

Article

Flat Glass or Crystal Dome Aperture? A Year-Long Comparative Analysis of the Performance of Light Pipes in Real Residential Settings and Climatic Conditions

Magda Sibley ^{1,*} and Antonio Peña-García ² ¹ The Welsh School of Architecture, Cardiff University, Cardiff CF10 3AT, UK² Department of Civil Engineering, University of Granada, 18010 Granada, Spain; pgarcia@ugr.es

* Correspondence: SibleyM@cardiff.ac.uk; Tel.: +44-7930988819

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Abstract: This paper presents the first comparative study of its type of the performance of light pipes with different types of apertures: a flat glass versus a bohemian crystal dome. Measurements were taken at 20-min intervals over a period of one year in the bathrooms of two newly built identical houses of the same orientation located in Manchester, UK. The comparative analysis of the data collected for both light pipes types reveals that the crystal domed aperture consistently outperforms the flat glass one. Furthermore, the difference in the recorded horizontal illuminance is most marked during the winter months and at the end of the one-year experiment, indicating that the crystal dome has better performance for low incident winter light and higher resistance for the long term effect of weathering and pollution. This study provides strong evidence based on long term real measurements. Such evidence informs architects' decisions when weighing up the aesthetic considerations of a flat glass aperture versus the higher illumination levels afforded by a crystal dome aperture with higher resistance to weathering and pollution.

Keywords: light pipe; crystal dome aperture; flat glass aperture; year-long comparative recorded illuminance; weathering; circadian entrainment

1. Introduction

Daylight illumination is the preferred method of getting light into buildings. This is usually accomplished by the use of windows placed in the façade walls. However, getting daylight into the centre of a deep plan space is difficult due to the distance from the building façade to the deep space to be lit. This is the case in both open plan layouts in large span buildings (such as offices, hospitals, retail centres) and in cellular, short-span buildings with separated enclosed spaces as is the case in housing.

Light pipes, also known as Tubular Daylight Guidance Systems (TDGS), were developed in the early 1990s as a solution to bring daylight from the roof or façades of a building into its deep windowless spaces [1–4]. They have been proven to be an environmentally friendly and healthier substitution for electric lighting of windowless spaces during daylight hours. They are marketed under a number of names such as “sun pipes”, “tubular skylights”, “tubular roof lights”, “sun tunnels”, or “tubular daylighting systems” [4]. The increasing interest in light pipes for introducing natural light in built spaces has led researchers to propose different methodologies and models to foresee indoor illuminances and compare different solutions [5–8]. This interest has taken into account the different climatic conditions around the world and the interest in the use of light pipes in buildings. However, most previous studies have considered their performance under overcast skies [9]. Besides habitable

built indoor spaces, light pipes have also been used to light other critical infrastructure spaces such as road tunnels, where they have been implemented either as standalone installations [10] or coupled with heliostats [11] and even fully with optical fibres [12]. Their use in tunnels is justified because lighting during the daytime of road tunnels is very expensive due to the long time needed by the human eye for light to dark adaptation. Besides light pipes themselves, light pipe apertures proposed to date have been either static or dynamic when provided with active systems that track the daily path of the sun in the sky [13].

Apertures of light pipes generally consist of a transparent collector (for instance a PVC or PMMA dome with anti-UV varnish) mounted on the roof, feeding a reflective tube, which terminates with a collected light diffuser. The performance of a light pipe is dependent on the nature of its collecting system; roof aperture, usually a collecting dome; the geographical location and orientation of the roof; diameter, length and geometry of the tube; the reflectivity of the tube internal surface; and the type of diffusers reaching the ceiling of the spaces to be lit. Other aspects like the increase of uniformity and the avoidance of glare through carefully selected diffusers have also been matters of intensive research in street lighting and other areas of lighting technology [14–16]. Even some imaginative solutions like the so-called Moser lamps have been proposed for purposes similar to light pipes [17]. The design of light pipe systems and materials has been evolving since the 1990s to reach maximum possible performances of its separate components. For example, modern tubes in light pipes have reached a reflectivity of 99.6%, close to ideal, from an initial reflectivity of 93% [4].

