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ARTIFICIAL LIGHT SOURCES IN ROMAN, BYZANTINE, AND POST- BYZANTINE ERAS: AN EVALUATION OF THEIR PERFORMANCE

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The assessment of the performance of ancient lighting devices may provide scholars with valuable information on the lighting conditions that existed in ancient houses, and on the level of optical comfort created by the use of those devices. Consequently, it also provides scholars with valuable information on the feasibility of activities performed during night time.

This paper focuses on the investigation of the performance of lighting devices, namely lamps and candles, used in Greece during the Roman, Byzantine, and Post-Byzantine eras. At the same time, we provide non-lighting specialists (e.g. archaeologists) with the tool to assess the performance of the lighting devices they study, as well as to estimate the amount of light emitted on a surface of interest.

The data provided in this paper was derived from a series of measurements and photometric calculations performed on copies of lighting devices in the Lighting Laboratory of the National Technical University of Athens. However, this was done with the aid of a goniophotometer (for the methodology of the measurements, see: Moullou *et al.* 2012a: 107-114; Moullou *et al.* 2012b: 236-244; Moullou *et al.*, in press).

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Definition of Terms and Minimum Illuminance Level for Optical Comfort

Luminus flux or luminous power, measured with the unit lumen, is the measure of the total amount of visible light emitted by a light source. Illuminance is the quantity of light on a working surface inside a room, and is measured with the unit lux. Thus, lux is a measure of the luminous flux per unit area i.e. one lux is equal to one lumen per square meter.

The lighting levels produced by modern lamps should not be compared with lighting levels produced by ancient light sources. For example, the illuminance in a room, lit with a modern lamp exceeds 300 lux. However, if the same room were lit with an oil lamp, the maximum illuminance would be 12 lux.

The same applies for the actual lighting needs. For example, according to European Standards, the lighting levels in an office used for reading and writing should be 250-500 lux. However, according to experimental data, reading (even) at a distance of 60 cm (font Times New Roman 16 pt) is feasible with 0.13 lux (Atmodipoero and Pardede 2004: 644-649).

The minimum lighting level for optical comfort is not easy to determine. This is because visual acuity depends not only on the lighting level, but also on biological factors unique to each individual such as age and the general conditions of the eyesight. For the purpose of our study, we use 0.13 lux as the lighting threshold established for comfortable reading as derived by the aforementioned experiments, as the minimum lighting level for optical comfort.

Measured Lighting Devices

Most of the spouted lamps used for the measurements are exact copies of existing lamps, purchased from the Archaeological Receipts Fund of the Hellenic Ministry of Culture and Sports. Therefore, the following copies were used:
Copies of clay spouted lamps:

- Terracotta lamp decorated with a cupid. From Louloudia/Kitros, Pieria, early 5th century, Museum of Byzantine Culture, no. BK 4513/2.
- Terracotta lamp decorated with the bust of an apostle. Unknown provenance. 5th century. Museum of Byzantine Culture, no. BK 4573/1.

Copies of metal spouted lamps:

- Bronze lamp with cruciform handle and shell-shaped lid. From Louloudia/Kitros, Pieria, 5th-6th century. Museum of Byzantine Culture, no. BA 51/3.
- Iron almond-shaped lamp from Mystras. Post-Byzantine period, probably 18th century. Mystras Museum, inv. no. 1442
- Bronze two-nozzled hanging lamp of late 19th century (was an offer of E. Tzannidaki, of Rethymnon, Crete).

Copy of a clay lantern (measured with the copy of the terracotta lamp decorated with a cupid inside):

- Clay lantern. From Thasos, Limenas, 5th-6th century, Kavala, Tokos Mansion, inv. no. ΘΛ 5/94.

The floating-wick lamps were constructed for the purposes of this research in G. Hatzinikolakis Pottery workshop in Heraklion Industrial Park, Crete. This was except for the glass lamp, of which we used a modern wine glass and a copy of clay Kandela, which was purchased from the Archaeological Receipts Fund of the Hellenic Ministry of Culture and Sports:

- Clay Kandela. From Gratini, Rhodope, 13th century, Kavala, Tokos Mansion, inv. no. ΡΓ1/79/Κ39

The handmade beeswax candles were purchased from the Prevelis Monastery in Crete and the tallow candles were constructed by E. Tzannidaki and D. Moullou. For the production of tallow, E. Tzannidaki and D. Moullou followed the instructions given by the 1st century physician, Dioscorides (*De materia medica* 2, 75.4).

