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# Accurate Modelling of Roman Lamps in Conimbriga using High Dynamic Range

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**Abstract**

*The Human Visual System has a remarkable ability to acquire colour and contrast of all the things that surround us. This is particularly evident in extreme lighting conditions such as bright light or dark environments. However, it is simply not possible to represent such a range of lighting on a typical display today. This is about to change. The field of High Dynamic Range (HDR) imagery allows us to capture and display the full range of human vision.*

*The use of technologies in the preservation and dissemination of cultural heritage can play an important role in the representation and interpretation of our past legacy. A major field of application is virtual reconstructions of ancient historical environments. In this domain, the way we see such (reconstructed) environments is particularly important in order to establish a correct interpretation of that historical setting.*

*In this paper we present a case study of the reconstruction of a Roman site. We generate HDR images of mosaics and frescoes from one of the most impressive monuments in the ruins of Conimbriga, Portugal, an ancient city of the Roman Empire. We show that the HDR viewing paradigm is well suited for archaeological interpretation, since its high contrast and chromaticity can disclose and present us an enhanced viewing experience, closer to how the artefacts may have been perceived in the past. To achieve the requisite level of precision, in addition to a precise geometric 3D model, it is crucial to integrate in the virtual simulation authentic physical data of the light used in the period under consideration. Thereby in order to create a realistic physical based environment we use in our lighting simulations real data obtained from Roman luminaries of that time.*

Categories and Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation - Display Algorithms; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - Virtual Reality; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - Color, Shading, Shadowing and Textures.

## 1. Introduction

In these last years, the number of projects involving historical reconstruction has increased significantly. The use of recent technologies has become a powerful tool to archaeologists for a better understanding of our cultural heritage legacy and thereby to attain a glimpse of the environments in which our ancestors lived. However, to accomplish such purpose, these reconstructions should be presented to us as they were really perceived by a local inhabitant, according to the illumination, materials used back then and, equally important, the characteristics of the Human Visual System (HVS).

The light captured by the human eye in a simple walk in the park on a sunny day, can accomplish a range of luminance and chromaticity truly extraordinary, but a major portion of this range can not be represented in typical display devices today. High Dynamic Range (HDR) is a computer graphics field of research that aims to correct such inaccuracy. In order to achieve such purpose new techniques have been developed to produce, store and visualize images and video that preserves the whole dynamic range captured by the HVS.

This paper presents a case study where we intend to employ this new viewing paradigm where it has significant potential, archaeological interpretation. The House of the Fountains, in the ruins of Conimbriga (Portugal), is a great Roman residential house whose original construction, dated from the beginnings of the first century, still preserves some of the original magnificent mosaics, fountains and frescoes (figure 1). In collaboration with the Monographic Museum of Conimbriga, our aim is to generate accurate and perceptually valid High Dynamic Range images of those frescoes and mosaics and visualize them in a HDR display.

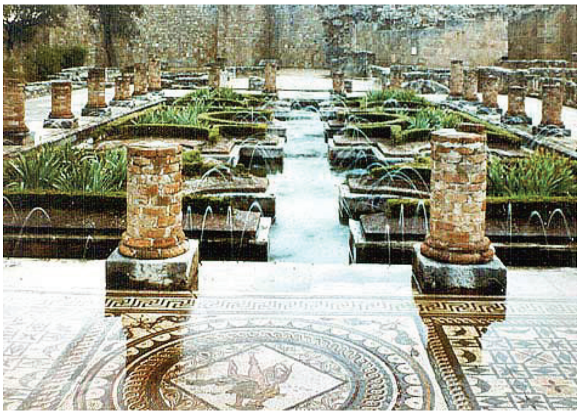


**Figure 1:** *Inner garden of the House of the Fountains showing some preserved fountains and mosaics.*

## 2. Overview

### 2.1 RGB

The 'true colour' RGB model has the ability to combine several million colours. Some may think that this enormous quantity is perfectly suited to digitally represent the whole electromagnetic spectrum visible to the HVS. That is not quite true. Chromaticity diagrams usually illustrate such limitations [Dev04]. Figure 2 present the *Commission Internationale de l'Eclairage* (CIE XYZ) chromaticity diagram showing the colour scope acquired by the HVS. In this diagram it is easily perceived a triangle. This triangle embraces the colour gamut visible in most of today's display devices. Therefore, any colour outside of that 'triangular spectra' needs to be mapped in order to have a representation in the display device colour gamut. This procedure obviously modifies the original colour, producing a new inaccurate one, leading to unreal reproductions of real scenes.