Although the light pipe technology has been available for almost 30 years, its adoption by architects at the early stages of design remains generally limited. This is due to several reasons of which aesthetics considerations remain dominant. Architects do not usually find light pipes as visually attractive solutions because of their protruding installation on the roof surface and the change of colour of their dome apertures with time because of weathering and pollution. Furthermore, most research into the performance of light pipes has concentrated mainly on laboratory experiments to measure and predict their performance. However, such experiments do not reflect accurately how light pipes perform when installed in real settings with changing lighting conditions in the sky and over a long period of time. Furthermore, most studies have focused on light pipes with acrylic or polycarbonate dome apertures and so far have not included crystal domes or flat glass light pipe apertures, which are more aesthetically pleasing and are less likely to change colour over time.

The examination of the studies so far completed on light pipes shows that none of them has investigated the relationship between installations using light pipes and non-visual effects like circadian entrainment in their users [18,19]. The currently available tools to predict corneal illuminance will allow designers to decide whether one room receiving natural light can have positive effects on the health of its users. Light pipes are therefore worthy of being studied with these considerations.

This paper is the first of its kind as it compares the horizontal illuminance afforded by light pipes of similar characteristics, installed in the windowless bathrooms of two identical houses with the same roof orientation but with different types of roof apertures: flat glass and crystal dome. It provides an original contribution to knowledge based on understanding the performance of the two light pipes over a period of one year, allowing an understanding of their real performance under different sky conditions and throughout the four seasons of a full year.

2. Materials and Methods

The aim of the experiment was to compare the performance of two similar light pipes of 35 cm tunnel diameter, light pipe reflectance of 98%, and ceiling diffusers but with different types of roof apertures: a flat glass aperture and a crystal dome aperture (Figure 1).



Figure 1. The two light pipes with different roof apertures but the same 35 cm tube diameter and ceiling diffusers. (a) Light pipe A with flat glass roof aperture with easy-to-clean coating; (b) light pipe B with crystal glass dome roof aperture.

Both types of light pipes were installed in similar conditions and orientations to provide light in two similar windowless bathrooms under pitched roofs with a South orientation (Figure 2).



Figure 2. Aerial view of the roofs of the semi-detached houses (in Moss Side, Manchester, UK. Source: Google Earth) with light pipes (red circles) of the same orientation but different apertures.

Figure 2 shows an aerial view of the newly built semi-detached houses where type A and type B light pipes were installed on similarly oriented roofs to provide light to windowless bathrooms on the first floor. The two identical semi-detached houses on the right of Figure 2 have the crystal domed light pipes (along with small solar panels used in another experiment), while the two houses on the left of Figure 2 have light pipes with flat glass roof apertures. Both apertures are transparent. The flat glass aperture is composed of 4mm clear toughened glass with clear self-cleaning coating on the outside. The dome aperture is made of Bohemian crystal that does not distort the natural colours of daylight. The surface of the crystal dome is very hard and smooth and is perfectly washed after rain, so smog and dust do not stick to it. The cost of the crystal domed light pipe is 30% higher than the one with the flat glass aperture.

All the houses are of similar dimensions and plans (Figure 3), half with a roof pitch oriented to the south, the other half with a roof pitch oriented to the north. The shape and pitch of the roof has been identified as a key factor when dealing with use of sunlight in buildings [20], so the selected houses have identical types of roof. Each house has two light pipes: one in the first-floor bathroom, the other one above the staircase landing (Figure 3).

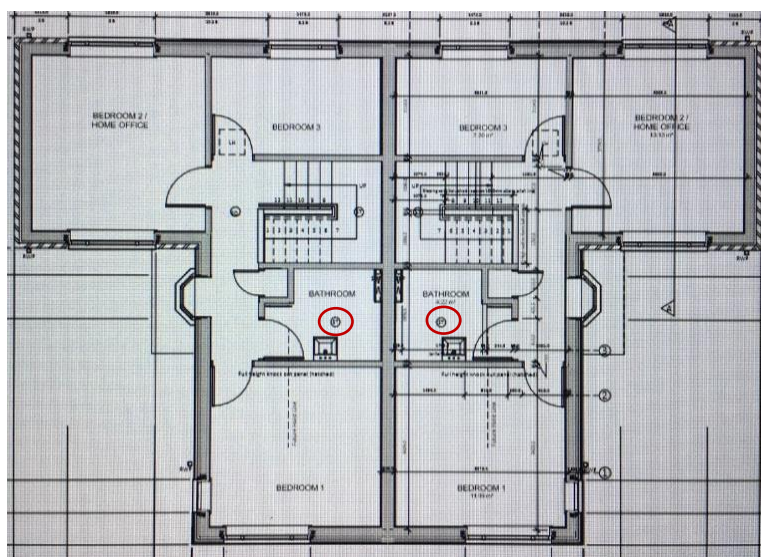


Figure 3. Identical plans of the first floor of the twin houses with similar light pipes in the bathrooms (red circles). Plans provided by Mosscafe Housing Association.

