DIGITAL HERITAGE (2025)
S. Campana, D. Ferdani, H. Graf, G. Guidi, Z. Hegarty, S. Pescarin, and F. Remondino (Editors)

Rediscovering Mural Paintings: Experiencing Medieval Art as Originally Conceived Through Historical Light Simulation

I. Munoz-Pandiella[1], M. Kaur-Singh[1], C. Bosch[2], C. Andujar[1], and X. Pueyo[3]

[1]Universitat Politècnica de Catalunya, Spain
[2]Universitat de Vic - Universitat Central de Catalunya, Spain
[3]Universitat de Girona, Spain

Abstract

The lighting of Cultural Heritage artifacts plays a crucial role in how we perceive and consequently understand artworks. However, lighting is typically designed to enhance the experience of contemporary visitors, often diverging significantly from the original conditions and techniques under which these works were created. This disconnect between historical and modern lighting conditions makes it difficult to fully understand the original visual experience. This issue is particularly evident in the case of Romanesque paintings, which are now exhibited in well-lit museums, but were originally displayed in dimly lit churches. In this paper, we present a method to bridge this gap, focusing on the paintings of a Romanesque church. We achieve this by simulating the original lighting conditions. Our approach encompasses the entire pipeline, from acquiring data of equivalent historical light sources and computing natural lighting to performing physically based rendering for accurate light simulation. Additionally, we have developed a web application that allows users to inspect and compare the resulting HDR images using different tone mapping and luminance operators. Our work provides a valuable tool for art historians and the general public to explore different lighting hypotheses and gain a deeper understanding of the experience of visiting a medieval church as originally conceived.

CCS Concepts

• ***Applied computing*** → ***Fine arts;*** • ***Human-centered computing*** → *Scientific visualization;* • ***Computing methodologies*** → ***Rendering;***

1. Introduction

In the study of Cultural Heritage, lighting conditions play an essential role in the perception and comprehension of artworks. However, the lighting conditions at which ancient artworks are exhibited today in museums often differ drastically from the lighting conditions at the time these artworks were created or meant to be observed. On the one hand, lighting configurations in museums are often optimized to enhance the visual appeal of artwork, to highlight specific features, and to improve the overall viewing experience for visitors, while ensuring its preservation by minimizing damage from excessive light exposure. On the other hand, the lighting conditions present at the time of the artwork's creation were more rigid and often obeyed different criteria, such as adjusting to available natural light, or following religious or symbolic narratives. This disparity between current exhibition methods and historical lighting techniques can severely hinder our understanding of the original visual experience intended by the artists.

This issue is particularly evident in the case of Romanesque paintings, many of which are now exhibited in well-lit museums but

Figure 1: *Lighting conditions in museums often differ substantially from those conditions at artwork creation time. Left: Photo of the remainings of a Medieval mural painting, exhibited in a physical mock-up of the original apse at the Museu Nacional d'Art de Catalunya in Barcelona. Right: Photo of the actual apse in the church, that shows a recreation of the original painting, illuminated with candlelight. Notice the dramatic effect of lighting on the appearance of the painting and its surroundings.*

were originally created to be viewed in the soft lighting of dimly lit churches, which often added an ethereal or mystical quality to the artwork.

With regard to natural light, many studies have analyzed how the observation of daylight has influenced art and architecture. In the case of Christian churches from the early Middle Ages, medieval writers described dramatic lighting effects aligned with the rising sun on important astronomical and liturgical dates [Ata15], and some researchers suggest that some pictorial compositions were designed to highlight specific figures at certain times and dates through the strategic placement of the paintings with respect to the windows [Ata15]. All these effects are impossible to observe by contemporary museum visitors, whose perception of the paintings is severely dominated by lighting conditions that, in most cases, differ significantly from the ones at creation time (see Figure 1).

In this paper, we introduce a research methodology designed to bridge the gap between the perception of artworks in museum exhibits and how these artworks were originally conceived by artists, focusing on medieval mural paintings. More precisely, our goal is to provide users the opportunity to understand these artworks by allowing them to be observed under the hypothesized historical lighting conditions.

Since our priority is to provide an accurate simulation of the original lighting conditions, we simulate them with physically-based rendering. Our approach encompasses the entire pipeline, from reconstructing light sources similar to those illuminating churches in the middle ages, to acquiring their spectral data and performing physically-based spectral rendering for accurate simulation of light scattering through the scene. Concerning the original light sources, we acquired the spectral distribution of artificial lights (such as oil lamps and candle lights) and computed sunlight considering the location and orientation of the church with respect to the Sun at certain dates and times. Since light entering through all the windows contributes to the final renders, we used a full reconstruction of the building's geometry, even though each render shows only one of the apses showing mural paintings.

Ultimately, the images to be rendered depend on multiple parameters: the architectural and pictorial phase of the monument (quite relevant in monuments with a rich history of transformations), the part of the church to be shown in the image, the viewpoint for showing that part, and the configuration of the natural light (including date and time) as well as the artificial light (number and location of candles and oil lamps), according to a collection of hypotheses from the art historians. We therefore developed a web application that allows users to select, visualize, and compare renders for different time periods, different regions of interest, and under the lighting conditions of different hypotheses. In our pipeline, spectral renders are converted into HDR images; our application also allows users to choose among different tone mapping and luminance operators to display these HDR images, as well as to compare two side-by-side renders by mapping the radiance difference onto a color gradient.

