Long Paper

Views on Ancient Lighting

Modelling Lighting Devices and Their Effects in Architecture

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Abstract: Lighting is the practise of the deliberate, sometimes combined, utilisation of daylight and artificial lighting devices to illuminate the human environment. Its effects can be reconstructed employing computational simulation from archaeological evidence, the findings of historical building research, and other sources. In the case of artificial lighting this requires modelling flames as the primary pre-modern sources of light. The models must reflect aspects that depend on the research questions typically addressed by lighting simulation, i.e., the emitted luminous flux, its directional distribution and spectral composition, fluctuations of size, intensity, shape and location of the flame, as well as its brightness and appearance. Therefore, the flame of a replica clay lamp filled with olive oil is experimentally characterised in terms of luminance of the flame, and the intensity distribution of its emission. This is the basis for a modelling approach that aims to account for the appearance of flames in terms of luminance, as well as their effect on a room in terms of illuminance. The combination of the flame model with different lighting devices is demonstrated, i.e., a Roman clay lamp and the glass lamps of a Byzantine polycandelon. Research questions with regards to exemplary lighting devices, e.g. a chandelier featuring 55 candles from the early 16th century, and their interplay with their architectural contexts are discussed. The paper presents preliminary results and lines of thought emerging from the authors' ongoing interdisciplinary research on pre-modern lighting devices, lighting practice, and their effects in architectural space.

Keywords: *lighting simulation—luminaire modelling—lychnology—artificial illumination*

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Introduction

Artificial lighting and daylighting are practices to deliberately bring light into the dark that respond to the design and use of architecture. If these are altered or lost, our knowledge about the history of the practices is indirect, inferred from archaeological evidence of preserved lighting devices, indications for window openings sometimes accompanied by finds of glass panes (Grobe et al., 2021, pp. 317–334), and other sources such as texts and illustrations (Papadopoulos and Moyes, 2021, pp. 1–15). From this fragmented knowledge the effects of lighting, which often results from the combined utilisation of daylight and other lighting devices, can be reconstructed employing computational simulation (Happa and Artusi, 2020, pp. 23–42; Noback et al., 2020 pp. 687–706; Schoueri and Texeira-Bastos, 2020, pp. 499–518).

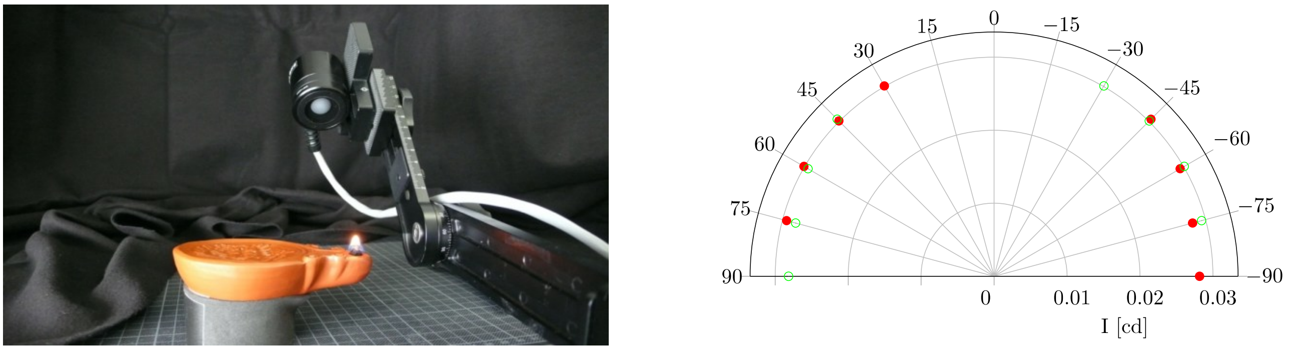
Lychnology as a sub-discipline of archaeology addresses pre-modern lighting. Pre-modern artificial lighting employs devices, or luminaires, such as torches, open fires, candles, and oil lamps (Motsianos and Garnett, 2019), that almost exclusively rely on flames (Weisbuch, 2018, pp. 89–112). Modelling the light emission of flames can be based on an analytical representation of combustion processes or phenomenological approaches, e. g. photometric measurements. The initial, approximately uniform emission from the flame illuminates the luminaire. Mirror-like surfaces or refractive solids, e. g. metal disks or glass lamps filled with fuels, modulate the flame-light and form complex distributions (Kider et al., 2009, pp. 33–40). Based on geometric models, simulation solves lighting in terms of physical quantities: imagery representing luminance distributions, or tabular data, e. g. illuminance distributions on surfaces. Their effects can be functional, e. g. the provision of illuminance for visual tasks, or perceptual, e. g. the appearance of space and surfaces (Noback et al., 2020, pp. 687–706) or the luminaires themselves, and are assessed with metrics and models of human visual response (Doulos et al., 2019, pp. 15–19).

