described in section *5.5 Display* of Chapter 5 (Physically Accurate Computer Graphics) are capable of representing a wide spectrum of light data, it was decided instead to rely upon traditional print media.

Print has the benefit of being accessible (no additional hardware are necessary) and tactile. The production of a physical object meant that a wide range of physical possibilities were available with which to contextualise the images. The composition and presentation of the images were used to influence the message which an image conveyed and to situate it within a broader narrative arc.

The transposition of the spectral data into a visible form was undertaken using a physically accurate photographic simulation. A virtual camera was assembled with the same physical characteristics as a medium format camera with an 80mm lens loaded with 120 format Kodak Gold 200 film or Ilford Delta 400 black and white.

The use of a photographic metaphor constitutes a statement that the images are not of an object of antiquity but of something inherently modern. This statement is reinforced by presenting the images within a portfolio style volume. The volume is intended to loosely resemble an exhibition catalogue. The use of this stylistic convention is intended to emphasise to the viewer that these images are of something current and extant and that they are not anachronistic photographs of objects pre-dating photographic technology.

The decision to print has the additional benefit that it allows very quick and straightforward colour control to take place. Every version is identical and is not subject to the variable effects of display devices.

Prior to printing, all images were mapped to the Adobe 1998 colour space in order to achieve a predictable and consistent transition between RGB and CMYK colour space. This is necessary in order to convert images from an additive colour space (commonly used for images intended to be displayed using screen media) to a subtractive colour space (necessary for the creation of reliable, consistent prints). Test samples with a palette of colours present in the final volume were printed by the publisher. The page layout files were then colour calibrated according to these prints in order to mitigate against the distortions implicit within the transition between additive and subtractive colour space and within the printing process.

8.5.1 Layout and the Presentation of Metadata

Metadata exists for each rendered image. The metadata describe the content of each image and ensure that the images are reproducible. The metadata for each of the images which feature in Chapter 10 (Results II) are reproduced in the rear of the volume. Some of these metadata (numbers 1-7 in the list below) describe the variables which were systematically explored within this research. These are represented using a flow chart as outlined in this chapter. The specific structure of the flow chart is detailed throughout this chapter. The specific options available for each variable are detailed in the text and represented in Figures 8.3,4,5,13,14 & 15. Other variables are also listed in the metadata for each image, these variables were altered freely in order to produce the desired visual effect. These are numbered 8-9 below. The following metadata fields will be used:

1. Statue 3D Data (see Figure 8.3-4)
2. Architectural Scenario (see Figure 8.13)
3. Pigment Hypothesis (see Figure 8.5)
4. Light Type (e.g. sun, oil Lamp)
5. Turbidity (Only if lit with Daylight, see Figure 8.14)
6. Position of Sun/Time of Day (Only if lit with Daylight, see Figure 8.14)
7. Light Position (Only if Artificial Light, see Figure 8.15)
8. Camera Location within Architectural Scenario (plan showing position)
9. Camera Settings (shutter speed, aperture, lens)

It was decided not to include these fields within the volume but instead to present necessary metadata in the form of descriptive captions.

8.5.2 Selection of Images to be Rendered

Images will be rendered according to a systematic exploration of variables outlined above with all possible alternatives being rendered. Not all of these images have been included within the book. The book is not intended to offer an exhaustive exploration of variables, but is designed instead to offer a representative insight into the impact which the variables have upon the appearance of the statue. Images were selected in order to illustrate a narrative which was developed in response to observations made of the entire image set. This narrative will be clearly expressed within the publication.

8.6 Documentation of Research

Documentation takes two forms. The first form of documentation, outlined above is the metadata which accompanies the images. The second form of documentation is the thesis itself. This thesis describes the project in detail, including descriptions of the aims and objectives of the research, theoretical approaches and assumptions and methodological approaches to the processing, visualisation and dissemination of data. The thesis also contains a detailed account of all data employed within the research.

Chapter 9

9 Results I

9.1 Introduction

The character of a computer generated image is defined by more than appearance. Two images which appear to be equally realistic or comparable may have different origins and may have been produced using entirely different processes. Computer graphics have the capacity to be 'photorealistic' and yet the epistemic value of a photograph is fundamentally different to that of a digitally synthesised image. While neither can claim to offer an unambiguous representation of reality, their relationships with the world and with the objects and energy which they depict differ greatly.

The purpose of this chapter is to provide the viewer with all of the information necessary in order to critically engage with the images. Established approaches to computer graphical representation have tended to emphasise realism, photorealism or notions of immersion, in order to describe the character of the computer generated image. These descriptions have had the effect of obscuring the relationship between images and the information or ideas upon which they are based.

This chapter is an attempt to expose these relationships. The information presented is sufficient to provide the reader with the means of critically engaging with the images presented in the Chapter 10 (Results II). Rather than simply suspending disbelief, or pretending that these are photographs because of the way in which they are presented, the viewer is invited to participate in the criticism of these images, to respond to them and to accept them for what they are.

9.2 Verification of Results

There are two points of potential inaccuracy within the simulation process. The first of these relates to the potential for disparity between the characteristics of proxy objects (or secondary data) and of the actual object depicted within the simulation. An example of this is the potential difference between the statue and the marble sample; the proxy object from which many of the measurements of surface properties were taken. The second source of potential inaccuracy arises from potential disparities between a data source (e.g. the marble sample) and the results of the simulation.

The verification process described here will address the latter. It will demonstrate the degree of accuracy with which the simulation has successfully reproduced the physical characteristics of the objects from which input data were derived. The former type of potential inaccuracy is dealt with in the description of the purpose and nature of supplementary data sources presented in the *6.3 Supplementary Data Capture* section of Chapter 6 (Methodology I).

Typically, physically accurate simulations of cultural heritage objects have tended to rely upon visual comparisons between photographs and rendered images in order to assess the level of accuracy which has been achieved during the data capture, modelling and rendering processes. While this technique is effective in providing a crude comparison between a representation of the original scene and a representation of the simulated scene it is limited in several ways. Firstly, and most significantly, this technique only allows a subjective qualitative judgement to be made. The viewer is reliant upon a visual impression to make an assessment of sameness. Secondly, it is not possible through a visual inspection of representations of this type to isolate or to inspect the accuracy with which individual variables have been simulated.