We believe that our work provides a valuable tool for art historians and nonprofessionals to test and explore different lighting hypotheses and gain a deeper understanding of the experience of medieval church worshippers and visitors.

2. Previous Work

To enhance the knowledge of Middle Ages frescoes, it is mandatory to approach as much as possible the perception of the frescoes under the lighting conditions of that time. Therefore, we have to simulate the behavior of light in a digital model of the church with the highest precision, focusing mainly on physically based techniques.

The simulation of daylight has been studied from both fields of Computer Graphics and Physics, and has been used for lighting in CH digital models [HBRW*12, HA20]. Some of the most relevant software contributions to achieve this goal date from the end of the 20th century [LS98, DKN*03]; although the subject has kept the interest of significant research laboratories for years [HW12, KJKN*14, MBM*17, YBF*22, GNWM24]. Apart from the use of general purpose simulation software, image-based approaches were also investigated by Happa et al. [HAD*09, HBRW*12] by means of taking on-site measures of the sky contribution to generate HDR environment maps. Given that participating media are also present due to dust and smoke, their effect was also studied by Gutiérrez et al. in [GSGC08]. Obviously, to be useful, we have to apply a technique that allows us to specify the date and time for which we need to compute the natural illumination. It is important too to verify whether the orientation of the church is really east-west [YBF*22].

Artificial illumination in churches in the Middle Ages was mainly done using candles and oil lamps [MG19, DJPS20]; therefore, it is needed to be able to simulate flame lighting. Research has been done for simulating flames since the 90s. Some are physically based [SF93, NFJ02] and others are empirical, sometimes enough to satisfy the requirements of many applications [Ina90, IM04, BLRR07]. The shape and movement of the flames are also important, but the most relevant feature of them is their emissivity, as shown in [GMaMC09]. Using HDR imaging for capturing ancient artificial lighting has also been addressed [Tai23]. Camparo simulated both daylight and artificial lighting to study social and spatial behaviors in the Roman house [Cam23].

For additional information on lighting in CH applications we recommend the survey of Happa et al. [HMD*10]. Even though this state-of-the-art paper dates from 2010, very little new contribution has been published since then [YBF*22].

3. Historical Aspects

Sant Quirze de Pedret is a small medieval church located in Catalonia, near the Pyrenees [Yar85]. Close to an important historical route, it holds great significance in the study of Medieval art for different reasons: the history of its construction, the undergone architectural modifications, the preservation of two pictorial layers resulting from different decorative campaigns, and the extraordinary quality of the paintings.

Originally built in the late 9th century as a single-nave structure with a quadrangular apse, it was expanded in the mid-10th century with two lateral aisles ending in horseshoe-shaped apsidioles (see Figure 2 top). The architectural transformation coincided with the church's first layer of mural decoration, while a second, more extensive program of Romanesque frescoes, was later super-

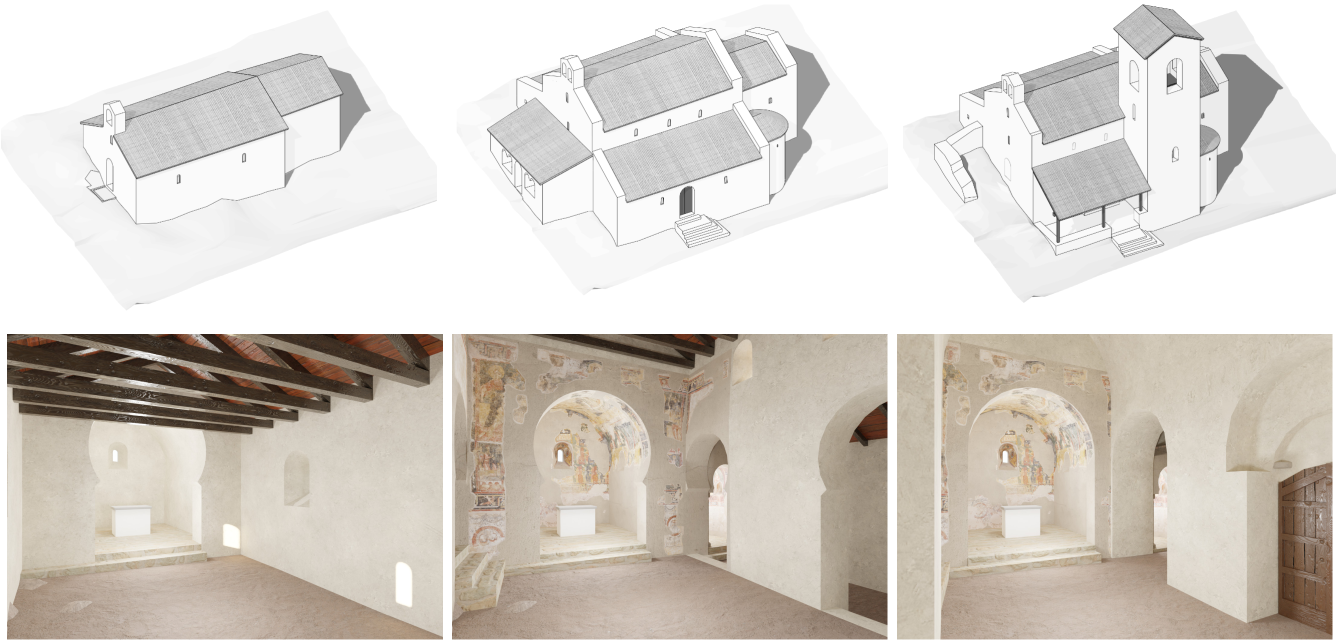

Figure 2: *Drawings (top) and digital models (bottom) recreated for the most significant architectural stages of the site. From left to right: 9th, 12th, and 13th century.*

imposed [LMCM95]. The paintings were partially concealed following structural damage in the 13th century, which led to major repairs and the loss of an aisle. Only the south apse frescoes remained visible until their rediscovery in the late 19th century. In the 20th century, most frescoes were finally removed and transferred to two different museums for their conservation, where they remain to this day [Man12, Cay22].