The height of the light pipe diffusers in the two bathrooms is 2.40 m from floor to ceiling, and the floor area of each bathroom is 4.22 m². Illuminance measurements were taken with HOBO light data loggers that were installed in identical places in the houses (Figure 4) at 2.00 m from the floor. This arrangement prevents the data loggers from impairing the usual activities in the bathrooms. Given the low height of the ceiling and the high reflectance of the walls in the bathrooms considered in this work, a similar illuminance is expected at the vertical plan of the mirrors and eye of the users.

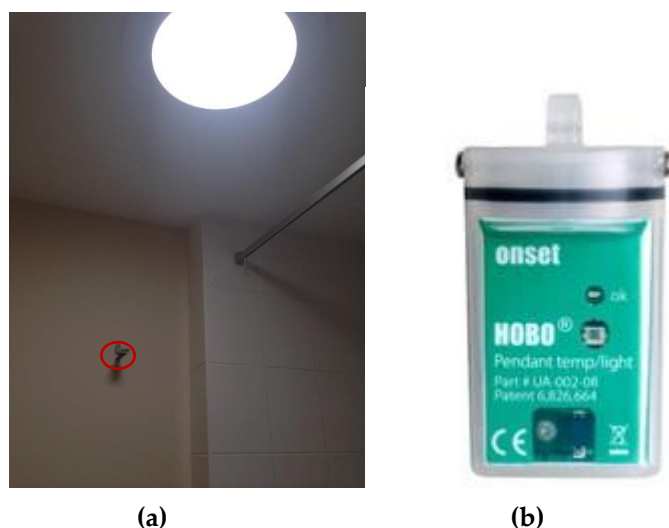


Figure 4. (a) Light diffuser in the ceiling of the bathrooms and position of the HOBO data logger and (b) water proof HOBO light data logger.

These waterproof HOBO pendant data loggers for illuminance measurements (with a range of 0 to 320,000 lx) were chosen due to their discreet small size and their ease of installation in the two bathrooms where high levels of humidity are likely to happen. They were installed in the same position within each of the two bathrooms (with different types of light pipes). This allowed for the synchronised recording of horizontal illuminance at comparable locations. The data loggers were set to record illuminance levels simultaneously in the two bathrooms every 20 min for almost a year between 23rd of July 2015 to 13th of July 2016. This allowed for reliable comparative data to be collected for all

the four seasons of the year as well as the assessment of the potential effect of weathering on the two types of light pipe apertures, i.e., crystal glass dome and flat glass.

3. Results

The weekly averages of recorded illuminance during daylight hours (06:00 to 21:00) were calculated for the 51 weeks of continuous 20-minute intervals of measurements, starting from 24th of July 2015 as illustrated in Figure 5.