The function of the verification process, and of this chapter, is to provide a means of ensuring and demonstrating the reliability of the simulation process. Rather than comparing complex rendered images to identically staged photographs, the verification process has produced simple quantitative and visual representations which isolate specific variables and allows them to be compared directly to the same phenomenon as it occurs in the real world. This allows for the observation and comparison of specific variables, such as colour or subsurface scattering. Consequently the viewer will have a far more intimate understanding of the images presented in Chapter 10 (Results II) and how they are constructed.

A detailed description of all experimentally derived data can be found Chapter 7 (Experimentally Derived Data). The manner by which these data were adapted for and incorporated into the simulation is described in Chapter 8 (Methodology II). Chapter 8 also describes the verification processes, the results of which are described here. The following chapter is broken down into discrete sections relating to different objects which featured within the simulation.

9.3 The Statue

9.3.1 Colour

The colour of the surface of the statue in the simulation was defined using data taken from a painted sample of marble (see section *6.3.2 Surface Recording* in Chapter 6: Methodology I, for a description of this object and the hypothetical reconstruction of the paint). RGB measurements taken from colour calibrated digital photographs of the marble sample are compared here to RGB values taken from a colour calibrated render of a virtual version of the same object (see Figure 9.1). Six areas were chosen for comparison across the object (see Figure 9.2).

As the images were not created using the same device it was not possible to conduct a direct pixel by pixel comparison of colour values. To address this problem, each image was divided into 4x4 pixel sectors. The mean RGB value of each sector was calculated. This avoided the need for precise pixel correlation. The sector which was measured in each case is indicated in Figure 9.2 and the results are presented in Table 9.1 and 9.2.

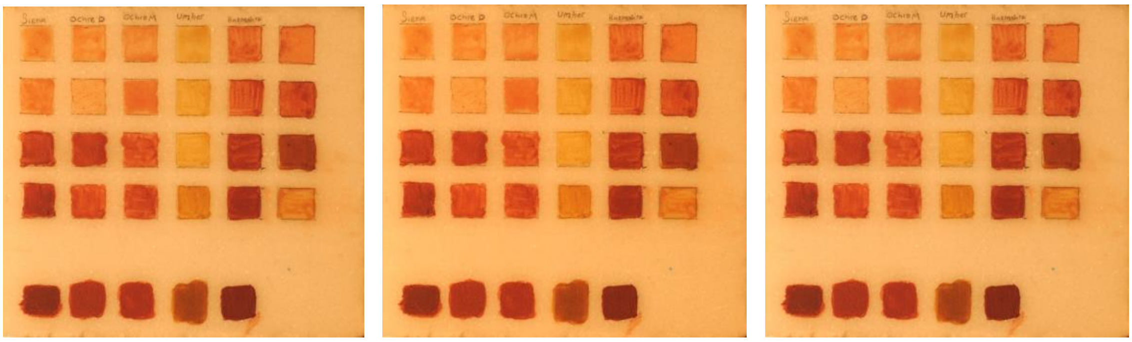

Figure 9.1 (Left) A photograph of the experimentally painted marble sample (photograph author's own)(Middle) A Photograph of the painted marble sample following the application of beeswax (Right) A rendered image (image author's own).

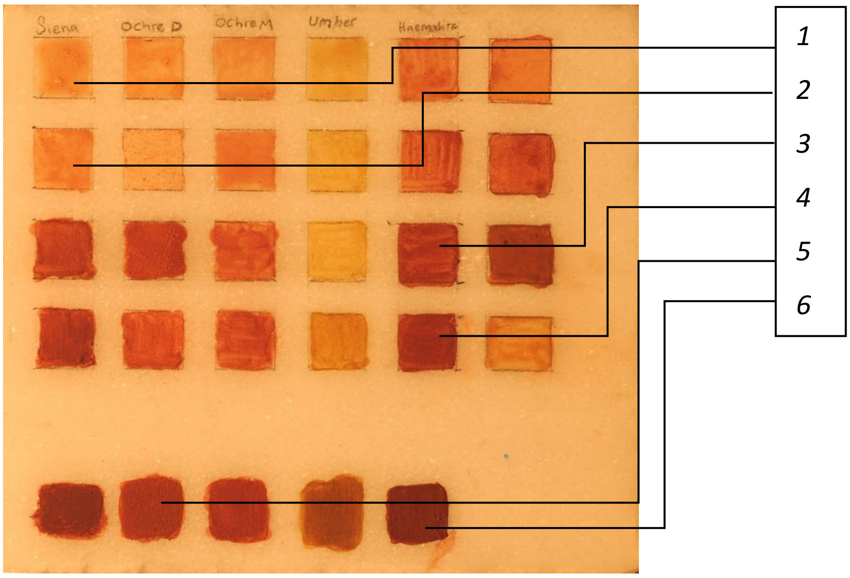

Figure 9.2, A Diagram showing each of the sectors of the marble sample which were compared. 1 - Lowest concentration sienna paint, 2 - Second lowest concentration sienna paint, 3 - Second highest concentration haematite paint, 4 - Highest concentration haematite paint, 5 - Double painted dark ochre, 6 - Double painted haematite

Sector ID	Angle of View	Sector Description	RGB in Photograph	RGB in Rendered Image	Colour Sample	
					Photo-graph	Render
1	90˚	Sienna – 1	241, 133, 42	249,151,60		
2	90˚	Sienna – 2	243, 118, 38	242,119,41		
3	90˚	Haematite – 3	162,42,18	159,49,22		
4	90˚	Haematite – 4	150,48,23	141,39,17		
5	90˚	Dark Ochre D	159,59,34	148,43,21		
6	90˚	Umber D	164,67,25	170,75,27		

Table 9.1 An RGB comparison of each sector before wax has been added when measured at 90˚. The colour swatches in the columns to the right allow an approximate visual comparison.

Sector ID	Angle of View	Sector Description	RGB in Photograph	RGB in Rendered Image	Colour Sample	
					Photo-graph	Render
1	90˚	Sienna - 1	239,128,40	250,149,58		
2	90˚	Sienna - 2	242,115,37	241,121,42		
3	90˚	Haematite - 3	162,42,22	159,47,20		
4	90˚	Haematite - 4	155,44,24	140,41,14		
5	90˚	DarkOchre D	161,40,32	146,42,20		
6	90˚	Umber D	163,66,24	172,74,25		

Table 9.2 An RGB comparison of each sector after wax has been added when measured at 90˚. The colour swatches in the columns to the right allow an approximate visual comparison.