In terms of lighting, Middle Ages' churches were lit by natural light (daylight) and artificial sources (candles or oil lamps) [MG19, DJPS20]. For natural light, we must consider the properties of the openings, such as their location, shape, state or covering material. Location and shape depend on the chosen century, due to the undergone architectural changes. The lighting entering the central nave, for instance, changed over the centuries due to the incorporation of aisles and other structural elements (see Figures 2). As for the covering material or state (open or closed), there is no reliable information. From indirect studies on the state of the paintings close to the windows, experts assume that windows did not have any closing system or covering. At last, the location and orientation of the church are also important, the latter being defined by a west-east orientation with a 17.5º deviation. Figure 3 shows the incoming daylight entering through the openings at different times, as well as the church's orientation.

Regarding artificial lighting, historians believe that two or four standing chandeliers were installed on the sides of the altar of the central apse, and one or two other flames on top of the table. This would ensure sufficient lighting during liturgical ceremonies in the absence of natural light. Oil lamps were often incorporated using polycandelons, which consists of a ring with several oil cups typically hanging from the ceiling of the main apse or other entrances.

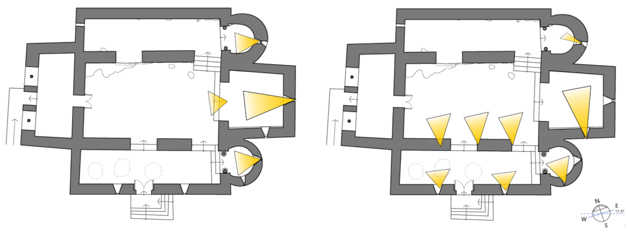

Figure 3: *Church plan for the 11-12th century showing the natural light entering the openings at sunrise (left) and noon (right). Church orientation is shown in the bottom right.*

Figure 4 shows the final layout of the artificial sources according to experts.

4. Site and Lighting Reconstruction

The historical architectural phases of the church were modeled in 3D according to existing plans and documentation, as well as art historians' feedback [MPAMLO*22] (see Figure 2 bottom). For the paintings, a set of photographic campaigns was carried out at the different sites (the two museums and the church remains). The same images were used to capture the underlying shape containing the paintings by means of photogrammetry. The 3D paintings captured were finally aligned and transferred to each model, and a virtual color restitution step was applied to restore their original colors [MPAC*23].

The artificial light sources were modeled similarly using a set of

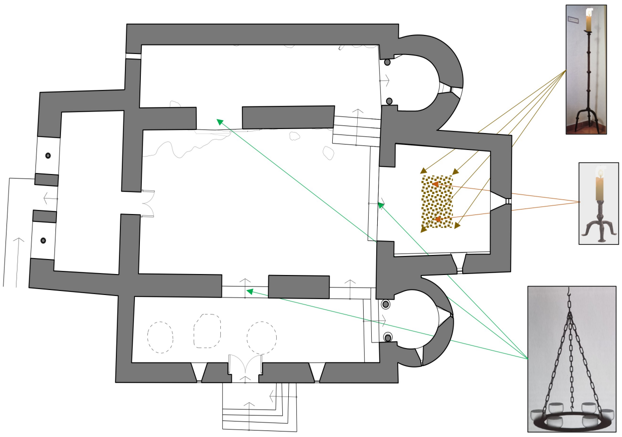

Figure 4: *Church plan for the 11-12th century showing the layout of artificial light sources according to art historians.*

Figure 5: *Setup used in the measurements of artificial light sources, here applied on the olive oil candle with salt. Right: EOP-146-2 optical probe coupled with a CAS140D spectrometer from Instrument Systems. Left: UI-1480SE-M-GL camera from iDS (for video recording).*

reference images. For the chandeliers, we resorted to pictures and measures of a real chandelier from the *Museu Comarcal de Berga*, which corresponds to the same epoch. The candles, both for the chandeliers and the altar, were based on an existing open source model. Regarding the table chandelier and the polycandelon, a set of historical pictures was finally used to generate the corresponding 3D models. See Figure 4 for examples of the pictures used to create the models.

In terms of spectral information, we collected a set of representative samples and measured their emissivity. We arranged two candles of paraffin wax of different wick thicknesses, one candle of beeswax, and two samples of oil lamps, one with added salt. The measurements were then performed in a specialized laboratory at the Center for Sensors, Instruments and Systems Development (CD6) of the *Universitat Politècnica de Catalunya*. For each source, we took measurements from different angles to evaluate their variability, both in elevation and azimuth. The measurement setup is shown in Figure 5, while Figure 6 shows the measured spectra for a specific direction. As can be seen, their spectra are generally smooth. Angle variations, though not shown, mostly resulted in an overall intensity/scaling effect of each spectrum. We thus resorted to the ones measured from the frontal direction.

