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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

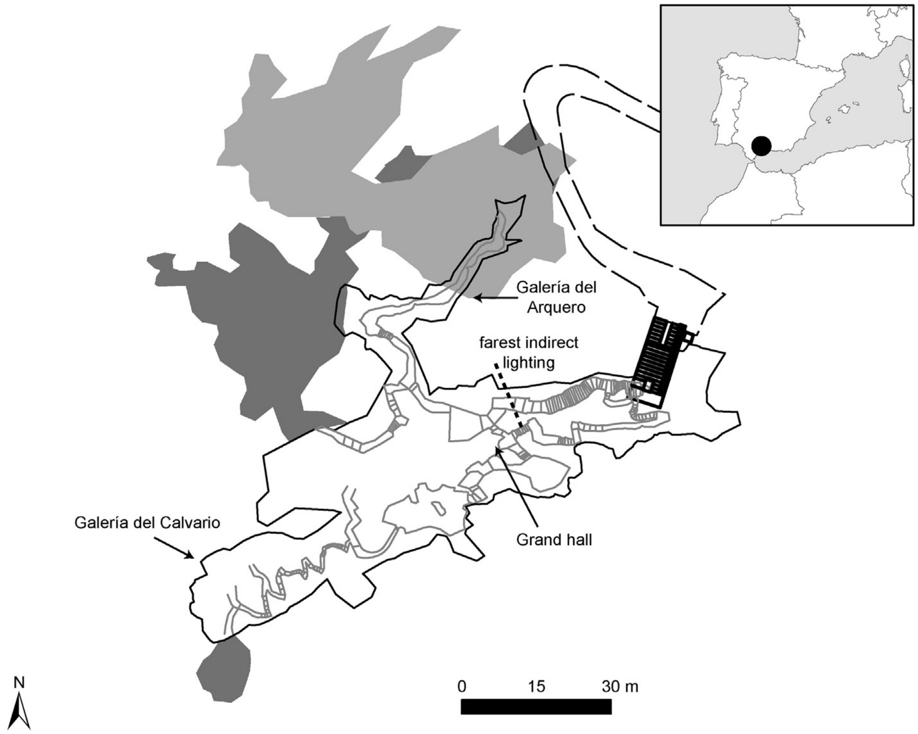

Fig. 1. Overview map of the Ardales Cave, Spain. The farest point where indirect lighting was observed by Hoffmeister et al. (2016) is indicated as well as further areas (grey filled areas), which were not recorded due to logistic constraints.

the three tallow lamps was measured by a total station. Generally, data in the project coordinate system were used for the simulations, whereas for mapping purposes the georeference was employed (WGS 84, UTM 30N). This was established by a rigid transformation with six similar points measured by the total station and the RTK-GPS.

The tallow lamps were implied as single light points at the specific destination. As a test, a further light was applied at each position about 2.8 m (2 m in each horizontal direction) away from the original light spot. The emission color was derived by connecting a node to a blackbody converter, which is set to 1,500 K reflecting the colour temperature of candles. According to the luminous efficacy of a candle, which has a luminous intensity of 1 cd (~12.6 lumen), this intensity was converted to 12 W, as it reflects the luminous efficacy (Yoshizawa, 2009). This value was used as the emission strength of the light point in Blender, which is also denoted in watt. The size of the light was set to 40 mm.

The virtual cameras were positioned at each lamp in a lateral, top and frontal view in order to examine light distribution, where the lateral and frontal views reflect human perception. This lateral position was chosen with a distance of about 10 m and the frontal view was taken in a front distance of about 2 m, both with a height above ground of ~1.6 m with a 90° angle to the floor. The top view was adjusted as close as possible to the ceiling of the cave. The virtual camera view of the lateral and perspective images reflect human eye vision, as these were set to a 40 mm focal length with a 35 mm sensor size (Cicala, 2012). The top view camera was set to a focal length of 20 mm in order to derive overviews. Every scene (1920 by 1080 pixels, HD quality) was rendered by the Cycles renderer engine set to path tracing with 400 samples, regarding full global illumination with reflective and refractive caustics. This computation takes ~1.5 h on a mid-range workstation (Intel® Xeon X5560, 12 GB RAM) without GPU-computation.

In addition, at each location of a lamp, a cross-section was established in order to examine the spatial relation. Likewise, a normally rendered view was established and all other parameters of the tool kit of Pastoors and Weniger (2011) were determined by the 3D cave model.

