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Simulation of tallow lamp light within the 3D model of the Ardales Cave, Spain

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ABSTRACT

The observation and analysis of caves and cave art enables to structure caves into different zones of use and simulations allow to estimate past living conditions. Nowadays, different remote sensing methods are used to document and analyse caves in 3D and high resolution. In this contribution, the virtual 3D model of the Ardales Cave in southern Spain derived by terrestrial laser scanning was employed for light distribution simulations. This cave shows hundreds of prehistoric images. At three different locations of tallow lamps, authentic light distribution simulations were conducted. The lighting simulation follows recent standards of global illumination by path tracing implemented by using the open-source software Blender. The results fit to previous findings and show the accuracy of this new approach. The results are combined with other metrics in order to quantify different areas in this cave. The study reveals that additional lamps seem to be necessary in order to allow decoration of the cave walls. In general, the open-source approach allows further implementations of other light sources and corresponding adjustments.

1. Introduction

Caves have been noted as harsh environments mostly unreachable by daylight. Nevertheless they have also served as shelter, for accommodation, workshops and storage, and some findings were interpreted as evidence of ritual purposes, such as formal burials (Bonsall and Tolan-Smith, 1997). As a basic human instinct objects and walls were engraved or painted in order to shape familiar places, known as cave art (Lawson, 2012). This instinct is documented by hundreds of sites across Europe showing cave art records from at least the Aurignacian culture (47–41 ka BP; Clottes, 2008), but also Neanderthals are associated to engravings older than 39 ka BP (Rodríguez-Vidal et al., 2014). Famous and oldest examples of small portable objects (*french*: *art mobilier*) are a female figurine of the Hohle Fels Cave, southwestern Germany (Conard, 2009), dated back to at least 35 ka BP. First engravings (*french*: *art rupestre*) from the early Aurignacian are reported from the Abris Castanet, France (White et al., 2012), and from the Chauvet Cave, France with the oldest occupation dated to 37–33.5 ka BP (Quiles et al., 2016). Besides the analysis of cave art itself by technique, style and theme, Robert (2016) emphasized the importance of the specific location of art in caves and the influence of the shape to the specific cave art.

The analysis of painted caves enables to reconstruct zones of different activity concentrations. Therefore an archaeospatial approach that regards, different light zones, chamber types, the path network, mode of movement, and available space was presented by Pastoors and Weniger (2011). An important factor in this system plays natural illumination as well as artificial lighting. While natural illumination is used to subdivide a cave in three light zones (daylight, half shade and dark), artificial lighting serves as a base for the determination of different chamber types. The illumination of a candle reaches up to 4 m with an intensity of illumination of around 0.25 lx, which is enough for controlled movement. Consequentially chambers are differentiated using this range. The path network is composed of lines of communication (side passages, passageway) and connecting points (crossing, junction, dead end, entrance). Dependent on the shape of the lines of communication three different ways of movement are differentiated: walking, crawling and climbing. For the estimation of the available space an area of 2 m^2 of space is required by each human. Based on this value, the maximum number of people that could have stayed in the same place at the same time is calculated.

In addition to this analysis, also other archaeological and geoarchaeolgical research enables to estimate past living conditions,

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behavior and patterns of movement. As an example, wood charcoal analysis yields information about the past environment, provision management and use for the illumination of watching and decoration of caves (Medina-Alcaide et al., 2015). In this case from the Nerja Cave, Spain, the discovery of vegetative buds of *Pinus sylvestris*, leads to the conclusion that the cave was visited during autumn or winter. The analysis of least cost paths in geographic information systems allows to model movements through landscapes (Howey, 2011; Surface-Evans and White, 2012). Spatial analysis on the distribution of material on the ground floor allow to estimate activities (Corchón et al., 2016).

For an accurate high-resolution documentation of painted caves, photogrammetry and terrestrial laser scanning (TLS) nowadays serve as reliable non-invasive tools (González-Aguilera et al., 2009; Rüther et al., 2009; Lerma et al., 2010; González-Aguilera et al., 2011; Grussenmeyer et al., 2012; Sadier et al., 2012; Lerma et al., 2013; overview in: Idrees and Pradhan, 2016), which can also be conducted with low-cost sensors (Hämmerle et al., 2014). In addition these methods are used for highly detailed studies, such as bones (Mitsopoulou et al., 2015) or footprints (Pastoors et al., 2016), as well as for airborne prospection (Doneus et al., 2008; Draganits et al., 2015). The 3D information of a whole cave established by these measurements was also used for shaping protection areas (Elez et al., 2013) and building of virtual information systems (Rodríguez-Gonzálvez et al., 2012). The detailed documentation of painted caves based on modern remote sensing methods offers an alternative to drawings, rubbings, or photography. For instance, high dynamic range imaging, reflectance transformation imaging (Happa et al., 2010) and structured-light scanning (Tusa et al., 2013) can be used for detailed documentations of cave art. Additionally, spectroscopy of rock paintings enables researchers to examine specific components of paintings (Hernanz et al., 2012; Martin-Sanchez et al., 2012).