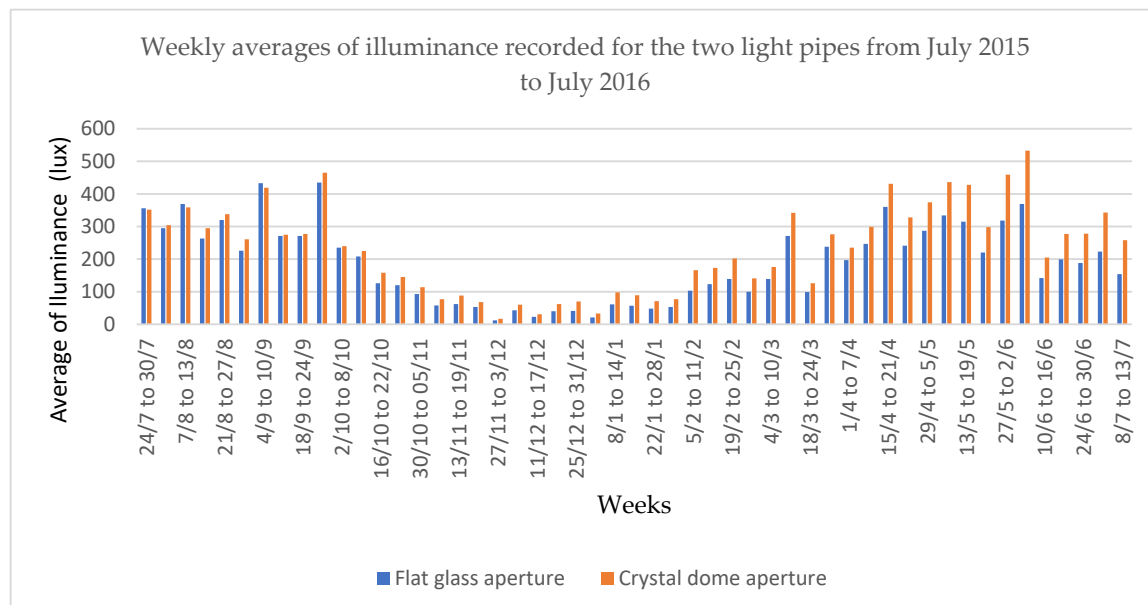


Figure 5. Comparative weekly averages of horizontal illuminance recorded for two light pipes with different roof apertures: flat glass and crystal dome.

Analysing these extensive data by working with average illuminances allows a more intuitive understanding of the differences in the performance of the two light pipes. These monthly averages are shown in Table 1 and Figure 6.

Table 1. Monthly average illuminance recorded for two light pipes: flat glass versus crystal dome aperture.

Date	Flat Glass (lux)	Crystal Dome (lux)
24 July to 23 August 2015	314	330
24 August to 23 September 2015	304	314
24 September to 23 October 2015	248	267
24 November to 23 December 2015	84	107
24 January to 23 February 2016	27	40
24 February to 23 March 2016	46	73
24 March to 23 April 2016	87	129
24 April to 23 May 2016	160	208
24 May to 23 June 2016	259	314
24 June to 23 July 2016	285	379
24 July to 23 August 2016	250	357
24 August to 23 September 2016	181	294

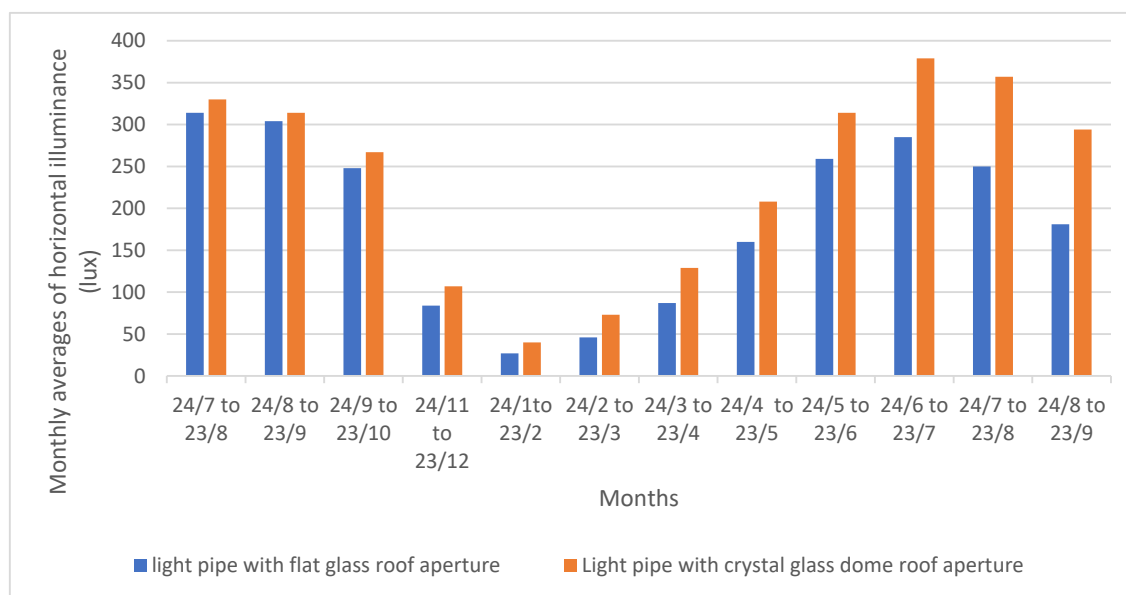


Figure 6. Comparative monthly average illuminance recorded for flat glass and crystal dome.