3. Results

In order to examine illumination in relation to cave art, the described method was applied to the Ardales Cave. Small tallow lamps at three specific locations were simulated. The location of these lamps was measured by a total station and thorough inspection of the 3D model and pictures recorded by the mounted camera. Likewise, the parameters of chamber type, path network, mode of movement and available space were derived from the 3D model, in order to structure the cave according to the tool kit of Pastoors and Weniger (2011).

All figures show a similar set-up, with two different camera points and orientations that reflect two different viewpoints on a specific area. The first viewpoint (A,C and E in each image) depicts an overview from about 10 m of distance, and the second viewpoint (F in each image) is chosen in order to show the nearest wall, where cave art is assigned. Likewise, B and D show top-views of every location from the most outward ceiling. For further orientation, a globally illuminated view E similar to A and C of every image and a cross section perpendicular through the lamp location is given in part G of every image, as well as a cave plan (H in every image) that illustrates every viewpoint and lamp location. As the illumination of each nearby wall by a single lamp seems to be not sufficient, an additional lamp at each location was added closer to the wall (shown in B, D and F of every image). Each simulated part of the figure by the Blender software is in RGB colors, depending on printer or screen settings.

The simulation results for all three locations generally reveal very low light conditions (Figs. 2–4). However, the results fit to the investigations of Pastoors and Weniger (2011), who state that this type of lamps reaches an intensity of illumination of 0.01 lx up to a

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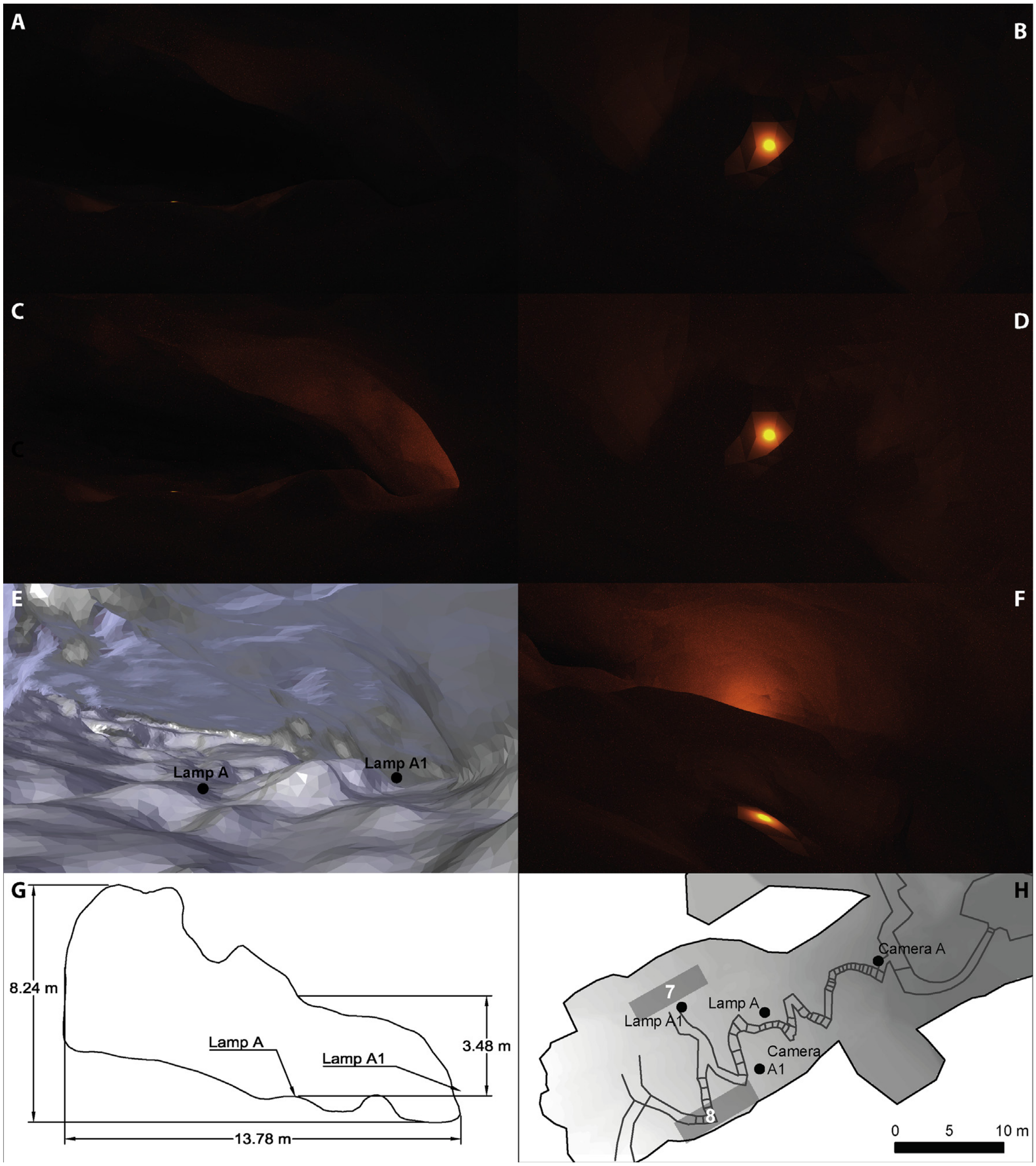