A plenitude of approaches exists in computer graphics to model flames and their visual effects. These techniques often focus on the dynamics of flames, e. g. by particle systems, but do hardly aim at their physical validity. Physically valid luminaire modelling, that is applicable in lighting simulation of architectural spaces with potentially many light sources, must maintain validity but hide the complexity of internal processes in the flame. This paper presents a method for the study of lighting and perception based on modelling luminaires and their effects on the illumination of architectural spaces with the lighting simulation suite *Radiance*. In the presented preliminary phase, the model of the flame is static, i.e., not accounting for movement, flicker, and intensity changes. The applicability of the method to selected cases of lighting devices and preliminary results shall be discussed, providing multiple perspectives onto the authors' ongoing and future research activities in the field.

Methods and cases

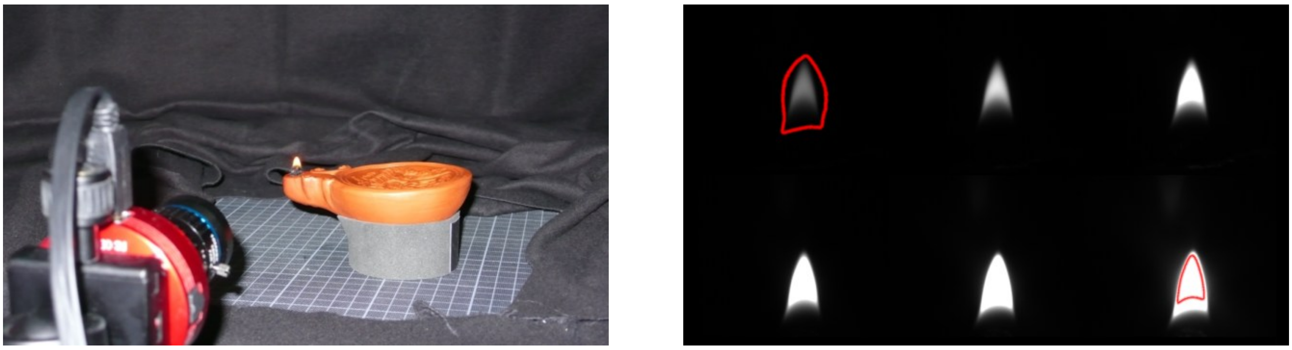
Characterisation of the luminous intensity distribution by flames

The effect of a small light source on its surroundings can be described by its emitted photometric flux (Φ measured in lumens) and its directional distribution (intensity I at any direction in candelas). This abstraction reduces the extents of the flame to one point at its centre. Therefore, it is valid only for cases when the distance D to the illuminated surface is relatively large compared to the source's diameter d, e. g. $D/d \geq 10$ (also referred to as *far-field condition*). Fig. 1a shows an experimental setup for the gonio-photometric, i.e., angle-dependent, acquisition of the intensity distribution emitted by the weak flame of a clay lamp replica. To minimize reflection from the top of the reservoir, it was covered with black cloth. The detector was rotated over the centre of the flame in increments of $\Delta\theta = 15°$. To arrive at stable results, the weak and fluctuating signal was integrated over $30\ s$. The intensity at each data-point can be computed from the measured average illuminance $\bar{E}$ as $I(\theta) = \bar{E}(\theta) \cdot D^2$.