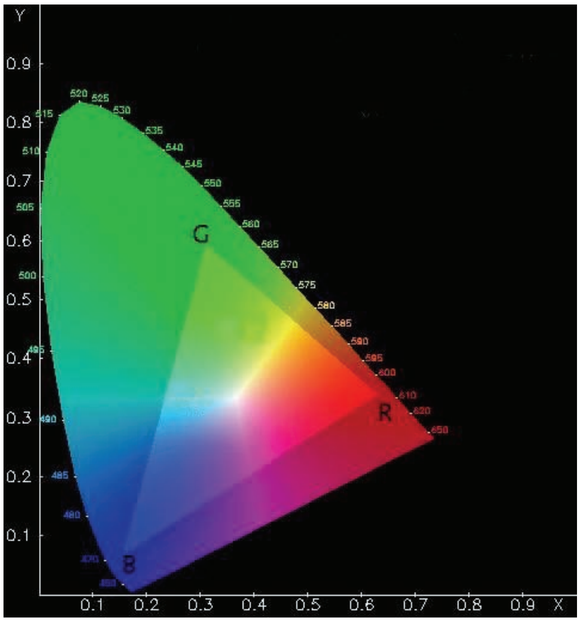



**Figure 2:** *RGB constraint in a CIE chromaticity diagram [Wal96]. Please note that the colours in this diagram are modified due to the limitations of the reading media, i.e. paper or screen.*

### 2.2 High Dynamic Range

A real scene can hold a tremendous level of contrast and luminance. For example, a sunny day can present us values higher than $10^5$ cd/m$^2$ and a starlight night values around $10^{-3}$ cd/m$^2$ [RWPD05]. The HVS has such capacity that easily adapts itself to everyday scenarios. Instantaneously it can capture contrasts of 10000:1 (4 orders of magnitude) and with some time of adaptation it can achieve values of 14 orders of magnitude. This occurs because of the receptors present in the human eye. These receptors consist of about 120 million rods and 8 million cones [BS94]. The former are highly sensitive to light but incapable to distinguish colour; the latter with a different response to wavelengths are responsible for perceiving colour.

Today's display devices are quite limited with respect to the range of luminance and colour that can present. For example, a computer display can achieve brightness values up to 600 cd/m$^2$ and a contrast ratio of 10000:1 and a state of the art TV values that can go up to 1500 cd/m$^2$ and 50000:1.

Thereby new ways to create, store and visualize are needed in order to achieve a visualization experience closer to the one perceived by the HVS. This was the motivation for research into High Dynamic Range.

The contents that we may want to reproduce and visualize can be acquired from real or virtual scenarios. To create an HDR image of a real scene we need to utilise all the light information present in that same scene. But, it may not be possible to acquire this from a single photograph of that scene. Instead this can be accomplished using several photographs of the same scene taken with different exposure times and then combined in a single HDR image [DM97]. To create a synthetic virtual HDR image the rendering software used needs to simulate the physical process of light propagation (including any present participating media) and its reaction when hitting any kind of surface (reflection, refraction and absorption). This is called Physically-Based Rendering. Radiance [WS03] has such ability and this is the rendering package used in our work (section 6).

In order to store all this new range of values that, as we saw in figure 2, cannot be stored in the traditional RGB format without loss of information, new file formats had to be developed. In table 1 we present some features of the most important ones: RGBE [War91], LogLuv TIFF [War98] and OpenEXR [BKH03].

| Format | Bits/pixel | Dynamic range | Luminance steps |
|---|---|---|---|
| RGB | 24 | 1,6 | Variable |
| RGBE | 32 | 76 | 1% |
| LogLuv | 32 | 38 | 0,3% |
| OpenEXR | 48 | 10,7 | 0,1% |

**Table 1:** *HDR file formats.*

It is in the field of visualising HDR images that a lot of work still needs to be done. Brightside Technologies were the first to develop an LCD display that together with modulated back-panel LEDs can be considered a HDR display. This 37" display can present a contrast ratio of around 200000:1 and brightness values that vary from 0,015 cd/m$^2$ to 3000 cd/m$^2$ In 2007 Brightside Technologies was acquired by Dolby Laboratories, Inc, but such HDR displays are yet to be commercially available.