Fig. 2. This figure shows the simulation results of tallow lamp A from a lateral perspective (A) with a distance of 10 m and a top view from the corresponding cave ceiling (B). Accordingly, the simulations are shown with the additional lamp A1 (B & D). For orientation and estimation of the results, a version of the lateral perspective without a lighting simulation is shown (E), as well as a frontal simulation with both lamps (F). The cross-section at the location of the lamp (G), as well as a map of a part of the cave with the locations of the lamps, the camera positions and archaeological zones is depicted (H).

distance of 38 m to a reflecting surface which is still enough for simple orientation. In this simulated case study, the tallow lamp light is clearly visible from the selected side views, which are in a distance of about 10 m (in all figures views A and C). Likewise, the single results show that light is visible on the walls and ceiling of the cave in distance of up to 4 m. In this area controlled movement is possible. However, the light hardly allows colour reception (distance of colour reception up to 2 m). Thus, further light sources are needed for engraving or painting purposes. The tested second lamp shows an enhancement of the illumination distribution at each spot.

Lamp A, displayed in Fig. 2, is able to illuminate a larger extent of the Galería del Calvario, in particular the wall and the ceiling of the cave on the right. This particular wall shows important engravings, which were also documented by a high-resolution structured-light scanner. However, the illumination only reaches areas with a distance of ~4 m. The left side in Fig. 2 A of Galería del Calvario is not lightened. The difference between view A (one lamp) and C (two lamps) underlines the importance of the second lamp in order to allow decoration of the wall. In particular, as the wall is partly hidden behind a small bump, which can be seen in the views E and F. The second lamp was directly placed in front of the wall (archaeological zone 7), as indicated on the floor map (H).

Overall, this area can be defined as wide-low chamber type, dead-end side passage, which might need climbing because it shows an inclination of about 32° (21 m of height by 33 m of length). The available space allows a maximum of about 250 people