9.3.2 Reflection Distribution

The reflective characteristics of the marble sample were verified against the rendered data using the same technique as outlined above. In this case however the comparison is made at two additional angles of view, at 90 degrees to the object (as above), at 60 degrees to the object, and at 30 degrees to the object. The light position remains fixed at all times. The purpose of these comparisons is to monitor change in the reflective characteristics of the object surface at different angles of view (see Table 9.2 for results).

Sector ID	Angle of View	Sector Description	RGB in Photograph	RGB in Rendered Image	Colour Sample	
					Photo-graph	Render
1	30˚	Sienna -1	243,139,42	244,136,45		
2	30˚	Sienna -2	242,121,40	244,119,39		
3	30˚	Haematite-3	177,50,18	185,55,31		
4	30˚	Haematite-4	162,54,28	168,49,27		
5	30˚	DarkOchre D	177,56,29	173,53,29		
6	30˚	Umber D	166,63,22	167,64,23		
7	60˚	Sienna-1	230,115,32	238,117,34		
8	60˚	Sienna -2	247,121,44	245,127,40		
9	60˚	Haematite-3	206,78,43	215,82,37		
10	60˚	Haematite-4	161,51,28	160,43,23		
11	60˚	DarkOchre D	171,51,26	176,60,35		
12	60˚	Umber D	158,60,23	152,55,20		

Table 9.3 An RGB comparison of each sector before wax was applied when measured at 60˚ and 30˚. The colour swatches in the columns to the right allow an approximate visual comparison.

Sector ID	Angle of View	Sector Description	RGB in Photograph	RGB in Rendered Image	Colour Sample	
					Photo-graph	Render
1	30˚	Sienna -1	247,135,40	247,133,47		
2	30˚	Sienna -2	240,124,39	248,118,41		
3	30˚	Haematite-3	175,50,21	190,51,31		
4	30˚	Haematite-4	160,52,31	167,51,25		
5	30˚	DarkOchre D	173,57,30	173,54,27		
6	30˚	Umber D	163,64,22	165,63,21		
7	60˚	Sienna-1	228,113,30	236,115,33		
8	60˚	Sienna -2	245,119,42	243,125,38		
9	60˚	Haematite-3	203,77,42	213,81,34		
10	60˚	Haematite-4	160,45,18	159,42,21		
11	60˚	DarkOchre D	169,53,29	173,50,33		
12	60˚	Umber D	158,62,24	152,49,21		

Table 9.4 An RGB comparison of each sector after wax has been applied when measured at 60˚ and 30˚. The colour swatches in the columns to the right allow an approximate visual comparison.

9.3.3 Subsurface Scattering

Unlike the colour data which are compared in the verification tests outlined above, the subsurface scattering properties of the marble were estimated using data acquired from an external source. Consequently the verification process was particularly significant in ascertaining the suitability of these estimated values for the purposes of this simulation. The rendered images, based upon these externally acquired data, were compared with photographs of the marble sample object. An LED light source was applied to the obverse (painted) side of the marble. The penetration and diffusion of light through the marble was measured by photographing the reverse side under controlled conditions. The object, lighting conditions and camera settings were replicated and a light simulation was run. The simulated result was then subtracted from the photographic result in order to achieve a measure of difference. This test was conducted in two areas, one painted and the other unpainted. The results are presented below in Figure 9.3 and Figure 9.4.

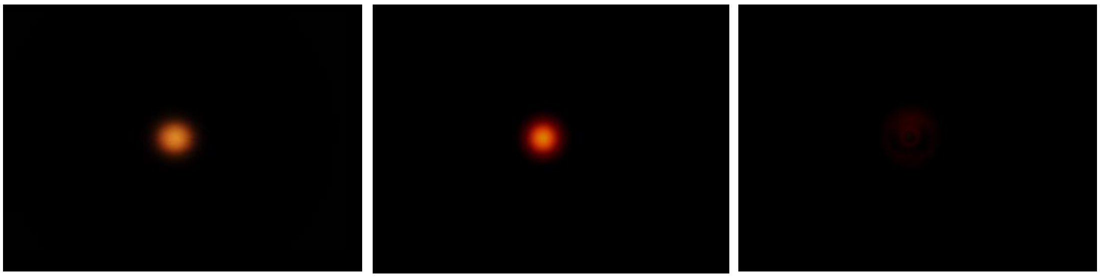

Figure 9.3 (Left) Photograph of LED light penetrating plain marble (Middle) simulated photograph of LED light penetrating plain marble (Right) the image in the middle subtracted from the left hand image (images authors own).

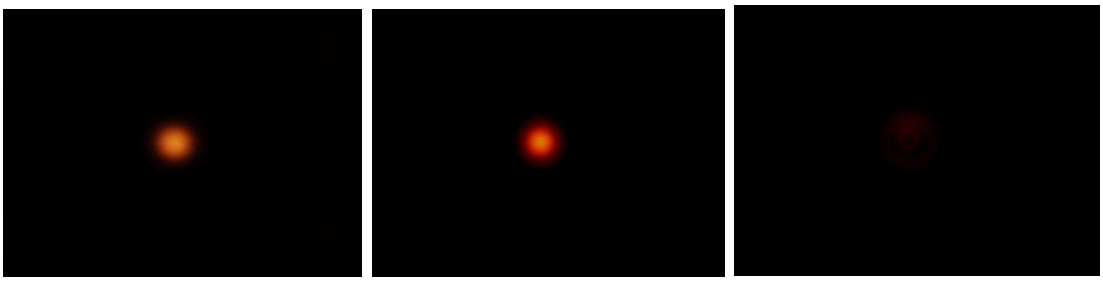

Figure 9.4 (Left) Photograph of LED light penetrating painted marble (Middle) simulated photograph of LED light penetrating painted marble (Right) the image in the middle subtracted from the left hand image (images author's own).

9.4 Architecture

Samples of each material in the simulation were tested using the same technique used to test the reproduction of colour and reflective characteristics of the statue (see Table 9.3).