a *b*

Fig. 1. Experimental gonio-photometric acquisition of the intensity distribution of light emitted by a dim flame a). The recorded intensities of $I\ (\theta) \approx 0.03$ cd are approximately constant between vertical ($\theta = 0°$) and horizontal ($\theta = -90°$ and $\theta = +90°$) sensor directions (b), red). No measurements were taken directly above the flame ($\theta = -30°\ to\ 15°$) to prevent damages to the detector. Mirroring the data-points (b), green) illustrates the near-constant distribution (© Authors).



a *b*

Fig. 2. Experimental acquisition of high dynamic range imagery of the flame a). Frames b) are acquired with varying exposure times and image regions of different exposure ranges, illustrated by the largest and smallest shapes (red) (© Authors).

For the given example of a dim[1], axially symmetric flame, the distribution (see Fig. 1b) is approximately constant for any elevation angle. The presented experimental results, that aim to describe only the flame's photometry, significantly differ from reported measurements on complete lamps. Moullou et al. (2012) and Lassandro et al. (2021) measured the intensity distributions of clay and glass lamps with different wicks and oils. The thickness and length of the wick were consistently identified as the most important parameters, that affect the size of the flame and thereby the emitted flux but not its spatial distribution. While Lassandro et al. (2021) observed an increase of intensity toward the top Moullou et al. (2012) measured an almost constant distribution with the minimum over the lamp but with high variance.

Acquisition of the shape and luminance of flames

A flame affects the perception of an architectural space not only by illuminating its boundary surfaces. The image, i.e., the shape and luminance of the flame, becomes a visible feature in the visually perceived space. The image can be captured by cameras, but conventional photography is challenged by the luminance range between the brightest and the dimmer regions of the flame.

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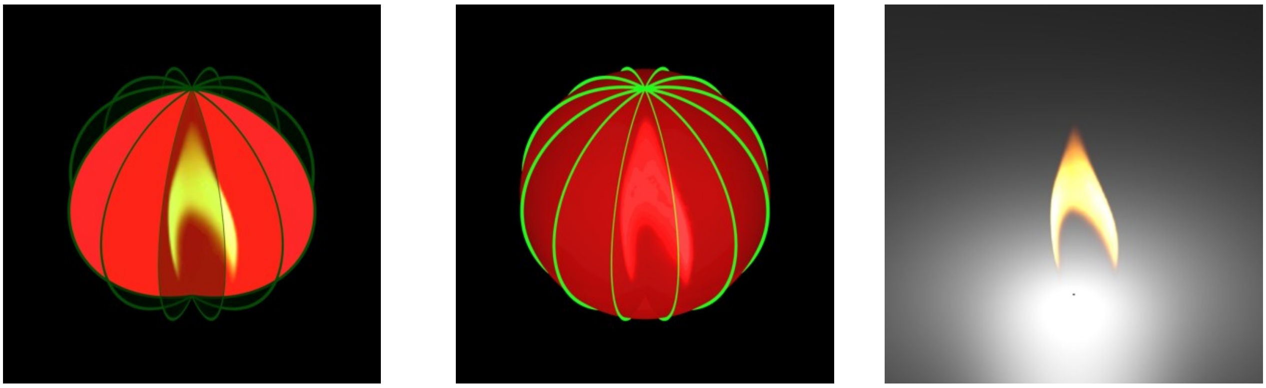
[1] The shown example is an extreme case of a dim flame. Significantly higher intensities were measured on other lamps featuring thicker and longer wicks.



a b c

Fig. 3. *Flame model comprising a set of image maps (a), green). Only one of these is visible at any time to represent the flame's appearance (a, red). Invisible proxy sphere surrounding the flame that illuminates the scene (b, red). Rendering of the combined model in front of a white surface in Radiance (© Authors).*

High Dynamic Range Imagery (HDRI; Pierson et al., 2020, pp. 140–169) was employed to produce a luminance map of the same flame that had been characterised in terms of photometric flux and intensity distribution. A monochrome camera without mechanical shutter and equipped with a telelens[2] captured frames with varying exposure times (see Fig. 2a and b). Since the camera's sensor features not only high sensitivity but also near-linear behaviour, the frames could be merged into HDRI without prior reconstruction of the response curve. The resulting HDRI covers the entire luminance range of the flame. Acquisition and processing of the imagery were implemented with the camera manufacturer's Software Development Kit (SDK), and the OpenCV library[3].