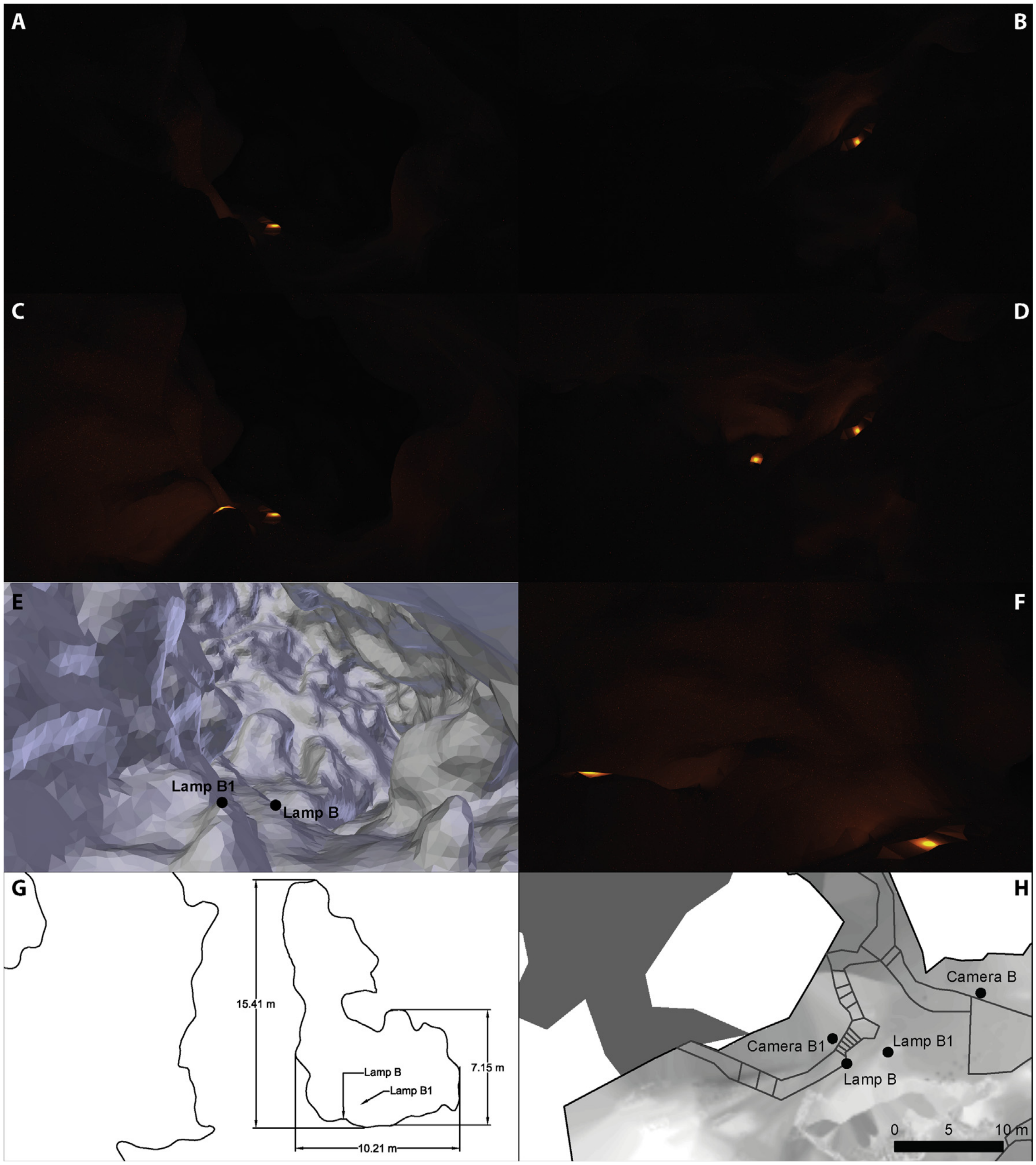

Fig. 3. This figure shows the simulation results of tallow lamp B from a lateral perspective (A) with a distance of 10 m and a top view from the corresponding cave ceiling (B). Accordingly, the simulations are shown with the additional lamp B1 (B & D). For orientation and estimation of the results, a version of the lateral perspective without a lighting simulation is shown (E), as well as a frontal simulation with both lamps (F). The cross-section at the location of the lamp (G), as well as a map of a part of the cave with the locations of the lamps, the camera positions and archaeological zones is depicted (H).

at the same time on 500 m^2, assuming 2 m^2 per individual. The local topography, as shown by Fig. 2 B and D, diminishes the distribution of light on the ground. The additional lamp adds light on the wall of geoarchaeological zone 7, which shows a remarkable engraving of a flamingo (Hoffmeister et al., 2016).

A completely different situation is depicted in Fig. 3, as the lamp is located in a slightly narrow but taller part of the cave (Fig. 3 G). Thus, the single lamp (A, B) illuminated directly the nearby wall. As it is positioned on a small ridge (E), it hardly illuminates the surrounding ground floor (as shown in the top-down view B). The additional lamp adds more light to the complexly shaped wall (C, D, F), but still hardly enhance orientation on the floor (D). This part can be defined as a medium high passageway of the cave, which allows space for 50 people. Particularly, the left wall shows more light, whereas on the right the illumination is also diminished by the local topography. Again the additional light (lamp B1, Fig. 3 C, D, F) enhances the participation at the corresponding wall.

More space is illuminated by lamp C (Fig. 4) next to position B, as the position of the lamp is situated in the so-called Grand Hall with a ceiling height of up to 15 m. In this case, the location of the lamp is close to a wall and directly allows to illuminate this wall (A). The second lamp allows a better orientation, as this location is a niche of the bigger hall. View F recorded from Camera C shows that there is an elevation difference between both lamps. This part represents a wide-high chamber type, which shows at least space for 90 people. Nowadays, this is the only entrance and exit of the cave, but might be at ancient times one of several passages. The lamp is located close to a wall and is only illuminating the wall on one side of the