Sector ID	Angle of View	Sector Description	RGB in Photograph	RGB in Rendered Image	Colour Sample	
					Photo-graph	Render
1	30˚	Blue Wall 1	77,86,93	72,82,89		
2	60˚	Blue Wall 1	80,89,98	79,82,89		
3	90˚	Blue Wall 1	89,96,104	87,90,95		
4	30˚	Red Wall 1	129,43,28	131,43,29		
5	60˚	Red Wall 1	135,54,44	142,54,40		
6	90˚	Red Wall 1	145,53,40	144,55,41		
7	30˚	White Mosaic	159,167,178	161,173,180		
8	60˚	White Mosaic	160,162,175	161,162,179		
9	90˚	White Mosaic	167,171,180	170,172,180		
10	30˚	Marble Floor	79,96,122	79,94,124		
11	60˚	Marble Floor	77,98,120	78,97,126		
12	90˚	Marble Floor	80,96,125	82,97,130		

Table 9.5 Results of testing for reproduction of colour and reflective characteristics of materials from the buildings. The colour swatches in the columns to the right allow an approximate visual comparison.

Chapter 10

10 Results II: Notes on the Accompanying Book

Instead of a conventional results section, the results of this thesis are presented within a separate printed volume. The volume presents a collection of images produced using the methodology described in this thesis. Rather than presenting these images within the context of a conventional academic publication they have been incorporated into a book featuring simulated photographs of the statue.

The publication echoes some of the conventions of an exhibition catalogue or collection of artist's work. It makes use of bold and unconventional layouts in order to focus attention on the images. A major motivation for presenting the images in this way is to emphasise the centrality of images and to overcome the subservient role which images often have to text within conventional archaeological publication. Within this publication the emphasis is placed upon the communicative power of the images rather than text.

The presentation of the images within a glossy printed publication is also significant because it emphasises the tactile and not just the visual aspects of engagement. This is intended to give the presentation of the images a performative dimension. The unconventional, even playful, nature of the presentational style encourages the viewer to critically engage with the images and with the book as a whole as an irregular artefact which requires interpretation.

The images presented in the book were produced using a set of skills closely aligned to conventional photography. The complexity of the photographic simulation within the renderer used allows the image maker to use all of the settings (explore times, lenses, aperture values etc.) which a photographer would use to compose and balance the colour with a photograph. The complete imposition of a photographic metaphor forced careful consideration of the subject and the ways in which different aspects of the statue could be highlighted. The virtual camera was built to behave like a medium format camera with an 80mm lens loaded with 120 format Kodak Gold 200 film or Ilford Delta 400 black and white. These settings were chosen because they mirror a real world camera with which the author is familiar. Building a virtual camera in this way imposed constraints upon the image making process which would not have been present if the photographic simulation had been only partially enforced. It also enables the image maker to think in a more tactile and spatial way about the images which were being produced.

It is important to recognise that this volume represents only one possible response to the archaeological process upon which it is based. Using different rendering algorithms and different modes of image reproduction it would be possible to produce a vast range of visual outputs from the same simulation. Regardless of the images which are produced the reliability and validity of the simulation process remains unaffected. This publication serves therefore as a demonstration of the versatility of archaeological computer graphics as a medium of expression and communication.

10.1 The Photographic Metaphor

Conceptually and mathematically all images in the results were produced using a photographic metaphor. The photographic metaphor begins with a simulation of photographic technology in order to visualise the results of the simulation but it also has profound implications on the way in which the images will eventually be perceived by viewers.

A simulation of light has no inherent visual characteristics. In addition to simulating the movement of light around a scene it is necessary (assuming that visual outputs are desired) to simulate some mechanism with which to convert these light calculations into visual content. Traditional approaches to virtual reality which aim to produce an immersive experience would, in an ideal scenario, produce visual content which is akin to that which would be experienced in the physical world. The user, in order to have a believable experience, would need to be exposed to a very wide spectrum of light at a wide range of luminosity which would enable their visual system to react as naturally as possible. It is the desire to achieve this level of immediacy and realism which has driven the development of technologies such as HDR screens as discussed in Chapter 5 (Physically Accurate Computer Graphics). This simulation of the human visual system has implications on the ontological status of the viewer. The viewer is invited to believe that they are interacting with the virtual world just as they might interact with the real world. It is upon this assumption that virtual reality applications were built.

Rather than simulating the human visual system, the results here use a simulation of photography. Rather than converting the light simulation into the broad spectrum of light needed to simulate human perception of the real world, the photographic simulation instead converts the results of the simulation into a narrower band of light which can be represented using conventional modes of image reproduction. Clearly this has practical benefits; viewers do not need specialist devices in order to access these images as they are intended to be seen. However, there are also significant conceptual benefits to using a simulation of photography. Rather than being immersive, the photographic metaphor allows the viewer to conceptualise the image with which they are engaging as something external. They are invited to see this as they would any other photograph.

This makes a firm statement that the viewer is outside of the virtual. This statement is reinforced by the use of print as the mode of reproduction. The viewer has a tangible object with which they can engage. The printed image is the end result of a highly accurate and carefully controlled process. All metadata including information relating to the data included within the simulation, relating to the simulation itself and relating to the simulated camera settings are provided alongside the image. Consequently, the image which the viewer is holding is a tangible extension of the virtual into physical space. A hybrid object produced using the same technology as a conventional photograph.

Chapter 11

11 Conclusion

In addressing the research question, a number of issues have been confronted within this thesis. In order to reflect this, the concluding remarks address each of the areas in turn. The chapter begins with an assessment of the contribution that the development of the methodology presented here has made to the potential future use of physically accurate computer graphics as archaeological tools. There then follows a discussion of the theoretical approach towards images which has been taken within this thesis. This chapter considers potential areas for development in the mediation and creative engagement with computer generated archaeological images.

Most significantly, the conclusions address the issue of sculptural polychromy and the insights which have been gained through the use of this technique. This assessment incorporates comments and observations made by a panel of experts who were asked to respond to the images which feature in Chapter 10 (Results II). Finally the chapter discusses future directions for work in this field.