It is possible, however, to visualize HDR content on a common low dynamic range (LDR) display. To do so, this contents need to go through the process known as tone mapping. Basically this process maps the out-of-range data present in that HDR content into that which can be displayed. Obviously this tone mapped version may lose valuable visual information compared with the original HDR image.

## 3. Related Work

In the last few years, the number of projects involving historical reconstruction has increased significantly. Two main factors are responsible for this: the technological developments that allow such reconstructions to be accomplished more easily, with a larger impact, affecting a greater number of people, and, the continuous and increasing interest of humanity about questions related to our cultural and architectural past. Several of these projects produced photorealistic views of reconstructed historical settings, but little attempt has been made to ensure that they are perceptually valid and thus a faithful simulation of how that scene may had been seen by their local inhabitants.

To date there are very few projects involving archaeological reconstruction that attempt to physically reproduce how that historical setting might have been perceived in the period under consideration [DC01] [DCB02][RC03][SCM04][BLRR06] and less that utilise HDR imagery [ZCBC07] since access to HDR display technology, as described in the previous section, is quite recent.

## 4. Case study

### 4.1 Roman illumination

Until less that two centuries ago only two types of illumination were used by man: natural light (sun, moonlight) and a more artificial one using fire/flame (hearths, lamps, candle, torches, etc.) [BLRR06][DCB02] [For66]. This is therefore true also in the period we are considering. Furthermore, Roman residential houses typically didn’t have windows [For66]. Consequently to illuminate the inner chambers they use mostly candles and lamps.

Despite the existence of documentation that states that Romans used torches affixed to the walls to light a room, after a certain period this type of illumination become more unusual. One possible reason arises from the fact that such an illumination method was responsible for many house fires [For66]. Thereby to light a house, the Romans used mostly lamps or candles since they were more stable, movable and easy to manipulate. This fact is clearly confirmed in our case study (Conimbriga) where dozens of oil lamps were discovered during the several excavations periods occurred in the archaeological site (figure 3).

It is believed that Romans imported the use of oil lamps (lucerna) from the Greek civilization [For66] given that there are traces of them only since the 3rd century B.C.. Those were manufactured mainly in clay or bronze and had a special spot for the wick (figure 3).

**Figure 3:** *Replicas of Roman oil lamps discovered in Conimbriga.*

These lucerna were positioned directly over the floor or in candlestick holders. Some could hold several lucerna others were just for one (figure 4).

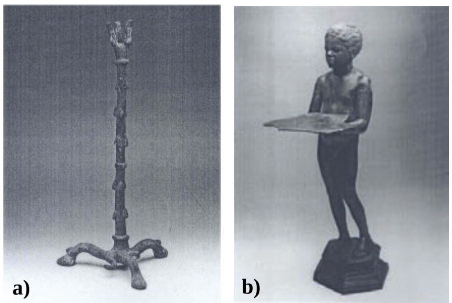



**Figure 4:** *Roman candlestick holders that support one lucerna a) and for several b).*

An important factor in this illumination method and therefore with direct implication in the results of our work, is the fuel used for the lucerna. Despite its use in the food chain, olive oil were the most common fuel used in the Roman era [DC01][For66]. In fact evidence shows this was the case throughout the Mediterranean region [KJW01]. This vegetable fuel produce a better quality flame when compared to others from animal source [For66] and when mixed with salt it produce a more stable and brighter flame [GMMC08][DC01][For66].

### 4.2 House of the Fountains

The ruins of Conimbriga are one of the most important remains of the Roman presence in Portugal. In collaboration with the Monographic Museum of Conimbriga this is the focus of our study.

The House of the Fountains is one the most impressive monuments in Conimbriga. The fact that this was the house of a high status personality in the city makes the entire architectonic ambiance, along with their numerous detailed mosaics and fountains in the inner garden, quite magnificent. Today is still possible to admire some of their fully intact mosaics (figures 1, 5 and 9). There was also another reason that support the option for this particular house in our study: it is the only one, in the whole ruins of Conimbriga, that still has remains of frescoes painted in the walls of some rooms (figure 5), particularly in “Sala da Caçada” (hunting room), due to the hunting scene portrayed in mosaic floor.