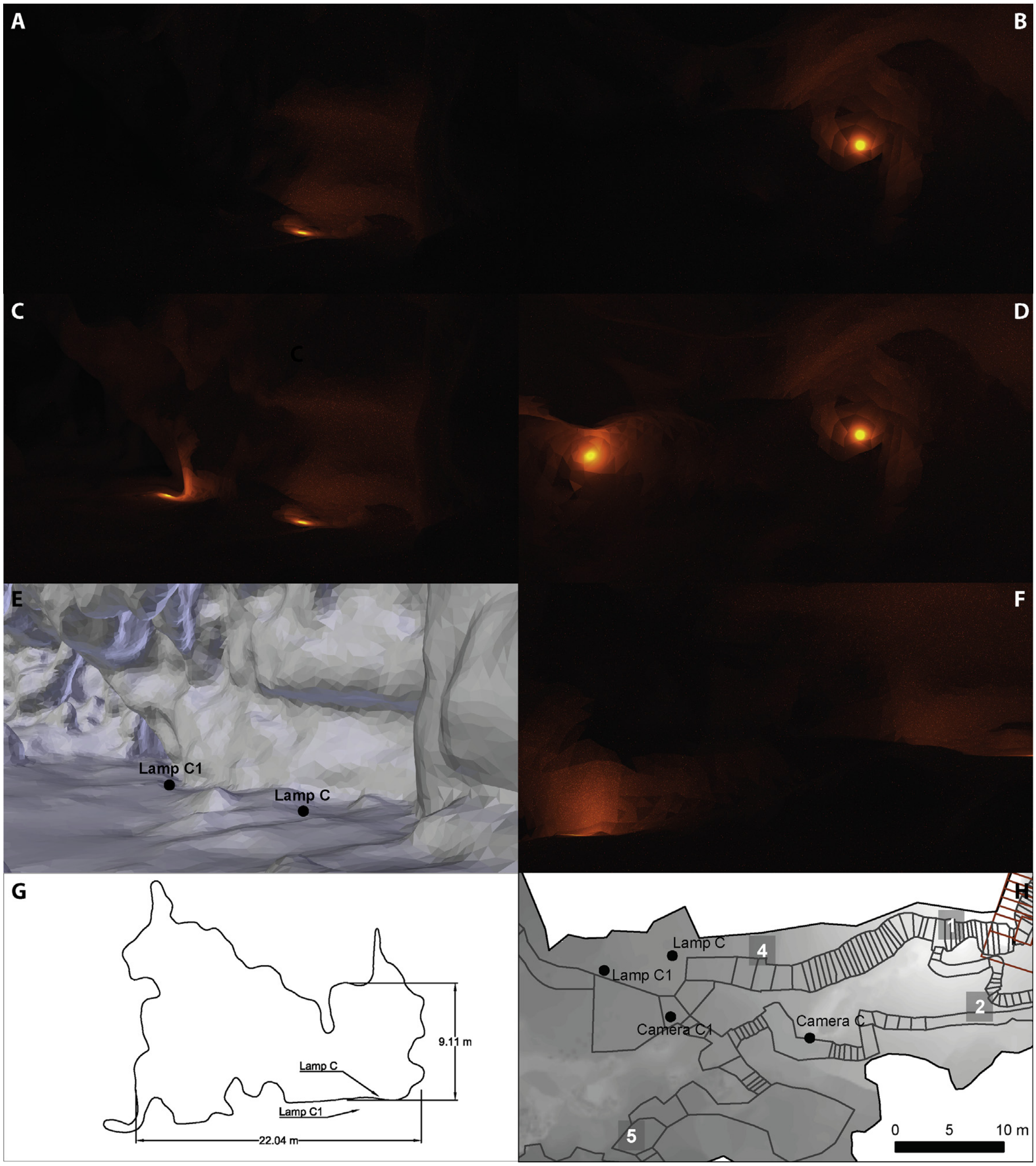

Fig. 4. This figure shows the simulation results of tallow lamp C from a lateral perspective (A) with a distance of 10 m and a top view from the corresponding cave ceiling (B). Accordingly, the simulations are shown with the additional lamp C1 (B & D). For orientation and estimation of the results, a version of the lateral perspective without a lighting simulation is shown (E), as well as a frontal simulation with both lamps (F). The cross-section at the location of the lamp (G), as well as a map of a part of the cave with the locations of the lamps, the camera positions and archaeological zones is depicted (H).

cave and hardly reaches parts of the ceiling. This area is related to previous findings (Hoffmeister et al., 2016), where indirect daylight slightly reaches the ground floor of the main hall. Thus, this area is still in the dark zone, but day or night time might be observed, as indicated in Fig. 1. All other locations depicted in this simulation are lying in the dark zone.