Modelling flames in lighting simulation

While lighting simulation software typically offers little support for flame-lighting, numerous approaches to model the emission and appearance of flames have been developed in the research field of computer graphics (Happa et al., 2010, pp. 23–42). Among these are models of computational fluid dynamics based on the internal combustion processes, particle systems, and recorded video, and image-based techniques that have been combined with an approximation of the illumination effect by invisible emissive *illum* proxies in *Radiance* (Devlin and Chalmers, 2001, pp. 43–48; Ward, 1994, pp. 459–472).

Based on the acquisition of the (approximately uniform) intensity distribution of the flame and the corresponding HDRI as outlined in the previous section, a flame model similar to that by Devlin and Chalmers (2001) was prepared (Fig. 3). The new model differs in that it does not add a photograph of the flame by a post-processing step in the image domain, but rather integrates it into the simulation model. The photograph modulates a *glow* source that does not contribute to the illumination. Other than in the original approach by Devlin and Chalmers (2001), that employs a set of *illlum* spheres of different radii arranged along a curve, a single spherical geometry was employed in this example.

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[2] The camera, a ZWO ASI 120 mm-s, is commonly used in amateur astronomy, features a 1/3" CMOS sensor and captures frames of 12 bit depth with exposure times between 64 µs and 2 s. For this research, it was equipped with a variable aperture, 6 mm to 16 mm c-mount lens, the PT3611614M10MP.

[3] https://opencv.org (Accessed: 10 January 2022).

Note that this, however, can be adjusted as long as the chosen geometry encloses the flame. The *illum* not only illuminates the scene, but also effectively blocks the contribution by the flame image[4].

The HDRI defining the flame's appearance forms its directly visible representation (Fig. 3a). To ensure the visibility of this 2D image from any point of view, a concentric set of image planes is defined (illustrated by the green rings in Fig. 3a), but only the one oriented closest toward the view position is visible (illustrated by the red plane in Fig. 3a). By blending the image map's opacity according to its pixel values, the flame model achieves a high degree of realism and acts as a freely parametrable light source in the scene (see Fig. 3c). The surfaces of the scene are illuminated by an invisible, enclosing geometry (see Fig. 3b). This proxy is modelled by the *illum* type implemented in *Radiance*. In the calculation of the illuminance of the scene, the proxy acts as a light source and blocks the contribution from the HDRI representation of the flame. The modelling approach directly corresponds to the results of flame photometry: HDRI photography provides the flame images, the measured intensity distribution parametrises the *illum* proxy. Furthermore, it is easily adopted, e.g. in interactive models.