5. Light Simulation

For the light simulation, we used Mitsuba 3 [JSR*22], a unitless physically based renderer that provides accurate lighting results when working with physically measured data. The scene was configured according to the types of light sources present in the proposed hypotheses.

For artificial lighting, we used the 3D models of light sources described earlier. The flame component of each model was defined as an emissive shape, which emits light based on the spectral data available for each specific light source. This setup allows us to test different combustion materials simply by changing the associated spectra. The spectra were weighted by the solid angle subtended by the flame shape, ensuring that the correct radiance was used in the simulations.

For natural lighting, we adopted a two-part approach: the Sun was modeled as a directional light source, while the sky was represented by a uniform environmental light. The corresponding spectra were as follows: for the Sun, we used direct solar irradiance; for the sky, we integrated the diffuse irradiance received by a horizontal surface. Although this approach does not account for potential variations in skylight, such simplification has a negligible effect on the final results, because of the low contribution of sky illumination with respect to the Sun. The radiances of the Sun and the sky were estimated using SMARTS (*Simple Model of the Atmospheric Radiative Transfer of Sunshine*), a model hosted by NREL that allows simulating the irradiance of the sun and sky under variable atmospheric conditions [Gue01]. The model was configured using the geographical coordinates of the site, the typical atmospheric conditions of the region, the historical period, and a set of selected dates and times. Figure 7 shows the spectral distribution used for natural lighting.

Since spectral information for the paintings is currently unavailable, we converted the available RGB photogrammetric data into spectral data using the uplifting technique provided by Mitsuba 3 [JH19]. The resulting spectral images were then converted back to RGB, taking into account human visual sensitivity. No further processing was applied, in order to keep the resulting HDR images as unaltered as possible.

Our simulations considered three key dates: December 25th, April 1st, and June 16th. These dates were selected based on recommendations from art historians, who identified them as liturgically significant for the church. For each date, three specific times were analyzed. First, 10:00 a.m. in local (current) time, to provide insight into how the church is illuminated at that same hour today. Furthermore, we selected 10:00 and 12:00 in solar time to represent

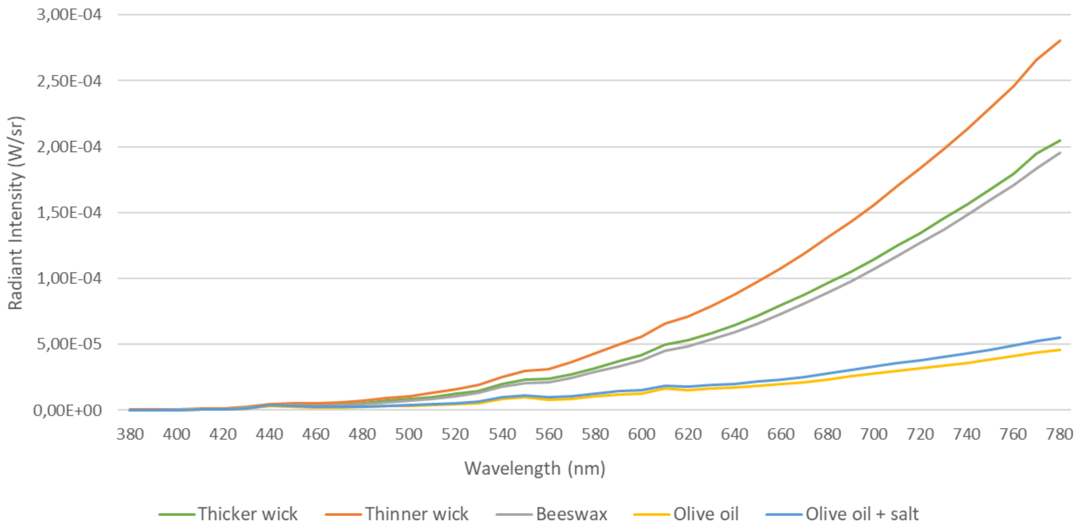

Figure 6: *Measured spectra for the different artificial light sources obtained from a frontal direction.*

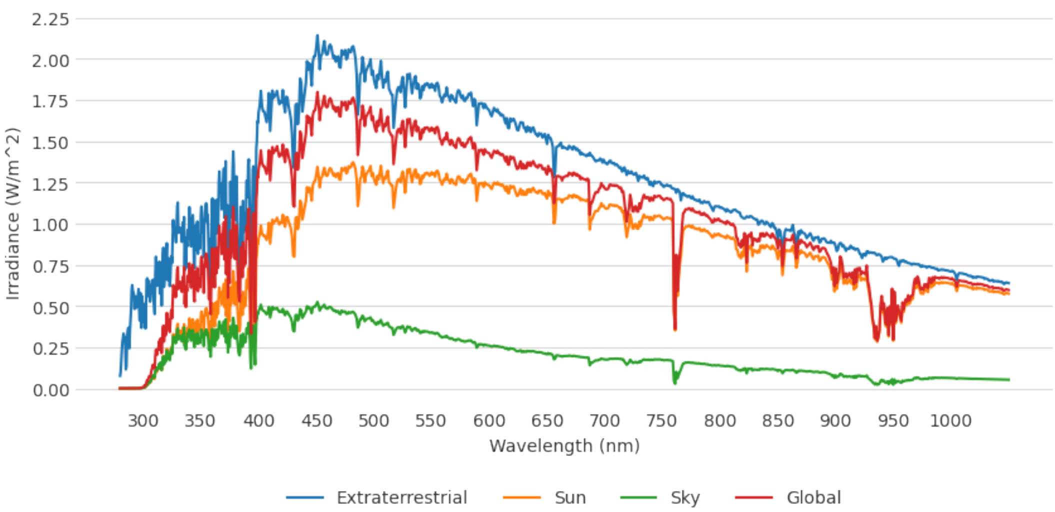

Figure 7: *Spectral power distribution of the natural lighting at Sant Quirze de Pedret, on June 16th at 13:53. The direct beam radiance is shown in orange, the sky radiance in green, their sum (total ground-level irradiance) in red, and the extraterrestrial irradiance in blue.*

moments likely to have been significant during liturgical practices in the historical context. It is important to note that during the period when the paintings were created, timekeeping was based on solar time, meaning that the same solar time corresponds to a different clock time today.