The flax, hemp, and cotton wicks were constructed (from purchased organic fibers) by E. Tzannidaki and D. Moullou. Wicks made of different manufacture methods (twisted/woven) and various dimensions were tested. Also, the ballota acetabulosa wicks were picked from the country side by D. Moullou. (For the kinds and types of wicks used in ancient Greece, see Moullou 2010: 136-140; Moullou 2011: 52-53; and for the wick types in Byzantium, see Motsianos 2011a: 393-403; Motsianos 2011b: 117-119).

The lamp fuel was organic olive oil extracted only by mechanical means, sesame oil, and handmade tallow (as mentioned above).

Lighting Efficiency of the Measured Lighting Devices

The results of the photometric measurements and calculations (presented in Tables 1-3) show that none of the lighting devices can be compared with the modern electric lamps that we use today. However, all the lighting devices provide a certain level of optical comfort especially if they are placed close to the surface of interest. In every case, when the distance between light and surface is less than 1 m, the lighting result is above the threshold of 0.13 lux.

It is evident that the least efficient type of lighting device is the floating wick lamp used with a ballota acetabulosa wick. At a distance above 1 m., the efficiency of the ballota acetabulosa floating wick lamp is significantly reduced and falls under the optical comfort threshold. Therefore, this kind of lamp-wick combination could not have been used for a high-light-requirement activity, unless the lamp was placed at a close distance.

The light produced by spouted lamps and candles is affected mainly by the type and dimensions of the wick. Generally, cotton is more efficient than flax which is more efficient than hemp. Any variation in the length or the thickness of the wick produces different results, though it appears that the length of the wick is a most significant factor in the lighting result. However, a double amount of light is achieved by doubling both the length and the thickness of the wick. The wicks' manufacture (twisted or woven fibers) seems to have only minor impacts on the lighting result.

As far as the fuel is concerned, it is worth noting that olive oil is more efficient than either sesame oil or animal fat (The tallow candle and the oil lamp were compared using the same kind and size of wick).

The data from Tables 1-3 can be used by non-lighting specialists to assess the luminous flux and the lighting results of any lamp. This is done by measuring the size of the nozzle-hole, provided the material of the wick has been decided upon.

Type	Fuel	Wick	Features	Wick length (cm)	Wick thickness (cm)	Lumens	Lux at 25 cm vertical[1]	Lux at 25 cm tilted[2]	Lux at 1 m vertical[3]
Clay bowl	Olive oil	Ballota Accetabulosa				3.0	5.46	4.73	0.34
	Tallow (Lamb fat)	Flax		1.0	0.5	8.9	14.62	12.66	0.91
Clay kandela	Olive oil	Flax	Full			3.6	6.90	5.97	0.43
			Half-filled			1.9	0.00	0.00	0.00
Glass	Olive oil	Flax	Full			2.3	3.96	3.43	0.25
			Half-filled			2.1	3.63	3.15	0.23
			Full	1.0	1.0	14.8	21.79	18.87	1.36

Table 1: Technical characteristics and photometric properties of floating-wick lamps

[1] Illuminance at a vertical surface at distance 25 cm from the light source.
[2] Illuminance at a tilted surface, 30° from the vertical, 25 cm from the light source.
[3] Illuminance at a vertical surface, 1 m from the light source.

Type	Fuel	Wick	Features	Wick length (cm)	Wick thickness (cm)	Lumens	Lux at 25 cm vertical	Lux at 25 cm tilted	Lux at 1 m vertical
Clay Lamp (1)	Olive oil	Twisted flax fibers		0.5	0.5	9.4	13.57	11.75	0.85
				0.5	1.0	16.2	23.42	20.29	1.46
				1.0	1.0	16.5	24.32	21.06	1.52
Clay Lamp (2)	Olive oil	Twisted flax fibers		1.0	1.5	17.5	25.28	21.89	1.58
				2.0	1.0	19.1	27.63	23.93	1.73
				2.0	2.0	39.8	57.46	49.76	3.59
Clay Lamp (1)	Olive oil	Wooven flax fibers		1.0	1.0	9.8	13.31	11.53	0.83
		Hemp Wooven		1.0	1.0	10.2	16.64	14.41	1.04
		Hemp		0.5	1.0	3.7	5.76	4.99	0.36
		Cotton wooven		1.0	1.0	11.5	18.08	15.66	1.13
		Cotton		0.5	1.0	16.4	23.66	20.49	1.48
				1.0	1.0	16.7	28.64	24.80	1.79
	Sesame oil	Flax		0.5	1.0	10.6	15.36	13.30	0.96
				1.0	1.0	13.5	19.55	16.93	1.22
Bronze, 5th century	Olive oil			1.0	1.0	13.1	18.37	15.91	1.15
Iron, Post Byzantine	Olive oil			1.0	1.0	12.3	17.06	14.77	1.07
Bronze,19th century	Olive oil			1.0	1.0	8.1	11.62	10.06	0.73
Lantern with Clay Lamp (1)	Olive oil	Flax		1.0	0.5	0.2	0.30	0.26	0.02