**Figure 5***: A view of “Sala da Caçada” today. We can perceive the full intact mosaic and vestiges of some frescoes in the wall.*

The original frescoes of this room were located between the columns and enclosed a certain particularity. They where aligned establishing a correspondence sequence between some of them (figure 6).

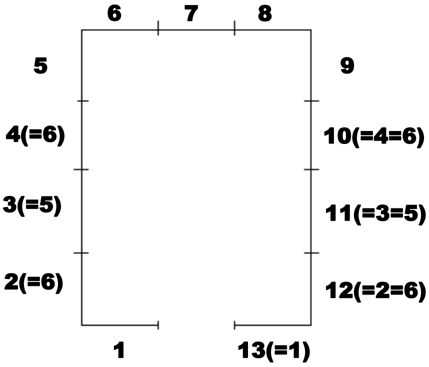



**Figure 6:** *The frescoes corresponding sequence in “Sala da Caçada”.*

## 5. Working process

The “Sala da Caçada” is the focus of our work. Here we intend to generate HDR images of the scene, using illumination of that period thus allowing us to have a glimpse of the past.

With our goals clearly identified we need to define a methodology to achieve them (figure 7). From an archaeological background, how do we create a fairly accurate (virtual) reconstruction of that historical site?

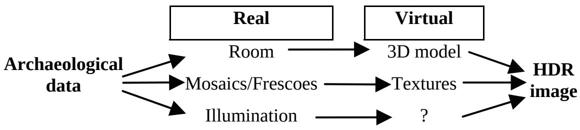



**Figure 7:** *Working pipeline.*

The geometric 3D model of the room was obtained after precise measurements ‘on site’ and with the collaboration of experts, mainly for the reconstruction of the upper fraction of the degraded walls and columns.

As visible in figure 5 the frescoes of the walls are in bad shape of conservation. In order to replicate them in our virtual model we need to take much care in the process of creating the textures. Like a puzzle, the images were digitally created assembling mostly real elements extracted from the vestiges of that frescoes (figure 8).

**Figure 8:** *One original fresco (top) and its digital reconstruction (bottom).*

One of the relics of this room is the fully intact mosaic floor. Since its dimension did not permit it to be acquired using a single full high resolution photograph, several high quality pictures were taken and then with digital manipulation a texture was created of the whole mosaic (figure 9).

**Figure 9:** *The full mosaic of "Sala da Caçada".*

A crucial element in our working pipeline is the reproduction of Roman illumination. To utilise in a virtual model real illumination data of Roman lamps, we had to physically rebuild a lucerna, in order to acquire the absolute value of their spectral properties and use them in the virtual scenario.

According to our references and the guidance of the experts, mainly the Director of the Monographic Museum of Conimbriga, we gathered very thoroughly all the components to utilise in our reconstructed lamp:

- Lucerna: replicas of discovered lucerna found during the excavations in Conimbriga were kindly offered by the Monographic Museum of Conimbriga (figure 3);
- Fuel: as showed in the previous section, olive oil was the most used fuel for these lamps, thereby we gather three samples of pure (without of any kind of addictives) olive oil from olives from the region of Conimbriga. Two of those samples were manufactured with old traditional methods (not allowed nowadays due to today's "civilization" standards) in order to get a closer composition to the ones used back then. The remaining sample was made in a modern mill, making it more close to a common commercial olive oil;
- Salt: as explained in the last section, salt was added to the fuel. To maintain a thorough manner of gathering components closer to the ones used in those days, clear pure salt was obtained directly from salt mines in Figueira da Foz;
- Wick: Cotton and flax wicks of several widths were obtained.

With these components we believe that is possible to "light" a Roman lamp as close as possible to an original one and, from that, extract the spectral properties of the light emitted by it when in combustion.

### 5.1 Lighting measurements

It is the contact of the fuel in combustion with the atmosphere that produces a flame. This flame has certain spectral properties which induce their colour, brightness, shape, etc. Now to achieve our goals we need to replicate those spectral properties in our virtual model. To do so we need to utilise a spectroradiometer to measure the absolute value of the spectral properties of the light radiated from that flame.