For the renderings, we selected two different viewpoints. The first is focused on the central apse, where key liturgical actions took place and where a significant portion of the painted decoration is concentrated. This view allows us to analyze how light affects the perception of the paintings in detail. The second viewpoint provides a more general perspective, offering a broader understanding of the interaction between light and the architecture of the church.

6. Visualization

We have developed a web application for the inspection and comparison of the light simulations obtained. The application takes as input the precomputed renders and allows users to navigate through them (zoom and pan) as well as to compare them side by side. The original HDR renders are displayed using a set of tone-mapping operators, where the user is able to choose the desired method and their parameters. The available operators include linear, Reinhard [RSSF02], and extended Reinhard [RWPD05]. The first two are controlled by a simple exposure parameter, whereas the latter uses Reinhard's *key* and L_{white} parameters. In all three cases, a final gamma correction is applied.

Figure 8: *Web application used to inspect and compare light simulations: interactive viewer allowing a side-by-side comparison of any pair of images. The viewer includes its own control panel on the top right.*

We also support the visualization of the luminance map by means of a perceptually uniform colormap, where the maximum luminance can be adjusted by the user. This operation is intended to visualize the energy distribution in the scene as a result of each light configuration. A final operation supported by the application is the computation of an image difference between the two renders. This operation also relies on a colormap, this time based on a diverging one (BWR), indicating in blue or red the places where the energy is higher in the left or right renders, respectively (see Figure 13). The image difference can be overlaid over one of the images and controlled by a maximum difference parameter to adjust the level of difference between the renders.

The interactive viewer (see Figure 8) is implemented using NodeJS and ThreeJS. It also relies on lil-gui for the control panel. The panel is based on a simple drop-down window that contains the image selectors and the different operations and parameters. The window is made available when needed to maximize the visualization area. We also created a simple Vue-based application with multiple tabs to allow users to select the subset of images to be inspected in the interactive viewer (see Figure 9).

7. Results and Discussion

The code for both the lighting simulation and the web app visualizer is available on https://github.com/UPC-ViRVIG/MuralLighting. A supplementary video demonstrating the main results is available at https://youtu.be/AUqzzYyuAXw.

Figure 10 shows examples of daylight simulations obtained for different dates and times. Notice that the interior of the church receives more light in winter (left) than in summer (middle), due to the Sun altitude being lower in the former. This is accentuated in the evening (right).

Regarding artificial lighting, Figure 11 shows simulations for several configurations of light sources. The first two belong to candles (paraffin wax), while the third one belongs to an oil lamp. The oil lamp illuminates especially the upper part of the apse, although the frontal wall receives more light due to the two additional lamps in the nave (see Figure 4). The right-most render shows all light sources at the same time.

We have also simulated the combination of natural and artificial lighting for some configurations. Figure 12 shows the combination of all artificial lights together with natural lighting on a spring day (April 1st, 2PM). This figure also shows the different operators available to the user, the first three corresponding to tone mapping, and the latter being the luminance map.

Finally, Figure 13 shows the difference tool applied to compare several lighting conditions, including daylight (left), artificial (middle), and artificial vs. both (right). As stated above, blue means that the surface receives more lighting in the first image/condition, red means that it receives more in the second one, and white when there is no difference. The third image shows an extreme situation, since the combination of daylight and artificial lights provides much more lighting than just the artificial ones.

All renderings are for now limited to a specific century (12th) and point of view (frontal, central apse), but we plan to incorporate additional configurations. This will allow users to evaluate how light affected other pictorial layers and how this is perceived from other viewpoints.