Table 2: Technical characteristics and photometric properties of spouted lamps

Type	Fuel	Wick	Features	Wick length (cm)	Wick thickness (cm)	Lumens	Lux at 25 cm vertical	Lux at 25 cm tilted	Lux at 1 m vertical
Beeswax		Cotton		1.0	0.5	16.6	22.43	19.43	1.40
Tallow candle	Lamb fat	Cotton		0.5	0.5	8.2	11.15	9.66	0.70
		Flax		0.5	0.5	5.8	7.81	6.76	0.49

Table 3: Technical characteristics and photometric properties of candles

Lighting Conditions inside a Room

The lighting conditions inside an enclosed space can be assessed with a variety of methods (see for example, Moullou *et al*. 2012a: 107-114), on the condition that the photometric properties of the lighting device (or devices), such as those presented in Tables 1-3 are available.

Of course, with the aid of Lighting Design software such as RELUX, an assessment of the lighting conditions throughout the room can be done easily, since it is possible to view the 3D distribution of lighting intensity (Moullou *et al*. 2012a: 107-114; Moullou and Topalis 2011b: 64-66).

Figure 1 will serve as an example in order to understand the lighting simulation procedure. In the lighting simulation software used, a model of the room which will be illuminated must be designed, and the lighting device must be placed inside the room. Inputs include the geometric properties and optical properties of the room, and the optical properties of the lighting device. In the case of Figure 1, a typical room with mud brick walls is designed in the RELUX environment and the lighting device is placed at the center of the room. By making the necessary calculations, the software provides the lighting distribution in 3D space (Fig. 2). Furthermore, there is also an option to define virtual measurement surfaces (surfaces of interest), and have the lighting result measured locally on the selected surfaces (Fig. 1).

Figure 2 a-f diagrams show the lighting intensity 3D distribution of the same room under different lighting scenarios. They include: a) a clay bowl with olive oil and a ballota acetabulosa wick; b) a clay lamp filled with olive oil and with a flax wick of 0.5 cm free length (the part of the wick that is outside the nozzle of the lamp) and 0.5 cm thickness; c) the same clay lamp with olive oil and a flax wick of 1 cm free length and 1 cm thickness; d) bronze double-nozzle Post-Byzantine lamp with olive oil and two flax wicks of 1 cm free length and 1 cm thickness each; e) a beeswax candle with a cotton wick of 1 cm free length and 0.5 cm thickness; and f) a tallow candle with a flax wick of 0.5 cm free length and 0.5 cm thickness.

In each diagram, we can see the way light is distributed from the light source. For example in Figure 2a, we observed that a floating–wick lamp emits light only upwards (indirect lighting), thus the space under the level of the lamp is mostly dark and poorly lit. From this chart, it is evident that a nocturnal activity (e.g. writing) with the aid of a floating-wick lamp (except for the glass lamp, which also emits a percentage of the total luminous flux downwards) would be more easily done on a vertical or a tilted surface than a horizontal one. This means that if someone wants to write (or read) under the light of a floating -wick lamp, he has to turn the writing surface towards the light.

Figures 2b, c and d show that spouted lamps emit a significant amount of light downwards (more than 30% of the total luminous flux), and they create direct-indirect lighting. The advantage of direct - indirect lighting is that it gives good results on work surfaces (Moullou and Topalis 2011a: 58-63). A candle, on the other hand, emits an equal amount of light spherically, creating a uniform lighting pattern (Fig. 2e,f). The advantage of uniform lighting is that light is distributed equally in every direction, making it more appropriate for general illumination.

It should be noted that the geometric and optical properties of the room play an important role in the lighting result. Figure 3a shows the room with mud brick walls, while Figure 3b shows the same room with white plastered walls. The reflectance factor in this case is increased by 45%. The comparison of the two figures shows that in the white plastered room, the effect of the reflectance is minor on the surface close to the lamp, because it is away from the walls and it cannot benefit from their reflectance; while in the whole room, due to the increased reflectance, the average illuminance increases about 13%. Generally, when working under low light levels (such as those created by the lighting devices used in antiquity), it is better to move the light source and the working surface close to the wall in order to benefit from the reflectance of the surfaces (especially in a room with light colored walls). However, for general lighting, a placement of the lamp close to the center of the room is more efficient (Moullou *et al.* in press).