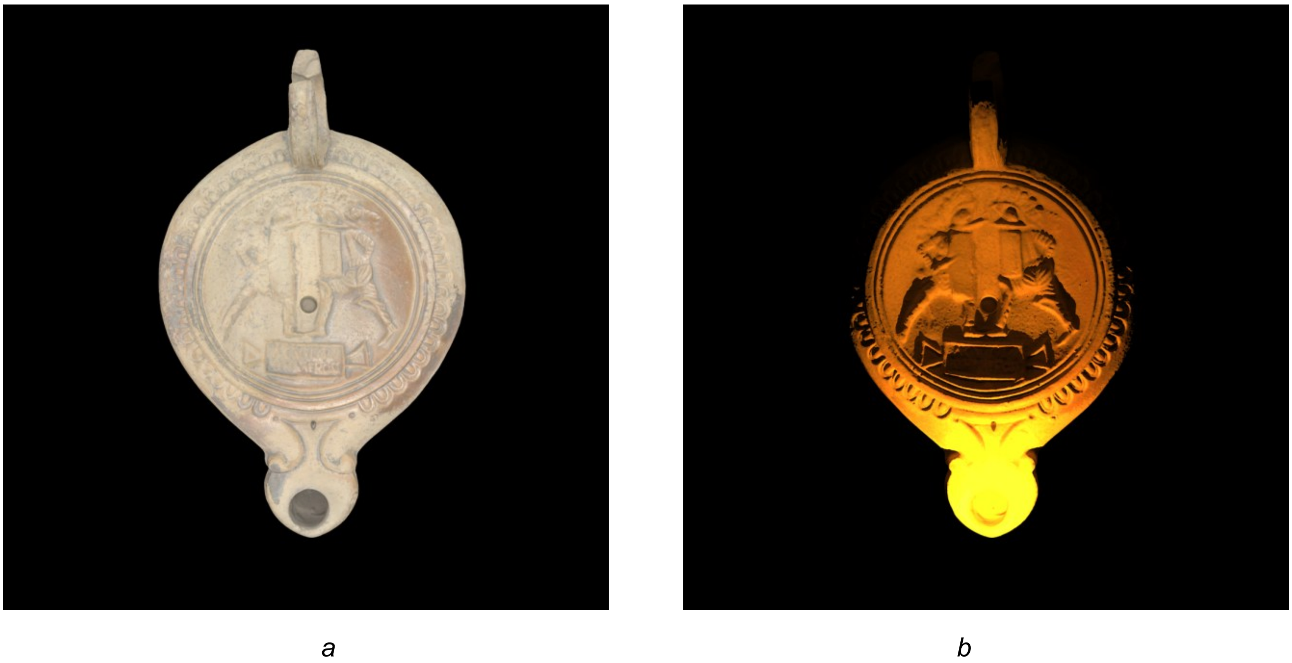

Fig. 4. Model of a Roman pottery lamp under diffuse daylight a) and illuminated solely by the flame model b) (© Authors).

Case 1: A Roman pottery lamp from Italy

A mould-made lamp from the second half of the first century CE, said to be from Pozzuoli,[5] was chosen as an example of a decorated, opaque oil lamp as produced in large amounts in antiquity. The relief on the top, showing two fighting gladiators with their inscribed names, suggests that the lamp had a decorative value besides its utility. The lamp's geometry has been digitized and is made available together with high resolution colour data by the British Museum. This allowed to prepare a model to test the appearance of the lamp and its relief in its current state of preservation. Contrasting typical depictions (Figure 4a), under realistic lighting conditions when the lamp was in use, the relief would not have received significant diffuse illumination. Rather the predominant, since closest, light

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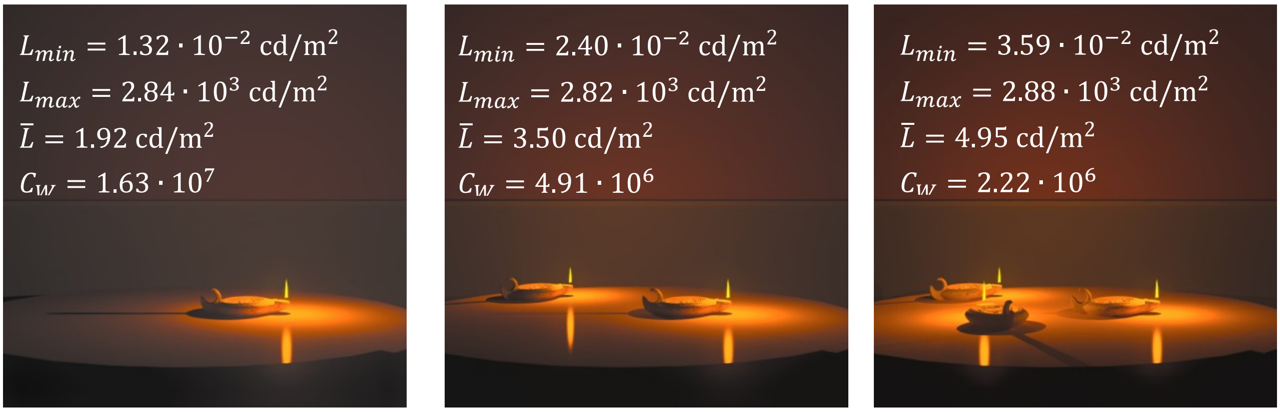
[4] Since the *illum* proxy shades other sources, contributions of different lights are computed separately in the case of nearby flames.