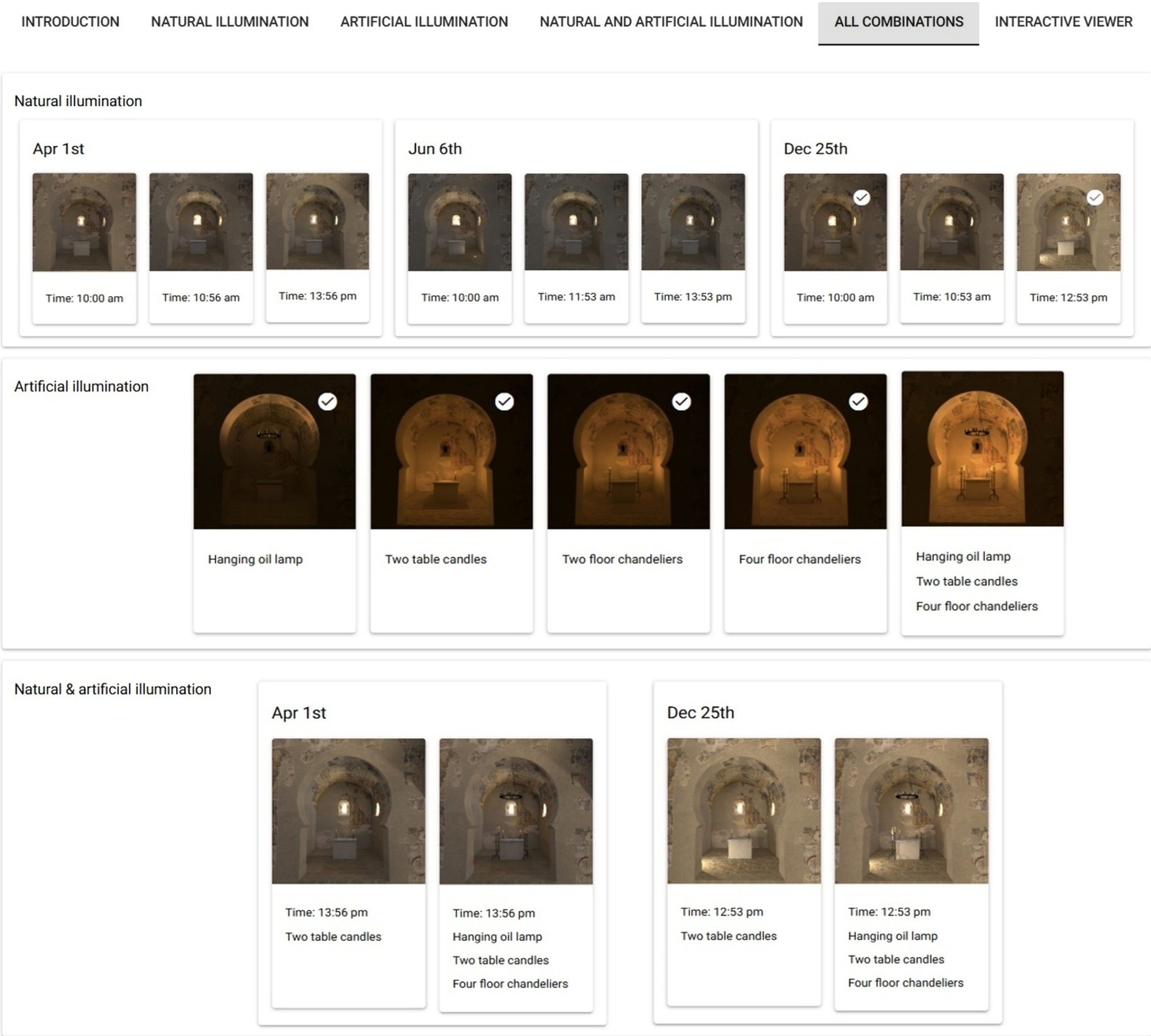

Figure 9: *Web application used to inspect and compare light simulations: GUI for selecting a subset of the images. The image shows the summary view with all lighting combinations. See the accompanying video.*

Figure 10: *Daylight simulations for different dates and times. From left to right: Dec. 25th 10AM, June 16th 10AM, and Dec. 25th 2PM.*

Figure 11: *Artificial light simulations. From left to right: table candlesticks, large candlesticks, oil lamp chandeliers, and all together.*

Figure 12: *Several operators applied for visualization. From left to right: linear, Reinhard, Reinhard extended, and luminance map.*

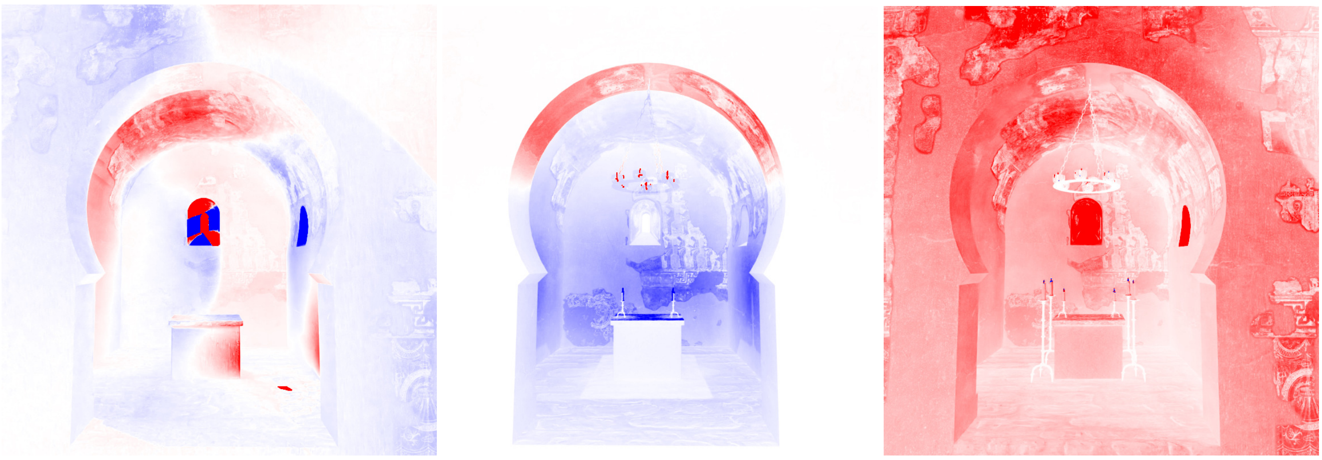

Figure 13: *Difference images. From left to right: Dec. 25th vs. June 16th 10AM (Figure 10), table candles vs. oil chandelier (Figure 11), and artificial sources without and with daylight (Figure 12).*