3.1. Comparative Analysis of the Performance of Flat Glass Versus Crystal Dome Apertures

A first glance at the figures above shows that the difference in both the weekly (Figure 5) and monthly (Figure 6) averages of recorded illuminance of the two types of apertures for the light pipes tends to systematically increase with time and is quite marked after one year of measurements; that is, the light pipe with the crystal glass dome aperture consistently outperforms the one with a flat aperture. This difference in performance is more marked in the summer months after almost one year. Figure 7a,b shows the remarkable lower illuminance during peak hours of the flat glass aperture in the months of July 2016 compared to July 2015. In the same way, the illuminance in the light pipe, the collecting system of which is a glass dome, is even higher in 2016 (due to meteorological conditions) and remains even much higher than in the case of the flat aperture.

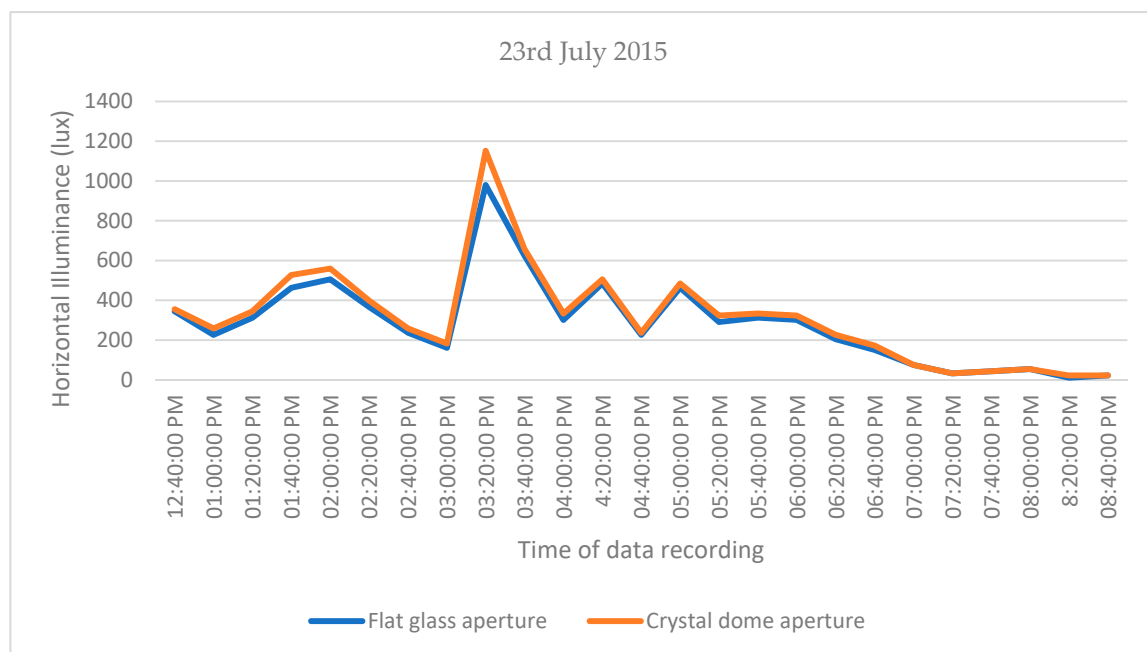
Both light pipes have their highest transmittance at the zenith position of the sun as expected.

These consistent results indicate the possible effect of weathering after one year of operation of the two differently shaped light pipe roof apertures whereby the roof crystal glass dome has a higher weathering resistance than that of the flat glass one, despite the fact that both have self-cleaning properties. This means a higher maintenance factor that ensures higher transmitted illuminance according to the well-known definition of illuminance as the ratio between available luminous flux and illuminated surface:

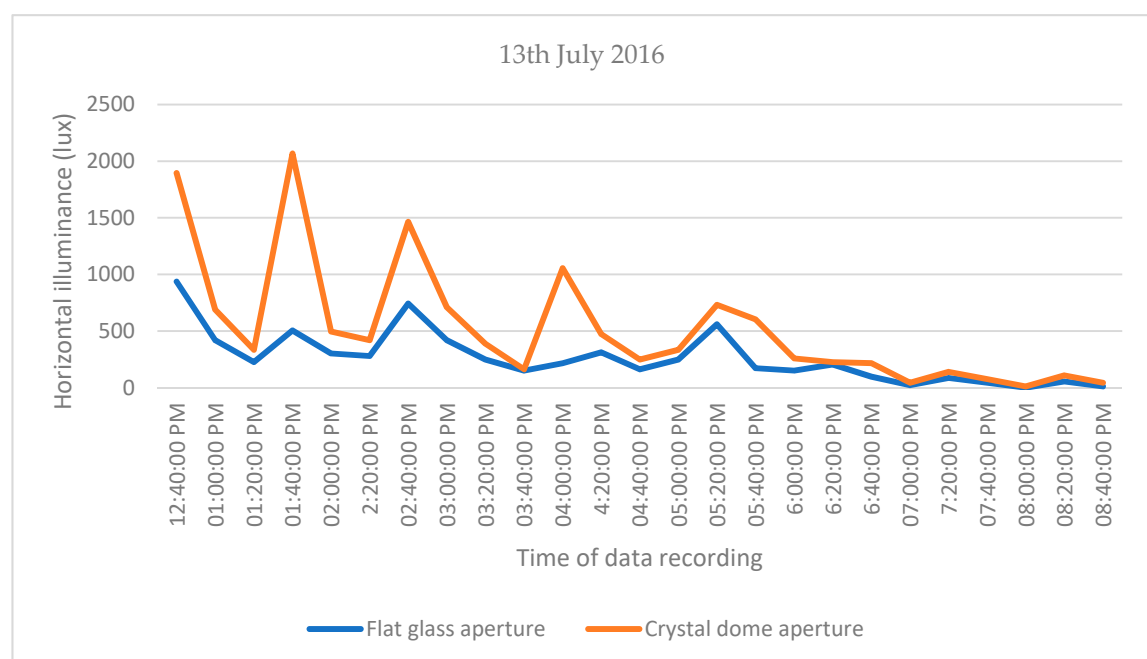
$$E = \frac{\Phi_L C_u C_m}{S} \quad (1)$$

where Φ_L is the luminous flux emitted by the luminary (in this case the diffuser); C_u is the utilization factor, that is, the ratio between the luminous flux reaching the working plane and the luminous flux emitted by the luminary; and C_m is the maintenance factor, which takes account of the loss in the luminous flux due to aging, accumulation of dirt, and other eventualities affecting the luminary. The closer C_m to 1, the higher the natural illuminance and, hence, the lowest maintenance operations and the lowest support of electrical lighting.

As a first result, the crystal dome is cheaper in the long term and has lower environmental impact in terms of workforce (displacements, investments in worker safety, etc.).



(a)



(b)

Figure 7. (a) Recorded Illuminance on 23 July 2015 and (b) on 13 July 2016 for the two types of apertures.

3.2. Effects on Circadian Entrainment

Even more impactful than the previous result, and concerning the evolution of the system through the time, is the capability of light-pipe-based systems to achieve circadian entrainment. As demonstrated in well-established research [21], the illuminance to influence the non-visual paths that regulate the main circadian rhythms, sleep, alertness, body temperature cycles, etc. (through the secretion and/or inhibition of melatonin and cortisol) is about 180 lux when dealing with daylight. According to the average data collected, we can say that approximately only 17 weeks a year would

have average illuminances lower than that required to get circadian impact. These data are very significant, since the measures in this research are taken in the UK, which is a rather cloudy country. In many other parts of the world, the systems tested, especially the one based on glass dome, would be more than enough to achieve circadian impact and the necessary entrainment to contribute to health and well-being.

During the winter months of December 2015 and January 2016, when the sun was low in the sky, the crystal domed light pipe had an increase in performance that exceeded 100% over that of the light pipe with the flat glass aperture as illustrated in Figure 8a,b. This clearly illustrates that the configuration of the crystal glass dome, with its higher capability of intercepting low incidence light has a major impact on higher illuminance afforded during winter, when it is mostly needed.