11.1 The Methodology: A Critical Assessment

A primary goal of the methodology presented within this thesis was to assess the potential value of physically accurate computer graphics as archaeological tools. Carrying out such an assessment required two different criteria to be taken into account. Firstly, it was necessary to consider the extent to which state of the art computer graphics technologies offer a useful archaeological tool. Secondly, it was necessary to consider the extent to which state of the art computer graphics methodologies can be realistically expected to be implemented within the context of research Archaeology. The first question has the most profound impact upon the future of computer graphics as archaeological tools but the implications of the second question are more pressing and more immediate. Whether or not the techniques described here offer a theoretical opportunity to Archaeology it is important to know whether or not they can be implemented with the resources and skill base commonly available within the field of archaeological research.

The methodology implemented here was shown by the results presented in Chapter 9 (Results I) to offer a reliable and accurate representation of the data inputted into the simulation. From these data, it is reasonable to suggest that a methodology similar to the one presented in this thesis offers an opportunity for archaeological researchers to produce images which are based upon physically accurate models of light and reflection.

The methodology presented here offers significant departures from the highly rigorous Predictive Rendering methodology developed by Wilkie et al. (2009). Nonetheless, the methodology is reliable and transparent. As Wilkie et al. state in their description of the methodology, the applications in which a full predictive rendering methodology are required are relatively few in number (ibid.). Archaeology starts at a disadvantage in the sense that a lot of the data which would be required in order to accurately simulate an object with total certainty have generally been lost. Consequently, the value and potential of computer graphics for Archaeology lays in the exploration of these absent data. These techniques have provided a means of exploring the gaps which these data have left in our understanding of these objects and hypothetically filling these holes with data produced in other ways according to informed hypotheses.

11.1.1 Methodological Adaption

The adaption of physically accurate computer graphics for use within an archaeological context has been driven by two sets of constraints. The first set of constraints related to the need to produce a methodology which could reasonably be expected to be reproduced outside of a dedicated Computer Science research centre. The second set of constraints related to the positive adaptation of physically accurate computer graphics methodologies to be useful and appropriate within the specific disciplinary requirements of archaeological research.

Limitations in resources and training mean that very few archaeologists have access to the technology or skill to implement the kind of methodological approach which Wilkie et al. describe (ibid.). A goal of this thesis has been to produce a methodological foundation for ongoing work within Archaeology and so whilst it was necessary that this work take a leading role in the application of new technology within the field of Archaeological Computing it was also important to introduce methodological processes which would be usable within Archaeology during the timeframe that the technological components of the thesis remained up to date.

Consequently, rather than relying upon data capture using specialist or experimental equipment the methodology incorporated a rigorous process of validating the results of simulations. This decision enabled the use of generic data and shading models and demonstrated that reliable computer graphical simulation could be undertaken using simple processes and technologies which are available to the vast majority of research archaeologists. Similarly LuxRender, the renderer used in the production of all of the final images, is open source and free to download and so the methodology can be replicated entirely using free and open source technology.

The methodology was designed in order to reflect the unique constraints and demands of the archaeological research process. The use of supplementary data sources to capture reflectance and geometric data reflected the fact that archaeological objects are often too fragile to be recorded, particularly if using techniques which require surface contact. The use of these data sources and the thorough way in which their use has been documented, sets a precedent in archaeological computer graphics which, if followed will help to ensure that research in this area can be both valid and transparent.

11.1.2 Hypothetical Reconstruction

Placing hypothetical reconstruction at the centre of the methodology helped to ensure that the endemic uncertainty which surrounds both the object of study and the concept of sculptural polychromy drove the research process, rather than being marginalised as a distraction from the process of image making.

The ability to hypothetically reconstruct absent data proved to be one of the major benefits of using a physically accurate computer graphics methodology. The images which have resulted from the methodology provide insights into the range of possible interpretations of Roman sculptural polychromy which current data supports. Naturally, this diversity might be expected to be greater if the sample of statues studied were broadened.

One of the great methodological strengths of using physically accurate computer graphics lay in the time spent collecting data and assembling the 3D model within which the simulations were conducted. As discussed in Chapter 4 (3D Computer Graphics), the modelling process is highly complex and nuanced and familiarises the researcher with the data in a unique way. The creative approach to image production, discussed below, was largely developed in response to the need to express not only a set of definitive representations but also to express some of the observations which came about through this process.

11.1.3 Future Work

The major contribution of this research to archaeology has been the development of a computer graphics methodology which is of relevance and value to archaeological research. For several reasons however, the methodology presented here is only a foundation for ongoing research.

11.1.3.1 Adapting the Methodology for Different Case Studies

This methodology was designed specifically in order to contribute to the study of Roman sculptural polychromy. Therefore, the range of methods used, reflect the unique challenges of representing painted statuary. Considerations such as the layering of materials in order to represent pigments and the emphasis placed upon subsurface scattering within the methodology may not be equally relevant in the representation of different kinds of objects. Archaeological research involves the study of a broad range of objects. This diversity is significant for two reasons. Firstly, the questions asked by Archaeologists of archaeological objects differ from case to case. Some objects will benefit enormously from visualisation whereas others will not. Within the group of objects which might benefit from visualisation, the challenges of visualisation and the questions which the researcher may wish to ask will require the development of a unique methodology. The methodology presented here provides a useful point of departure for other methodologies which seek to represent complex archaeological objects.

11.1.3.2 Informing Future Methodologies

The nature of Computer Science is such that specific methods soon become obsolete. It is anticipated therefore that the theoretical components of this thesis, and the underlying principles of the methodology, will retain their relevance far longer than the specific techniques described. The primary methodological challenge to have arisen from this thesis is the need to maintain an awareness of technological innovation and to make sure that where possible improvements to this methodology are made. As mentioned above, this is an archaeological methodology both in the sense that it is designed to reflect the disciplinary requirements of Archaeology, but also in the sense that it has been designed only to incorporate technologies which archaeologists might realistically be expected to have access to. It is reasonable to suggest that many of the technologies and processes which Wilkie et al. describe in their predictive rendering methodology will be widely available within commercial and open source software in the near future (2009). Equally, data capture devices which have been the preserve of specialist researchers will soon be more readily accessible to archaeological researchers due to falling costs and improved usability. Consequently, further work in this area involves making sure that Archaeology makes use of these technologies as they become readily available. It is also important that Archaeology maintains an inquisitive attitude to the development of computer graphics and a resourceful approach to the development of methodological approaches.