Besides the documentation of cave sites and rock art, the gathered 3D information can also be used for the analysis of specific research questions. For instance, a flooding simulation for the Cussac Cave, France was conducted in order to prove detected inundation levels of the cave (Jaubert et al., 2016). Rüther et al. (2009) concluded based on a 3D model of the Wonderwerk Cave, South Africa and the surrounding area, that the existence of a further entrance was highly unlikely. Hoffmeister et al. (2016) applied a similar approach to the Ardales Cave in southern Spain in order to reveal possible areas of further entrances.

As a further analysis tool and for representation purposes, physically accurate, *authentic* illumination simulations (Chalmers et al., 2006) can be applied to 3D models in order to receive information about past living conditions (Happa et al., 2010). Masuda et al. (2008) showed that specific areas of the Fugoppe Cave, Japan, were potentially reached by sunlight, which enabled painting. In this and other cases the software suite Radiance was used, which uses the finite element algorithm radiosity (Ward, 1994). In contrast, ray tracing algorithms more easily allow to stochastically render global illumination (Happa et al., 2010), and are able to simulate also other types of surfaces such as glossy or specular materials (Happa et al., 2009). In Hoffmeister et al. (2016) path tracing was used for an illumination simulation, which demonstrated where sunlight might have reached the cave by virtually removing the modern entrance building and by reconstructing the ancient entrance.

In contrast to the previously presented approaches, an illumination simulation with the free and open-source tool Blender was applied in this contribution, which is since the implementation of the renderer engine Cycles at the end of 2011 capable of path tracing (Blender Foundation, 2015a). This software can be used to simulate 3D data in science (e.g. Kent, 2013) and was applied here to appropriately simulate artificial light of small tallow lamps at specific spots in the Ardales Cave, Spain in order to investigate illumination as a part of the archaeospatial approach of Pastoors and Weniger (2011). In addition, the geomorphometric information of the established and reconstructed 3D cave model (Hoffmeister et al., 2016) was considered for the tools of this approach. This allows to distinguish different areas of human activity within a cave.

2. Materials and method

2.1. The 3D model of the Ardales Cave

The previously proposed method of tallow lamp light simulation was applied to the Ardales Cave in order to gain new insights into ancient living conditions. The Ardales Cave is located in the south of Spain near the Strait of Gibraltar (cf. Fig. 1). This region inhabits various archaeological sites of prehistoric research interest, as the Strait of Gibraltar may has served as a bridge or barrier of human dispersal (Richter et al., 2012) and the region is discussed to be the last refuge of Neanderthals. Their survival was documented by radiocarbon dating until about 28 ka BP (Finlayson et al., 2006), which is however still disputed (Kehl et al., 2013; Wood et al., 2013). The Ardales cave was discovered in 1821 after an earth tremor exposed the entrance (Lawson, 2012). Since the 1850s the cave became a touristic attraction, as the stalagmites in the main hall are for example very impressive. During that time pathways, lights and the entrance building were added. Generally, the cave comprises several complexly shaped galleries and halls with about 250 panels of rock art (paintings and engravings), as well as bones and artefacts that prove prehistoric human occupation (Cantalejo et al., 2006). Animal figures, which are mostly found in the backward areas of the cave, mostly show hinds, stags, horses and ibex (Lawson, 2012). Likewise, remains of lamps were found (Cantalejo et al., 2015) and three locations are examined in this contribution.

As described in detail by Hoffmeister et al. (2016), the major part of the cave and the surrounding hill was recorded by terrestrial laser scanning with 61 single scan positions. For this purpose, a TLS LMS-Z420i from Riegl, Austria (Riegl, 2015) was applied which uses a time-of-flight range detection. A 3D model of the cave and the exterior hill were established. The dataset was georeferenced by using real-time kinematic GPS measurements (RTK-GPS) and all data of all surveys were integrated by transformations. In addition, four panels with the most important engravings were measured by a structured-light scanner (type: Breuckmann smartSCAN^{3D}-Duo) and were also successfully integrated in the whole dataset. In order to achieve ancient lightning conditions the model of the recent cave was altered by virtually removing the entrance building. This model with a minimum edge length of 10 cm reflects the ancient entrance situation. Further available color information data, obtained during the scanning process with a digital camera (type: Nikon D200, equipped with an external light type NPE light CN-240CH and mounted on top of the TLS LMS-Z420i), was not taken into account for the illumination simulation. These pictures exhibit shading and depend on viewing positions and specific lighting properties.

2.2. Illumination simulation

For the illumination simulation the open-source software Blender was used in version 2.75a (Blender Foundation, 2015b). The previously described 3D model (Section 2.1) was imported as an OBJ-File. The surface material of the cave model was set to a diffuse BSDF (bidirectional scattering distribution function) surface with mean RGB-color (0.75, 0.63, 0.59) derived from several points of the pictures taken by the mounted Nikon D200 camera. The location of

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