In order to understand and visualize the lighting conditions in houses with colorful and elaborate decoration, we chose to simulate as a case study, the lighting conditions in two rooms of *Casa dei Cubicoli Floreali o del Frutteto* (I.9,5) in Pompeii (1st century): the triclinium (room 11) and the so called "blue" cubiculum (room 8). Both rooms have beautiful paintings which have survived in remarkable condition, and they are regarded as fine examples of 3rd style painting. The triclinium is decorated with architectural motifs separating panels of mythological scenes painted against a black background (dark colored surfaces). The decoration of the cubiculum consists of garden scenes against a blue background, with rich bird life, flowers, statues, and fountains (light colored surfaces). Both floors were covered with mosaics of geometric patterns. (For more information on the house and its decoration, see indicatively PPM 1990-1999, vol. II: 15-35, 52-92; Sichtermann 1980: 457-461; Richardson 1988: 224-225)

The lighting simulations were carried out with the lighting design software, RELUX. The reconstruction of the decoration follows the BSR Pompeii Project reconstruction of the room by the British School at Rome and the University of Auckland - Centre for Academic Development (Berry 1998: 56-57). The following parameters were chosen for each of the above mentioned scenarios: simple spouted lamp olive oil, with flax wick (twisted, 1 cm thick, 1 cm free length).

Triclinium (room 11)

For the lighting simulation of the triclinium (Fig. 4a), two scenarios were evaluated: a) with one lamp placed on lampstand (a lamp and a decorated lampstand were found inside the room, along with good quality bronze and ceramic tableware, see Berry 1998: 60) (Fig. 4b); and b) with two lamps on lampstands, in order to check the difference in the lighting result when a second lamp is used (Fig. 4c). The virtual measurement surfaces we used to measure the lighting result locally are: a small horizontal surface on each couch and a rather large horizontal surface covering the whole room, used for calculating the general illuminance inside the room.

- Lighting simulation with the use of one lamp

The results have showed that despite the dark (black prevailing) colors of the decoration, the average illuminance in the room with the use of one lamp is 0.41 lux and the maximum illuminance is 2.91 lux (Fig. 5a). At the same time, the illuminance on all the virtual surfaces is also considered efficient, since the values are much higher than the limit of the 0.13 lux (1.13 lux, 0.72 lux and 0.25 lux).

- Lighting simulation with the use of two lamps

With the use of two lamps, the average illuminance in the room is 0.65 lux and the maximum illuminance is 3.19 lux (Fig. 5b). The illuminance on all the virtual surfaces is also increased, (1.29 lux, 1.19 lux, and 0.45 lux respectively). Thus, the use of the second lamp increases the lighting result by 40%.

This analysis shows that the use of one lamp in the room was enough for the function of this room as a banqueting hall. Thus, the finding of the lamp inside this room was not an accidental finding. It was the appropriate lighting device, which permitted the comfortable performance of night-time activities.

Cubiculum (room 8)

For the cubiculum, a scenario with one lamp on a lampstand was evaluated (Fig. 6a,b). The virtual measurement surfaces are: a small horizontal surface on the side of the bed closest to the lamp, and one large horizontal surface covering the whole room, used for calculating the general illuminance (Fig. 6a). Although horizontal surfaces give worse lighting results than for example tilted or vertical surfaces, we decided to use them in order to receive the minimum illumination result on the area of interest.

The results of the evaluation of the cubiculum indicated that the average illuminance in the room is 1.07 lux, while the maximum illuminance is 3.4 lux (Fig. 6c). The illuminance on the measured surface close to the lamp is 2.11 lux. The lighting result is considered good and is appropriate for the performance of light demanding activities such as reading and writing.

Comparing the above lighting simulations, we observed that the lighting conditions in the cubiculum are better than the conditions in the triclinium even with the use of two lamps. This directly results from the fact that the lighter colored decoration of the cubiculum offers better reflection factors. Although, the cubiculum is a smaller room (total est. area of 7 m^2 compared with a total est. area of 21 m^2 for the triclinium), it therefore has an (equal) amount of light distributed within a smaller area.

Concluding Remarks

Lamps and candles created fair and sufficient lighting conditions during night-time. People could move around with relative ease at night with all the lighting devices measured. With the exception of floating-wick lamps with ballota acetabulosa wicks, the lamps evaluated, provided satisfactory general illumination and allowed for the performance of light demanding activities, such as reading and writing even at some distance from the light source. It is important to note that the luminosity (and consequently, the lighting effect) of the spouted lamp can be significantly increased while it is still burning, simply by pulling out a greater length of the wick.

Because of the absence of powerful lamps, the lighting results for an enclosed space are significantly affected by the placement of the light source, the area of the room, and the color value and reflectance factors of the structural surfaces. The most important factor determining the lighting levels is the distance between the lighting device and the surface of interest. Therefore, people in the past would have had to place their lighting devices close to them to increase their lighting sufficiency.

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