11.2 Image Making

The decision to consider image making and the display of images as a process distinct from, yet related to, the processes of data capture, modelling and rendering which tend to characterise descriptions of computer graphical work in Archaeology was significant and fundamentally affected the character of this work.

The approach chosen was based upon a desire to communicate not only the results of the simulation but also something of the processes which led up to that point. It was also intended to de-stabilise existing pre-conceptions about archaeological computer graphics and consequently encourage people to critically engage with the images.

The decision to present the images in a distinct volume and to give them the form of photographs is described in the introduction to Chapter 10 (Results II) which is contained within the thesis.. However, this was one possible response and any number of alternative responses might have yielded very different outputs. Other methods of experimental visualisation were trialled before this medium was chosen and other avenues for visualisation will be pursued as part of this research ongoing (see Figure 11.1).

Figure 11.1 Alternative media might be used to reproduce archaeological computer graphics. In this case rendered images were screen printed. The variety of effects was quite different to that which might ordinarily be expected from computer graphics (photograph author's own).

11.2.1 Image Making: Further Work

Chapter 4 (3D Computer Graphics) concludes with a call for image makers in Archaeology who use computer graphics to think more creatively about the outputs which they produce. There is much to be gained by archaeological computer graphics makers of all kinds paying greater attention to the process of image making as a discreet creative area and considering the potential impact which different decisions might have upon the perception of their work.

The research here will continue with a multimedia exhibition to be held at the Museo Archeologico Virtuale in Herculaneum, the date of which is yet to be confirmed. The exhibition will use video, images, projection and 3D print to provide a range of alternative interactions with the project.

11.3 Contribution to Understandings of Painted Statuary

The extent to which the development of this methodology and the presentation of the resulting images might contribute towards understandings of Roman painted statuary was a question which was answered in conjunction with a panel of experts. Their responses to the images helped to inform the following section and were particularly valuable in helping to develop a plan for future work in this area. The panel was made up of two specialists in the practical reconstruction of polychrome sculpture (Specialists A & B), a specialist in the technical analysis of coloured ancient sculpture (Specialist C) and an expert in the archaeology of Herculaneum (Specialist D) and an expert in the study of the arrangement and display of Roman sculpture (Specialist E) .

The goal of the thesis was to produce representations of an example of Roman painted statuary which would contribute towards understandings of the phenomenon of statue painting as a materially constituted, contextually dependent and temporally variable process.

The research has been successful in this goal in the sense that the resulting images accurately depict a range of hypotheses relating to the material composition of painted statuary. The panel were all eager to emphasise the importance of accuracy in the production of visualisations of this type and were pleased that it has had such a central role within the methodology of the thesis. One of the panel commented that;

> *"The characteristics of materials are very important, but difficult to show in any kind of copy. As long as hypothetic reconstructions are made with sensibility and the circumstances are explained, hypothetic reconstructions are meaningful, since they show what the work of art might have looked like."*
>
> - Specialist A

While another stated that:

"The level of accuracy is a sine qua non for simulations/visualisation of this kind. And: This kind of simulation is the only one which allows the incorporation of an archaeologically documented setting."

- Specialist C

This comment was an endorsement of the approach taken in the methodology and the emphasis placed upon accuracy and context. Experts were enthusiastic about the level of detail such as the use of texture and simulated brush strokes and were keen to emphasise the potential of the process of statue painting as a potential area for future research. To one panel member this level of detail offered the potential for future research in this field they observed that:

"The possibility of thus testing of hypotheses of surface texture in polychromy is of great interest, from the view of painterly techniques and intentions."

- Specialist A

This comment as well as comments from other panel members, some of which will be introduced below, helped to define the ongoing direction of this research through emphasising the importance of technique and intention on the part of those who made the statues.

Some of the panel members, highlighted the fact that the images were not photo-realistic and questioned what they felt to be a disparity between the objects and the resulting images. This disparity, which is evident in the images presented within Chapter 10 (Results II), reflects the emphasis of the methodology upon data-led physical accuracy and has been implemented at the expense of the apparent realism which may have been achieved through conventional computer graphics approaches. This was unavoidable within the context of this research methodology due to the current state of technology and the desire to use techniques and approaches which were compatible with foreseeable use within an archaeological context. In order to address this issue the methodology would have to be re-balanced towards the incorporation of a greater volume of hypothetical data. A specific critique in this area was a comment by Specialist D that the surface of the statue had a smoothness which was reminiscent of a plaster cast of a statue. The topography of this surface was defined by laser scan data, to have improved the level of detail would have relied upon the incorporation of 3D data derived using less accurate means. This kind of problem will, in time be resolved by the rapidly increasing resolution of 3D data capture technologies. For the foreseeable future there are the kinds of subjective choices which image makers must make in order to design a methodology appropriate to the research question.

11.3.1 Future Work

A number of future research directions have been identified for work conducted in this area. A comment which was often repeated by the panel of experts was that the research could be expanded to include other examples of statuary or other architectural scenarios. Panel members also highlighted specific areas in which the capture of larger quantities of data might be interesting from a research perspective. This would certainly be a natural extension to work of this type.

The expansion of this research to incorporate other examples of painted statuary is entirely feasible. The methodology is straight-forwardly transferable for use in the representation of any painted statue and could be used to represent painted statuary from other periods where similar techniques were used. The inclusion of more architectural scenarios is also entirely possible and would only require a period of data collection and modelling akin to that described in the methodology of this thesis.

In addition to identifying the potential value involved in increasing the scale of the project panel members also identified particular areas which would provide interesting grounds for future work. Two areas identified were the recording and representation of other sculptural marbles and the interpretation of statue painting practice. These areas are inter-related. One panel member made the following comment:

> *"Though it is still very early days, the results obtained within the framework of the [name omitted] project suggest that the crystalline structure of a marble, and the character of the final finish of the marble surfaces constitute a decisive interface with the painted polychromy applied to it. At least on 'high end' sculpture. One may think of the importance the quality of a canvas has for the latitude of effects available to a painter."*

- Specialist C

Only one marble material was modelled as part of this research. Its properties were based upon colour values collected specifically for this work. The subsurface scattering model however was based upon a piece of pre-existing computer science research (Jensen, Marschner et al. 2001). Its appropriateness was ensured through a process of validation against data collected directly from a marble sample. A useful extension to this research would be a dedicated research project to record the reflective characteristics of different examples of Roman sculptural marble and to assess the impact which marble type has upon the appearance of paint which has been applied to the surface of the material.