[5] British Museum asset number 1613683440, a photograph is available at https://www.britishmuseum.org/collection/image/1613683440

source was its own flame. This case, the lamp was combined with the previously described flame model (but parametrised for a larger flame) and a top view corresponding to the photograph was rendered (Fig. 4 b).



a *b* *c*

Fig. 5. Additive effect of sources on illumination and contrast: Exemplary room illuminated by one lamp a). While average illuminance $\bar{L}$ on the wall and minimum luminance L_{min} in the shadows increase with the number of lamps, Weber contrast $C_W = (L_{max} - L_{min})/L_{min}$ decreases since the maximum luminance L_{max} at each flame is constant b), c) (© Authors).

Fig. 5 shows oil lamps with an intensity of $4\ \mathrm{cd}$ and correlated colour temperature of $1780\ \mathrm{K}$ in a predominantly diffuse reflecting environment.[6] Placing a single oil lamp on a table (Figure 5 a) results in pronounced shadows of the lamp and the furniture, and smooth gradients in the illumination of nearby walls. Surfaces next to the flame are brightly illuminated. Adding more oil lamps (Figure 5 b, c) results in more complex half shadows. While the brightness of the individual flames remains constant, the background luminance increases. This decreases contrast and supports colour.

Case 2: Glass lamps on a Byzantine polycandelon from Turkey

A typical form of Byzantine oil lamps resembles a glass funnel (Fig. 6a). The stem is meant to fit into a hole and may keep the wick, that floats on top of the oil, in the centre of the lamp. The upper part containing most of the oil is widened to form a beaker or bowl (Çakmakcı, 2008). Groups of such lamps could be held by devices such as the 6th century silver circular polycandelon shown by Fig. 6 b. It can hold 12 lamps by its outer ring, and an additional four within. If clean and polished, the silver surfaces must have featured significant specular reflectance. Combined with typical glass lamps, this polycandelon is expected to produce a complex reflection and refraction pattern.

Preliminary models of the polycandelon and a glass lamp were prepared (Fig. 6 c). The polycandelon was approximated by vertical extrusion of its contours (with specular and diffuse reflectance set to $\sigma_s = 0.73$ and $\sigma_d = 0.04$). The lamp's glass reservoir was modelled by revolving the section around the vertical, defining a glass solid. The contained oil forms a second dielectric solid. This leads to three kinds of optical interfaces between air and glass, air and oil, and oil and glass. Reflection and transmission at these interfaces are described by the refractive indices of the solids ($n = 1.52$ for glass, $n = 1.45$ for oil). Absorption by the oil that further modulates the transmitted spectrum was not

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[6] To model human response, the luminance images were tonemapped with the *pcond* command of *Radiance*. The software simulates the reduced acuity and colour vision in dark image regions, veiling glare surrounding bright regions, and contrast sensitivity (-h switches of the command).

taken into account, since the effect is subtle and affects only the less pronounced downward emission. At the centre of each glass lamp, slightly above the surface of the contained fuel, the previously introduced flame model was inserted.

To illustrate the interplay of such a light-source and a typical interior of its time with highly specular surfaces, the model is introduced into a simplified vaulted room with gold mosaics (Fig. 6 c). The mosaics are represented by a layered procedural model that modulates reflection according to the perturbation of the surface geometry at micro-, meso- and macro-scales and is parameterized in accordance with measurements on a gold-glass tessera (Noback et al., 2020, pp. 687–706).

a b c

Fig. 6. Section of a glass lamp (Fig. from a catalogue; Çakmakcı, 2008) as basis for modelling a). Polycandelon at Antalya Museum, Turkey[7] *b). Simulation of the combined effects of refraction by glass lamps and reflection by polycandelon and gold-mosaic (c), tonemapping as in Fig. 5) (© Authors).*

Case 3: The chandelier with the Virgin Mary from Nuremberg

The chandelier with the statue of the Virgin Mary by Veit Stoß (see Fig. 7) was created in 1518 for the St. Lorenz Church in Nuremberg. With a height of 2.5 m and diameter of 2.3 m, it holds 55 candles, 11 candles on each of its five arms (Henkelmann, 2020, pp. 97–134). The centrally placed figure of the Virgin Mary is thus evenly surrounded and illuminated from all sides. Mounted slightly elevated, however, the figure of the Virgin is illuminated from below.