8. Conclusions

In this paper, we present a method for showing mural paintings in the presumed lighting conditions under which they were originally conceived and perceived by medieval worshipers and visitors. We have stressed the huge gap between typical illumination settings at museums, where large collections of Romanesque art are preserved, and the original illumination. Such illumination differences affected both natural lighting (impossible or unfeasible to reproduce in museums) and artificial lighting. Despite extensive research, art historians often consider multiple hypotheses regarding the different elements that defined the illumination setting, including the number, type, and spatial distribution of candles and oil lamps, as well as other parameters such as wick thickness of oil composition. For this reason, it is important to reproduce and compare all of these hypotheses.

Our method included all the necessary steps to digitally simulate historical lighting conditions using physically-based rendering: reconstructing the original light sources (such as candles and sunlight), measuring their spectra, modeling the church architecture at different architectural phases, and rendering scenes under various historical hypotheses. We developed a Web application to allow users (both experts and non-experts) to explore and compare these simulations. The application includes a collection of tabs for grouping the renders according to different criteria, and an interactive viewer that allows users to compare pairs of renderings side-by-side. Due to the dim light of medieval churches, HDR rendering was essential, and the application allows users to select the desired tone mapping method and adjust their parameters. In summary, the tool digitally reproduces the paintings in the presumed original atmosphere, greatly enhancing their perception and facilitating their understanding.

For future work, we plan to measure the spectral reflectance of the paintings and integrate these data into our rendering pipeline to improve the fidelity of the simulations. We believe that this will allow for a more accurate study of how metameric pigments appear under different lighting conditions. Additionally, we aim to investigate the relationship between the spectral reflectance of the paintings and the weathering processes that have affected them over time, which could provide important insights into how the paintings' appearance has changed since their creation. We also plan to extend the work by transferring the simulated lighting information onto the mesh (e.g., as a texture layer) to enable interactive visualization of the models.

An additional area of interest is how human visual perception in dim conditions influences the experience of viewing the paintings, particularly given the limited intensity of historical light sources, especially during twilight or night. We believe that incorporating the distinct behaviors of rods and cones under these conditions can improve the realism of the generated images. Another promising direction to explore is evaluating how these light simulations affect users emotionally and cognitively. This involves understanding not only the visual perception but also how people emotionally respond to, interpret, and connect with cultural heritage when the original illumination is recreated. Finally, we plan to extend this work to virtual reality experiences for cultural heritage. We believe that the immersive nature of virtual reality can significantly improve our understanding of how the interaction between light and painted surfaces is perceived, allowing users to rediscover these mural paintings.

Acknowledgements

This work has been partially supported by the projects PID2021-122136OB-C21 and PID2021-122136OB-C22 funded by MCIN/AEI/ 10.13039/501100011033 and by FEDER A way of making Europe, and by the Department of Research and Universities of the Generalitat de Catalunya (2021 SGR 01035).

References

[Ata15] ATAOGUZ K.: *Role of Light–Shadow Hierophanies in Early Medieval Art*. Springer New York, New York, NY, 2015, pp. 1733–1741. 2

[BLRR07] Bridault F., Leblond M., Rousselle F., Renaud C.: Real-time rendering and animation of plentiful flames. In *Proceedings of the Third Eurographics Conference on Natural Phenomena* (Goslar, DEU, 2007), NPH'07, Eurographics Association, p. 31–38. 2

[Cam23] Campanaro, Danilo Marco: *Illumination matters. Revisiting the Roman house in a new light*. PhD thesis, Lund University, 04 2023. URL: `https://lup.lub.lu.se/search/files/144878976/Danilo_Marco_Campanaro_WEBB.pdf`. 2

[Cay22] Cayuela B.: *Sant Quirze de Pedret, un paisatge pictòric romànic*, vol. 3 of *Ars Picta. Temes*. Edicions de la Universitat de Barcelona, Barcelona, 2022. 3

[DJPS20] David M., Jurković M., Pannuzi S., Stasolla F. R.: Luminosa saecla/ the luminous centuries – lighting systems in churches between late antiquity and the middle ages. *Hortus Artium Medievalium 26* (2020), 9–159. 2, 3

[DKN*03] Dobashi Y., Kaneda K., Nakashima T., Yamashita H., Nishita T., Tadamura K.: Skylight for interior lighting design. *Computer Graphics Forum 13* (02 2003), 85 – 96. 2

[GMaMC09] Gonçalves A., Magalhães L., Moura J. a., Chalmers A.: High Dynamic Range—A Gateway for Predictive Ancient Lighting. *J. Comput. Cult. Herit. 2*, 1 (July 2009). 2

[GNWM24] Grobe L. O., Noback A., Wasilewski S. W., Mächler C.: Zonal reconstruction of daylighting in historic built environments: A workflow to model and evaluate light in spatial and temporal domains. *Heritage 7*, 11 (2024), 5963–5975. 2

[GSGC08] Gutierrez D., Sundstedt V., Gomez F., Chalmers A.: Modeling Light Scattering for Virtual Heritage. *J. Comput. Cult. Herit. 1*, 2 (Nov. 2008). 2

[Gue01] Gueymard C. A.: Parameterized transmittance model for direct beam and circumsolar spectral irradiance. *Solar Energy 71*, 5 (2001), 325–346. 4