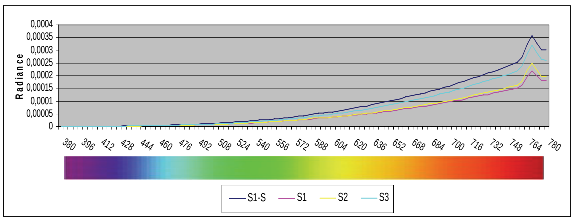
To conduct those lighting experiments a very thorough process needs to be prepared in order to acquire valid and accurate values. The final setup of the experiments was performed in the following conditions:

- Completely dark room;
- Close sealed room so there won't be any drafts that could cause the flame to flicker;

- Against a board perfectly diffuse and with a high reflectance factor (the one we utilise has approximately a 99% reflectance factor);
- Measures were made with all of our olive oil samples and with different configurations (salt and no salt);
- To prevent a misleading single reading, ten readings (with the Spectroradiometer) for each configuration were made in order to determine the average value;
- Measures in intervals of 4 nm in the visible scope of the electromagnetic spectrum.

**Figure 10:** *The light emitted by the lamp (left) is almost entirely reflected in the white board (middle) which is then captured by the spectroradiometer (right).*

The next chart discloses the results of these experiments (graphic 1).




**Graphic 1:** *Chart with the results of the lighting measurements with four different configurations.*

The rose and yellow lines present the results obtained from the two samples of olive oil manufactured with old traditional methods (S1 and S2), which as we can see produce the lower value results, thus lower light intensity. Whereas the light blue line is from the sample closer to a common commercial olive oil since it's the one manufactured in a modern mill (S3). By these results we can predict that the olive oil (fuel) manufacture procedure has implications in the light intensity produced by an olive oil lamp in a Roman residence or by other civilization that used the same lighting method. Ancient old methods manufacture thus produce inferior values of intensity.

In section 4.1 it was noted that Romans usually added salt to the fuel because it produces a more stable and brighter flame. Our experiment confirms that evidence. The dark blue line in the chart (S1-S), which produced the higher results, was obtained from the first sample (S1), precisely the one that had the lower values. The more amazing thing is the fact that there is a real increase in light intensity more than 60%. This confirms the documentation evidence and the judgment of the experts.

## 6. Virtual model

Having a geometric 3D model, the textures and the light information data, we have all the ingredients to assemble and create the scene final setup.

To achieve the purposes of this work, the software renderer used to generate the HDR images are crucial. That renderer has to be able not just to process a geometrical textured 3D model, but also must have the ability to physically simulate the light propagation over the participating media and thus produce a viewing experience closer to how the artefacts may have been perceived in the past. Radiance [WS03], created by Greg Ward, is a state of the art free open source rendering package (http://radsite.lbl.gov). This renowned software is able to produce lighting simulations, even with luminaries of flame combustion that accurately model the law of physics regarding the light propagation and interaction with the surfaces [MCTG00]. Moreover it produces images in their native file format with enough data to cover the dynamic range captured by the HVS.

**Figure 11:** *"Sala da Caçada" illuminated by an electric light of 111W.*

In figures 11, 12 and 13 we present images of "Sala da Caçada" using different lighting configurations. Figure 11 show the room illuminated by a common fluorescent electric light of 111W. In figure 12 we see a matching image in the exact same viewpoint now illuminated by Roman olive oil lamps (lucerna), positioned around the room using candlestick holders as suggested by experts. In figure 13 a rendered image is shown from a similar viewpoint as in figure 5. To light these lucerna we utilise as fuel the olive oil sample 1 with the addition of salt (graphic 1).