Due to its size and the splendor of its light, the chandelier serves not only the source of illumination for the sanctuary with its choir stalls and high altar but accentuates the inner choir as highest-ranking space of the parish church. Furthermore, up to the present the chandelier of the Virgin Mary forms an ensemble with the so-called *Englischer Gruß* by Veit Stoß, a depiction of the annunciation framed in an open rosary hanging from the Eastern vaults of the sanctuary, with regards to both iconography and illumination. The number of candles e. g. refers to the 55 medieval prayers of the rosary. Their light did not fall on the sculptures by chance, but the chandelier and the rosary were deliberately placed in relation to each other in such way that the arrangement with a distance of approx. 8.5 m produces a soft illumination of the carved figures depicting the announcement.

The light, however, not only highlighted the sculptures, but also iconographically linked the Marian chandelier and the Annunciation group by visualizing Jesus Christ, the light of the world (John 8:12), announced by the archangel and entered the world through the Virgin Mary (Henkelmann 2018, pp.

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[7] Antalya Museum inventory number #A.1054, photograph by Dick Osseman: https://pbase.com/dosseman/image/159765773

45–62). In conclusion, the chandelier and the sculpture formed a closely interrelated ensemble that can only be understood in its meaning through the light emanating from the chandelier and connecting both elements.

The wealthy patrician Anton II. Tucher from Nuremberg, who donated the ensemble, directed in his testament that the 55 candles of the chandelier should be ignited on every Christmas over a period of ten years after his death. There are no written sources with regards to other uses of the chandelier. However, due to the amount of required wax candles, that were an expensive good in medieval times, one can assume that the chandelier was illuminated only on important fest days, especially high feast days like Christmas or Easter and Marian feast days.

Discussion

Characterisation and modelling of flames in lighting simulation

In previous research, the reported differences between light intensity distributions have not received an in-depth discussion. One may propose the subtle differences of the flame shapes and the reflection by the reservoir of the sprouted lamps as possible explanations for the apparent differences. Moullou et al. (2012) show an image of a sprouted lamp with a wick that is tilted from the vertical by approx. 60 °, leading to a horizontally prolonged shape that may explain the higher intensity for directions close to horizontal. The asymmetric distribution of a sprouted lamp shows the strong sensitivity to the geometry of the reservoir, which defines a cut-off angle at which direct emission is entirely blocked. Lassandro et al. (2021) do not show the measured flame in detail, but the maximum for near-vertical directions could have been influenced by the reflective properties of the lamp. Both effects were minimized in the experiment presented in this paper.

While the difficulties to interpret measured photometric data of flames and the lack of discussion of apparent contradictions indicate a need for further research in the field, all measured distributions are at least close to constant for directions where the flame is not obstructed by the reservoir. This may suggest that for modelling the illumination of architectural spaces, the assumption of a constant distribution by the flame may be sufficiently accurate, while great care should be taken to replicate the reservoir's geometry – defining the cut-off angle – and the size, thickness, and orientation of the wick – effecting the size and shape of the flame as well as the total flux emitted by the lamp.

The total acquisition time for all frames merged into one luminance map is defined by the required dynamic range – suggesting the number of frames – and the lowest luminance value to be accounted for – defining the maximum exposure time. This leads to a dilemma when flames of variable shape and intensity shall be captured, since the dynamic range (in particular the lower luminance range) has to be traded against the temporal resolution (e.g., the 'frame-rate' of the acquired HDRI). This limitation may be addressed e. g. by custom cameras for high dynamic range video.

Fig. 7. Chandelier with the Virgin Mary in St. Lorenz Church, Nuremberg, Germany. (© Vera Henkelmann mit freundlicher Genehmigung der Ev. Kirchengemeinde St. Lorenz Nürnberg).