4. Discussion

The presented method was applied to the 3D model of the Ardales Cave (Hoffmeister et al., 2016). This 3D model is a quite adequate representation of the current cave, however several areas were not recorded, due to logistical constraints. Other authors similarly concluded that in the harsh cave environments TLS is a suitable non-invasive method and were also able to establish 3D models and maps from their data records (González-Aguilera et al., 2009; Rüther et al., 2009; Idrees and Pradhan, 2016). However, the tessellated model is always an approximation. In this case, a minimum edge length of 10 cm was used. For several specific areas in the Ardales cave, models in a higher resolution could be established and provided. This approach already shows suitable results and additionally, the method can be easily adjusted to a new and complete 3D cave model with an additional illumination simulation of new or more lamp locations.

Path tracing as an algorithm, which stochastically computes global illumination and thus indirect lighting was used for this cave scenario. In contrast to outdoor scenarios, where the major contribution of light typically originates from direct lighting. In this form, the algorithm does not model passed media and thus does not reflect refraction or scattering of light, e.g. due to dust particles in the air, into account. Extensions of the algorithm exist (Happa et al., 2010) that promote the rendering equation to account for media. The high humidity and particle matter from flames in the cave might change the refractivity. Likewise, the path tracing allows, instead of local illumination to adequately model reflections, and is also capable to regard wet or glossy surfaces (Happa et al., 2009). However, textures are not yet regarded here, as these were not satisfyingly recorded.

In contrast to accurate, dynamical models of flames (Nguyen et al., 2002; Bridault-Louchez et al., 2006) or steady models of candle light, a single point light was used in this approach. This model emits a colour temperature adequately set by a black body conversion of 1,500 K. The size and temperature of the lamp can easily be adjusted to new archaeological findings, which reflect for example fuel type, size and wicks. The implementation in the open-source Blender software is easily applicable by numerous tutorials and the support of a large community (Kent, 2013). Thus, also all other types of illumination can be simulated, for instance, torch light as found in the nearby Nerja cave (Medina-Alcaide et al., 2015).

In general it has to be noted that images for print or display involve the conversion to a color space, such as (i) a cyan, magenta, yellow, and key (black) color space for printers (CMYK), or (ii) a red, green, and blue (RGB) color space for computer displays. Even with a calibrated computer display or new HDR displays (Happa et al., 2010), the actual brightness is biased, e.g. by the brightness of the display or light in the room. Thus, a workflow that simulates the distribution of photometric values and allows to distinguish between the monochromatic perception in the mesopic (>0.003 cd/m^2) and scotopic vision range (<0.003 cd/m^2), as well as photopic vision of colors (luminance >3 cd/m^2) (Yoshizawa, 2009) would be more reliable and comparable.

The results of the simulations reflect the calculations of Pastoors and Weniger (2011), where small candles were able to illuminate distances up to 4 m with enough light for controlled movement. The presented simulations confirm the chamber types proposed by Pastoors and Weniger (2011). For instance the ceilings of the low chamber types are illuminated (Fig. 2), but in contrast the high chamber types show no sufficient illumination on the ceilings (Figs. 3 and 4). However, these maximum radii of illumination are clearly shortened by the local topography of the cave, which is adequately simulated in this approach. In this case study, the amount of luminance of one lamp is most likely not enough in all examples to allow color perception on the surrounding walls.

The described results as well as the accurate determination of further parameters, like path type and available space based on the 3D cave model, enable the quantitative and detailed determination of the selected areas in the manner of the toolkit of Pastoors and Weniger (2011). In addition, the whole toolset and the 3D documentation allows to analyse cave art from several perspectives and in particular in the surrounding context (Robert, 2016). Thus, overall an accurate method is presented, which allows to achieve detailed objective information on the spatial organisation in the cave. As light can be more accurately simulated, also ancient living conditions are shown.

5. Conclusions

In this contribution a new implementation of illumination simulation was provided in order to determine accurate and objective past conditions in a cave. Based on the established 3D model of the Ardales Cave recorded by terrestrial laser scanning, the determination of chamber sizes, relations and distances is straightforward. Light of tallow lamps was adequately simulated by an approach relying on path tracing for global illumination implemented in the Blender software, which is expandable and adjustable. The 3D model and all measurements can be easily exchanged and visualized. In this case, single lamps allow orientation, but for decoration purposes further lamps or other illumination seems to be necessary.

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