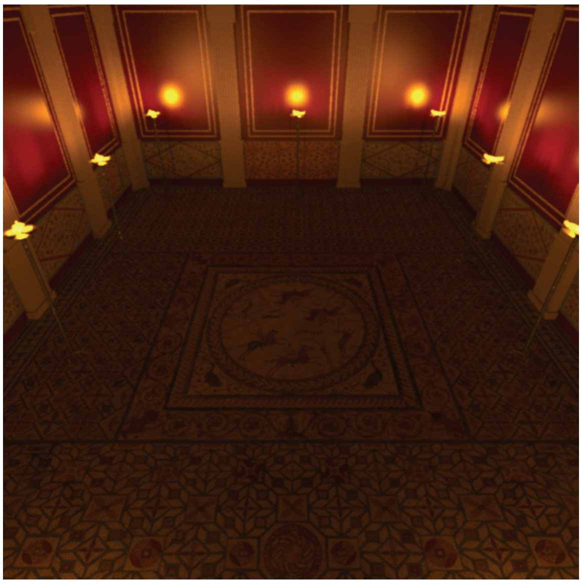


**Figure 12:** *Room illuminated by Roman lamps (lucerna) using as fuel the olive oil sample with salt.*

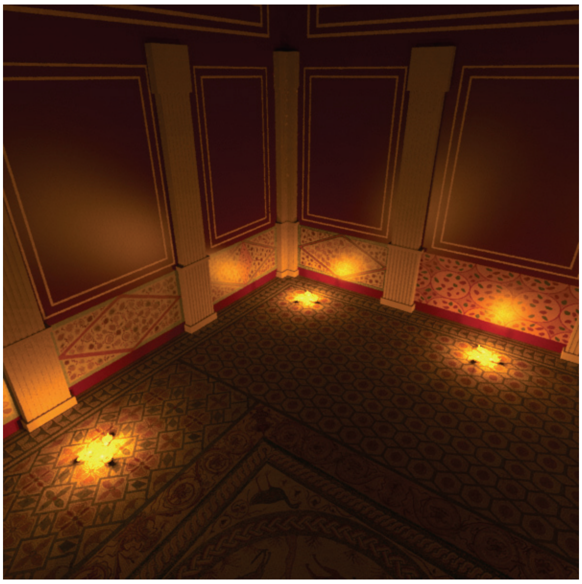


**Figure 13:** *The virtual representation of "Sala da Caçada" using Roman illumination from a similar standpoint as in figure 5.*

Comparing the first image (figure 11) with the other two, the differences are substantial. The fact the material surfaces are highly specular are quite emphasised when viewed under Roman illumination. This is not apparent in the electric light version. But the most obvious aspect when comparing those images is the differences in the perception of the artefacts (mosaic and frescoes) in both situations. The Roman light, due to its lower intensity and spectral properties, give a warmer and cosy ambience to the whole room.

Please note that these images are tone mapped copies from the original HDR images rendered with Radiance. As a consequence and as we saw in section 2.2 they lose some visual information.

## 7. Conclusion and future work

Since the Middle Ages, perhaps even before, the questions related to the historical and cultural past, especially related to archaeological finds, have exerted an enormous and mysterious allure on mankind. Ever since then, humans have come up with methods and forms to recreate such places, in order to satisfy this recognized natural and ancestral curiosity. However to have a real perception of the environments in which our ancestors lived we need, beside the development of a precise geometric 3D model, to integrate accurate representations of the illumination used in the period under consideration. Having these aims, the visualization media of these reconstructions are crucial. The visual acuity of HDR imagery can disclose and present us enhanced viewing experiences, closer to how those historical settings may have been perceived in the past, which is not easily achieved by other means.

Even though it is not possible to visualize HDR images within this paper, it is clear that seeing ancient artefacts using different light sources, rather than the ones used in the period under investigation, produce significantly distorted visual results. The visualization of these artefacts under a Roman lucerna candle light presents us a considerable different way to interpret that piece of our history. The specular surfaces combined with this lighting method show some subtleness which gives this room in particular a very pleasant feeling, quite different from the rough and almost unnatural scenario perceived with modern electric light.

It is this sort of results that enhances our understanding of the past. This physically-based approach, together with other resources, including documented evidence and the opinion of experts, can support several fields of archaeological investigations and promote a deeper knowledge about, in our case, the Roman civilization and way of life.

Another issue is important regarding the use of HDR in this particular case study. The fact that generally Roman residential houses had very few exterior windows and due to the use of those oil lamps, traditionally with low light intensity, meant that Romans perceived their frescoes and mosaics in quite dim conditions. This is precisely a matter where HDR features most emerge, since the visual acuity of the HVS in dark environments, even after a few minutes of adaptation [LSC04], can not be perceived using a traditional low dynamic range display.

As future work first we intent to improve the rendered images by adding features of how the human eye adapts over time. This will enable us to visualize the environments depending on how long the viewer has been in the environment. Furthermore, we intend to conduct a detailed perceptual user study using the HDR display mentioned in section 2.2. These tests will focus on determining, in that same display, the perceptual differences between HDR images and their tone mapped (i.e. their LDR) versions. With these experiments we intend to demonstrate that the loss of visual information which occurs in the tone mapped image has significant implications in the visualization of ancient artefacts, particularly when viewed under extreme lighting conditions. In this way we will try to establish real benefits of using (true) HDR imagery in a cultural heritage context.