As highlighted by the panel member in the previous comment, the relationship between the work of the statue painter and the materials is a matter of great interest. The way in which statue painters in the Roman world worked is now largely unknown except through surviving examples of their work (Bradley 2009a; Brinkmann, Primavesi et al. 2010). This thesis has proved that physically accurate computer graphics have the capacity to allow a fuller understanding of how these materials would have interacted with each other and how they would have appeared when seen within different contexts. If combined with a fuller assessment of hypothetical painting styles and techniques this could offer great insight into the potential which these materials offered to Roman statue painters. One of the expert panel made the following comment:

> *"It is not just a matter of applying scientific methods on art – art has values that are not measurable but nevertheless understood and appreciated."*

- Specialist B

The sensitivity to the process of making and of the skill of the craftsperson resonates with the discussion of image making presented within this thesis and also to the collaborative relationship with Prof. Beth Harland, the tempera painting expert who has featured within this thesis. Discussions regarding the ability of the craftsperson to interpret the creative activities of past people are more complex and the incorporation of these ideas into further research would require a great deal of theoretical consideration (Gosden 2001; Budden 2007). It would however represent an interesting extension to this research and to other computer graphics research to begin to develop collaborations with craftspeople who have expertise in working with different materials and processes and to use this relationship to produce visualisations of archaeological objects informed by different sets of sensitivities and different conceptualisations of craft and skill.

Visualisation using physically accurate computer graphical approaches has the capacity to become a normal part of archaeological practice. Increasingly, developments in software mean that physically accurate approaches are supported within mainstream computer graphics software. The physically accurate renderer used in the work presented here (LuxRender) is described as a research renderer and is open source. This means that it is under constant development by researchers and amateur users and is available for free. The methodology presented here is built upon earlier work in Computer Science which sought to demonstrate the usefulness of these techniques in Archaeology (Martinez and Chalmers 2004; Sundstedt, Chalmers et al. 2004; Sundstedt, Gutierrez et al. 2005; Gutierrez, Sundstedt et al. 2007; Gutierrez, Sundstedt et al. 2008; Happa, Artusi et al. 2009; Happa, Williams et al. 2009). Taking these efforts as inspiration this thesis sought to adapt and develop these techniques so that they could be more effectively employed within an archaeological landscape. By developing a methodology which is usable by archaeologists and which is tailored to the theoretical demands of archaeological research it is hoped that this represents the first step towards an authentically archaeological response to physically accurate computer graphics.

Appendix A: Tabulated Spectral Data

Wavelength measurements of all materials measured with the photospectrometer sampled at 5nm intervals between 340-830nm

Wavelength	Pentelic Marble	Dark Ochre	Haemetite	Med Ochre 1	Med Ochre 2	Siena	Umber
340	0.6601	0.2048	0.2235	0.2566	0.7271	0.1903	0.1767
345	0.6601	0.2048	0.2235	0.2566	2.2813	0.1903	0.1767
350	0.6601	0.2048	0.2235	0.2566	0.8062	0.1903	0.1767
355	0.6601	0.2048	0.2235	0.2566	0.5630	0.1903	0.1767
360	0.6601	0.2048	0.2235	0.2566	0.4851	0.1903	0.1767
365	0.6601	0.2048	0.2235	0.2566	0.3733	0.1903	0.1767
370	0.6601	0.2048	0.2235	0.2566	0.1875	0.1903	0.1767
375	0.6601	0.2048	0.2235	0.3856	0.2012	0.1903	0.1767
380	0.6000	0.1134	0.1758	0.2017	0.1151	0.1125	0.1391
385	0.6226	0.1137	0.1880	0.2401	0.0986	0.1404	0.1021
390	0.6419	0.1238	0.1692	0.2506	0.0740	0.1426	0.1235
395	0.6337	0.1372	0.1756	0.2635	0.1062	0.1238	0.1205
400	0.6404	0.1286	0.1634	0.2664	0.0622	0.1255	0.1039
405	0.6418	0.1183	0.1768	0.2412	0.0754	0.1241	0.1158
410	0.6545	0.1179	0.1709	0.2428	0.0730	0.1194	0.1046
415	0.6530	0.1161	0.1628	0.2456	0.0685	0.1122	0.0958
420	0.6555	0.1134	0.1629	0.2521	0.0711	0.1162	0.0997
425	0.6593	0.1135	0.1631	0.2452	0.0692	0.1211	0.0973
430	0.6603	0.1120	0.1574	0.2424	0.0672	0.1166	0.0996
435	0.6657	0.1114	0.1605	0.2481	0.0647	0.1163	0.0955
440	0.6694	0.1112	0.1591	0.2454	0.0654	0.1149	0.0988
445	0.6692	0.1129	0.1584	0.2489	0.0626	0.1147	0.0985
450	0.6742	0.1090	0.1584	0.2461	0.0645	0.1147	0.1010
455	0.6774	0.1120	0.1595	0.2485	0.0680	0.1166	0.1035
460	0.6810	0.1107	0.1576	0.2486	0.0638	0.1143	0.1003
465	0.6827	0.1121	0.1609	0.2500	0.0637	0.1131	0.1004
470	0.6843	0.1104	0.1576	0.2467	0.0638	0.1142	0.0991
475	0.6842	0.1112	0.1581	0.2478	0.0626	0.1134	0.1001
480	0.6868	0.1115	0.1588	0.2509	0.0646	0.1134	0.1022
485	0.6884	0.1117	0.1578	0.2488	0.0644	0.1130	0.1006
490	0.6892	0.1118	0.1570	0.2502	0.0644	0.1156	0.1010
495	0.6915	0.1090	0.1564	0.2491	0.0640	0.1121	0.1021
500	0.6910	0.1114	0.1579	0.2535	0.0642	0.1138	0.1036
505	0.6934	0.1113	0.1575	0.2553	0.0639	0.1136	0.1056
510	0.6940	0.1110	0.1570	0.2568	0.0635	0.1132	0.1073
515	0.6950	0.1101	0.1576	0.2570	0.0635	0.1133	0.1109