[HA20] Happa J., Artusi A.: *Studying Illumination and Cultural Heritage*. Springer International Publishing, Cham, 2020, pp. 23–42. 2

[HAD*09] Happa J., Artusi A., Dubla P., Bashford-Rogers T., Debattista K., Hulusic V., Chalmers A.: The Virtual Reconstruction and Daylight Illumination of the Panagia Angeloktisti. In *VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage* (2009), The Eurographics Association. 2

[HBRW*12] Happa J., Bashford-Rogers T., Wilkie A., Artusi A., Debattista K., Chalmers A.: Cultural heritage predictive rendering. *Computer Graphics Forum 31*, 6 (2012), 1823–1836. 2

[HMD*10] Happa J., Mudge M., Debattista K., Artusi A., Gonçalves A., Chalmers A.: Illuminating the past: State of the art. *Virtual Reality 14* (09 2010), 155–182. 2

[HW12] Hosek L., Wilkie A.: An analytic model for full spectral skydome radiance. *ACM Trans. Graph. 31*, 4 (July 2012). 2

[IM04] Ihrke I., Magnor M.: Image-based tomographic reconstruction of flames. In *Proceedings of the 2004 ACM SIGGRAPH/Eurographics Symposium on Computer Animation* (Goslar, DEU, 2004), SCA '04, Eurographics Association, p. 365–373. 2

[Ina90] Inakage M.: A simple model of flames. In *CG International '90: Computer Graphics around the World* (Berlin, Heidelberg, 1990), CG International '90, Springer-Verlag, p. 71–81. 2

[JH19] Jakob W., Hanika J.: A low-dimensional function space for efficient spectral upsampling. *Computer Graphics Forum (Proceedings of Eurographics) 38*, 2 (Mar. 2019). 4

[JSR*22] Jakob W., Speierer S., Roussel N., Nimier-David M., Vicini D., Zeltner T., Nicolet B., Crespo M., Leroy V., Zhang Z.: Mitsuba 3 renderer, 2022. https://mitsuba-renderer.org. 4

[KJKN*14] Kider Jr. J., Knowlton D., Newlin J., Li Y., Greenberg D.: A framework for the experimental comparison of solar and skydome illumination. *ACM Transactions on Graphics 33* (11 2014), 1–12. 2

[LMCM95] López Mullor A., Caixal Mata A.: *Església de Sant Quirze de Pedret, Cercs. Excavacions arqueològiques. Campanyes 1989–1992*, vol. VI of *Quaderns científics i tècnics*. Diputació de Barcelona, Barcelona, 1995. 3

[LS98] Larson G. W., Shakespeare R.: *Rendering with Radiance: the art and science of lighting visualization*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1998. 2

[Man12] Mancho C.: *La peinture murale du haut Moyen Âge en Catalogne*. Brepols, Turnhout, 2012. 3

[MBM*17] Muñoz-Pandiella I., Bosch C., Mérillou N., Pueyo X., Mérillou S.: Real-time solar exposure simulation in complex cities. *Computer Graphics Forum 36* (04 2017). 2

[MG19] Motsianos I., Garnett K. S. (Eds.): *Glass, wax and metal: lighting technologies in late antique, Byzantine and medieval times*. Archaeopress Archaeology, Oxford, 2019. 2, 3

[MPAC*23] Munoz-Pandiella I., Andujar C., Cayuela B., Pueyo X., Bosch C.: Automated digital color restitution of mural paintings using minimal art historian input. *Computers & Graphics 114* (2023), 316–325. 3

[MPAMLO*22] Muñoz Pandiella I., Argudo Medrano Ó., Lorès Otzet I., Font Comas J., Àvila Casademont G., Pueyo Sandez F. X., Andújar Gran C. A.: Digital reintegration of distributed mural paintings at different architectural phases: the case of st. quirze de pedret. In *GCH 2022, Eurographics Workshop on Graphics and Cultural Heritage* (2022), pp. 67–76. 3

[NFJ02] Nguyen D. Q., Fedkiw R., Jensen H. W.: Physically based modeling and animation of fire. *Proceedings of the 29th annual conference on Computer graphics and interactive techniques* (2002). 2

[RSSF02] Reinhard E., Stark M., Shirley P., Ferwerda J.: Photographic tone reproduction for digital images. *ACM Transactions on Graphics 21*, 3 (2002), 267–276. 5

[RWPD05] Reinhard E., Ward G., Pattanaik S., Debevec P.: *High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting*. Morgan Kaufmann, 2005. 5

[SF93] Stam J., Fiume E.: Turbulent wind fields for gaseous phenomena. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques* (1993), SIGGRAPH '93, p. 369–376. 2

[Tai23] Tai N.-C.: Digital archiving of the spatial experience of cultural heritage sites with ancient lighting. *J. Comput. Cult. Herit. 16*, 3 (Aug. 2023). 2

[Yar85] Yarza J.: Les pintures de sant quirze de pedret. In *Catalunya Romànica, XII. El Berguedà*. Enciclopèdia Catalana, Barcelona, 1985, pp. 218–234. 2

[YBF*22] Yeager T., Bogdanović J., Forehand L., Danilović D., Dragović M., Chatterjee D., Gasper J., Pejić M., Čučaković A., Martinenko A., et al.: Modeling the sunlight illumination of the church at Studenica monastery. *Natural Light in Medieval Churches 88* (2022), 253–277. 2