Decorative, opaque oil lamps

The exemplary pottery lamp, a simple case at first sight, reveals that studying illumination by this prevalent luminaire calls for systematic research on its effects in several domains – that of the lamp itself, and that of the architectural space where it was used.

The perception of the decoration differs significantly when seen under the illumination by the flame when compared to the even illumination under which archaeological artefacts are commonly depicted and studied. The variability of flame shape and position, e.g. in the presence of air flows, have not been studied in this research but can be expected to further impact the perception.

The fact that the luminous flux of an oil lamp cannot be scaled almost freely as is the case with modern lighting means that illumination increases not with the intensity, but with the number of light sources. This opens a multitude of questions on the perception of architecture, of decoration and wall-painting, and the application of non-diffuse surface finishes. They concern the diverging effect of multiple lamps on illuminance and contrast, the perception of colour, the nature of shadows, and the fulfilment of requirements for visual tasks.

Flames, transparency, and specular reflection

The polycandelon presents itself as an extended source of bright light. Placed in the field of view it forces the eye to adapt, leading to perception of the room as dark. This is not diminished by the highly specular optical behaviour of the gold mosaic that itself features a high contrast between view dependent highlights and a dark background. The polycandelon reflects most of the light to the ceiling and leaves the rest of the room in darkness, augmenting these effects.

In the mosaic two types of specular reflections can be identified: mirror-like images of the flames reflected at the glass surfaces and a wider spread glossy reflection on the gold layer. Both are perturbed by the perturbated orientation of the individual tesserae. This introduces geometric glitter that is dynamized by small offsets of the viewpoint. The combination of these effects with that of moving and flickering flames on the appearance of the gold mosaic have yet to be studied by simulation.

The chandelier and Its relation to architecture

The chandelier illustrates further aspects relevant to the study of lighting liturgical spaces. First, it not only forms a lighting device but is also part of the illuminated furnishing that has to be interpreted not only as a functional but religious ensemble. Second, the context defines a liturgical schedule that may have set the luminous conditions, e. g. the presence of – even dim – daylight as well as the position of observers and the connotation of spaces in the church. Experimental approaches to study such spatio-temporal dimensions of the effects of a chandelier over extended periods are limited not only by the practical effort of repeated experiments, but also by the liturgical use of the church space. Therefore, lighting simulation is hoped to provide a means to expand the study of the chandelier from theoretical deliberation and snap-shot observations to account for the spatio-temporal dimension typical for the use – and probably the illumination – of liturgical spaces.

Conclusions

The reported methods[8] and results give an insight in ongoing investigations and the development and formulation of new research questions. They are preliminary and propose discussion and questions rather than offering undisputed answers. The authors' backgrounds in different disciplines reflects the multidisciplinary nature of the research field, which is advanced by the joint objective to study lighting devices, lighting practice and effects, and the architectural contexts in combination.

The examples of the relief on a clay lamp and the polycandelon demonstrate that the understanding of luminaires as artefacts can be enriched if illumination is taken into account. The chandelier with the Virgin Mary stands as an example for a luminaire designed for a specific architectural context. It further introduces the spatio-temporal dimensions if the use of a lighting device can be related to liturgical schedules and the spatial attribution of meaning and importance. One central aspect of all presented lighting, its dynamic nature, was not assessed yet but expands its study to yet another temporal dimension.

Besides enriching the study of objects and architectures themselves, the systematic research of lighting in the historical sciences may contribute to an understanding of the perception of architecture in the past. Here, lighting simulation may directly contribute to sensory studies that may support the interpretation of what illuminated and what was illuminated across the disciplines.

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[8] The models prepared for this paper are available in a Git repository: https://c4science.ch/source/CHNT26-Lighting-Simulation/

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Conflict of Interests Disclosure

No potential competing interests have been reported by the authors.

Author Contributions.

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Writing – original draft: L.O. Grobe, A. Noback, V. Henkelmann, R. Bielfeldt, F. Lang

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[9] Project record in DFG's funding database GEFRIS: https://gepris.dfg.de/gepris/projekt/456917156

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