Appendix A

Wavelength	Pentelic Marble	Dark Ochre	Haemetite	Med Ochre 1	Med Ochre 2	Siena	Umber
520	0.6955	0.1119	0.1575	0.2598	0.0641	0.1142	0.1150
525	0.6962	0.1136	0.1587	0.2639	0.0666	0.1147	0.1209
530	0.6975	0.1140	0.1582	0.2666	0.0662	0.1144	0.1253
535	0.6992	0.1152	0.1598	0.2708	0.0679	0.1160	0.1333
540	0.6996	0.1166	0.1600	0.2740	0.0690	0.1168	0.1400
545	0.6998	0.1181	0.1620	0.2789	0.0707	0.1181	0.1480
550	0.7009	0.1210	0.1630	0.2844	0.0725	0.1191	0.1564
555	0.6999	0.1239	0.1653	0.2901	0.0760	0.1211	0.1648
560	0.7008	0.1290	0.1691	0.2962	0.0798	0.1241	0.1732
565	0.7025	0.1340	0.1729	0.3013	0.0860	0.1276	0.1809
570	0.7028	0.1402	0.1773	0.3070	0.0922	0.1316	0.1871
575	0.7025	0.1481	0.1837	0.3134	0.1017	0.1369	0.1929
580	0.7021	0.1570	0.1916	0.3210	0.1126	0.1418	0.1985
585	0.7016	0.1677	0.2003	0.3303	0.1259	0.1494	0.2039
590	0.7017	0.1806	0.2102	0.3404	0.1417	0.1575	0.2091
595	0.7036	0.1949	0.2196	0.3516	0.1602	0.1664	0.2141
600	0.7038	0.2020	0.2213	0.3530	0.1715	0.1697	0.2149
605	0.7026	0.2101	0.2276	0.3587	0.1810	0.1760	0.2174
610	0.7024	0.2188	0.2327	0.3655	0.1913	0.1831	0.2202
615	0.6997	0.2273	0.2374	0.3716	0.2014	0.1896	0.2226
620	0.6981	0.2344	0.2378	0.3740	0.2120	0.1929	0.2251
625	0.6996	0.2425	0.2404	0.3802	0.2220	0.1988	0.2287
630	0.7015	0.2504	0.2433	0.3860	0.2303	0.2043	0.2322
635	0.7030	0.2566	0.2454	0.3912	0.2377	0.2098	0.2354
640	0.7045	0.2634	0.2483	0.3959	0.2457	0.2155	0.2391
645	0.7051	0.2694	0.2512	0.4002	0.2533	0.2216	0.2435
650	0.7039	0.2751	0.2533	0.4044	0.2598	0.2260	0.2470
655	0.7034	0.2814	0.2558	0.4107	0.2667	0.2309	0.2520
660	0.7028	0.2878	0.2581	0.4163	0.2734	0.2359	0.2565
665	0.7023	0.2946	0.2606	0.4228	0.2811	0.2414	0.2607
670	0.7024	0.3023	0.2644	0.4291	0.2887	0.2466	0.2671
675	0.7028	0.3090	0.2669	0.4348	0.2968	0.2520	0.2719
680	0.7036	0.3165	0.2699	0.4401	0.3058	0.2587	0.2781
685	0.7048	0.3242	0.2733	0.4454	0.3140	0.2652	0.2839
690	0.7059	0.3325	0.2768	0.4510	0.3232	0.2723	0.2907
695	0.7052	0.3406	0.2802	0.4569	0.3308	0.2785	0.2968
700	0.7047	0.3489	0.2843	0.4645	0.3391	0.2858	0.3043
705	0.7043	0.3577	0.2883	0.4725	0.3477	0.2922	0.3120
710	0.7042	0.3659	0.2924	0.4802	0.3558	0.2992	0.3200
715	0.7038	0.3733	0.2961	0.4880	0.3625	0.3052	0.3280
720	0.7042	0.3802	0.2998	0.4947	0.3694	0.3114	0.3360
725	0.7042	0.3860	0.3034	0.4999	0.3751	0.3167	0.3438

Wavelength	Pentelic Marble	Dark Ochre	Haemetite	Med Ochre 1	Med Ochre 2	Siena	Umber
730	0.7040	0.3901	0.3061	0.5052	0.3798	0.3211	0.3511
735	0.7047	0.3931	0.3081	0.5077	0.3838	0.3251	0.3582
740	0.7047	0.3946	0.3098	0.5111	0.3861	0.3277	0.3650
745	0.7045	0.3948	0.3110	0.5127	0.3877	0.3297	0.3711
750	0.7035	0.3938	0.3120	0.5157	0.3876	0.3302	0.3769
755	0.7026	0.3920	0.3118	0.5179	0.3864	0.3295	0.3818
760	0.7017	0.3890	0.3116	0.5191	0.3847	0.3275	0.3862
765	0.7009	0.3861	0.3112	0.5210	0.3824	0.3258	0.3901
770	0.7001	0.3825	0.3105	0.5233	0.3800	0.3237	0.3940
775	0.7001	0.3787	0.3100	0.5239	0.3769	0.3211	0.3968
780	0.6999	0.3742	0.3084	0.5234	0.3739	0.3178	0.3985
785	0.6993	0.3692	0.3068	0.5216	0.3702	0.3144	0.3995
790	0.6994	0.3652	0.3052	0.5200	0.3667	0.3114	0.4002
795	0.6989	0.3596	0.3029	0.5170	0.3631	0.3078	0.3996
800	0.6992	0.3551	0.3009	0.5143	0.3603	0.3045	0.3987
805	0.6987	0.3502	0.2987	0.5107	0.3570	0.3012	0.3975
810	0.6975	0.3460	0.2966	0.5078	0.3534	0.2976	0.3955
815	0.6963	0.3423	0.2945	0.5054	0.3504	0.2946	0.3937
820	0.6945	0.3384	0.2925	0.5046	0.3464	0.2917	0.3915
825	0.6935	0.3358	0.2913	0.5027	0.3445	0.2892	0.3893
830	0.6916	0.3332	0.2900	0.5018	0.3418	0.2869	0.3871

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