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## References

[BKH03] BOGART R., KAINZ F., HESS D.: *The OpenEXR File Format*. Siggraph 2003 Technical Sketch. 2003.

[BLRR06] BRIDAULT-LOUCHEZ F., LEBLOND M., ROUSSELLE F., RENAUD C.: *Enhanced illumination of reconstructed dynamic environments using a real-time flame model*. Afrigraph'06: Proceedings of the 4th international conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa. ACM Press, pp. 31–40. 2006.

[BS94] BLAKE R., SEKULER R.: *Perception*. McGraw-Hill, third edition, 1994.

[DC01] DEVLIN K., CHALMERS A.: *Realistic Visualisation of the Pompeii Frescoes*. Afrigraph'01: Proceedings of the 1st International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, pages 43-48. ACM Press, 2001.

[DCB02] DEVLIN K., CHALMERS A., BROWN D.: *Predictive lighting and perception in archaeological representations*. UNESCO "World Heritage in the Digital Age" 30th Anniversary Digital Congress. 2002.

[Dev04] DEVLIN A. K.: *Perceptual fidelity for digital image display*. PhD Thesis. University of Bristol, 2004.

[DM97] DEBEVEC P., MALIK J.: *Recovering High Dynamic Range Radiance Maps from Photographs*. Computer Graphics (Proceedings of SIGGRAPH 97), ACM, 1997.

[For66] FORBES R. J.: *Studies in Ancient Technology (Volume VI)*. Leiden & Brill, Netherlands, 1966.

[GMMC08] GONÇALVES A., MAGALHÃES L., MOURA J., CHALMERS A.: *High Fidelity Illumination in Archaeology - A Roman Legacy in Portugal*. In 6th World Archaeological Congress, WAC, Dublin, 2008.

[KJW01] KIMPE K., JACOBS P., WAELKENS M.: *Analysis of Oil Used in Late Roman Oil Lamps with Different Mass Spectrometric Techniques Revealed the Presence of Predominantly Olive Oil Together with Traces of Animal Fat*. Journal of Chromatography, A, 937, 87-95. 2001.

[LSC04] LEDDA P., SANTOS L., CHALMERS A.: *A local model of eye adaptation for high dynamic range images*. Afrigraph'04: Proceedings of the 3rd international conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, ACM Press New York, pp. 151-160, 2004.

[MCTG00] MCNAMARA A., CHALMERS A., TROSCIANKO T., GILCHRIST I.: *Comparing Real and Synthetic Scenes using Human Judgements of Lightness*. 11th Eurographics Workshop on Rendering. 2000.

[RC03] ROUSSOS I., CHALMERS A.: *High fidelity lighting of Knossos*. In Proceedings of VAST2003, pages 47–56. 2003.

[RWPD05] REINHARD E., WARD G., PATTANAIK S., DEBEVEC P.: *High Dynamic Range Imaging: Acquisition, Display and Image-Based Lighting*. Morgan Kaufmann Publishers, 2005.

[SCM04] SUNDSTEDT V., CHALMERS A., MARTINEZ P.: *High Fidelity Reconstruction of the Ancient Egyptian Temple of Kalabsha*. Afrigraph'04: Proceedings of the 3rd International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, pages 107-113. ACM Press. 2004.

[Wal96] WALTER J.: *Colour Rendering of Spectra*. 1996, www.fourmilab.ch/documents/specrend/.

[War91] WARD G.: *Real Pixels*. In Graphics Gems II, Academic Press, 80-83. 1991.

[War98] WARD G.: *The LogLuv Encoding for Full Gamut, High Dynamic Range Images*. Journal of Graphics Tools, 3(1):15-31. 1998.

[WS03] WARD G., SHAKESPEARE R.: *Rendering with Radiance: The Art and Science of Lighting Visualisation (Revised edition)*. Morgan Kaufmann Publishers, 2003.

[ZCBC07] ZÁNYI E., CHRYSANTHOU Y., BASHFORD-ROGERS T., CHALMERS A.: *High dynamic Range Display of Authentically Illuminated Byzantine Art from Cyprus*. In Proceedings of VAST2007, 2007.