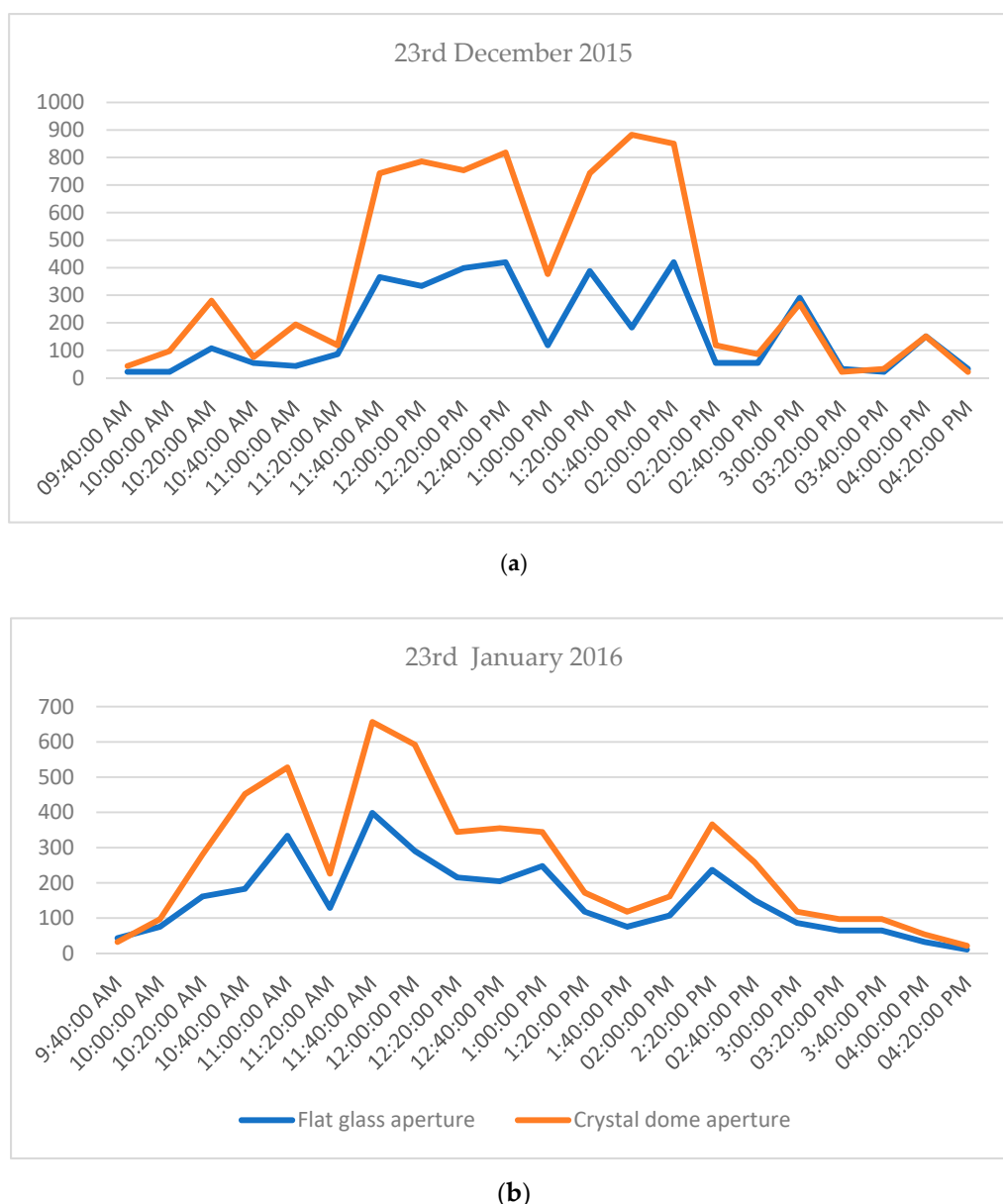


Figure 8. (a) Comparative recorded illuminance on 23 December 2015 and (b) on the 23 January 2016.

In summary, the proposed domed system can satisfy both visual and non-visual requirements for a healthy start to the day. A dimmable support electrical lighting system can be used to supply extra luminous flux or light during night-time. Such electrical lighting could consist of a LED source with a

correlated colour temperature (CCT) quite similar to the daylight CIE D65 in order to complement the natural light entering through the light-pipe system.

4. Discussion and Conclusions

Sustainable lighting nowadays is much more than ensuring the safety and energy efficiency performance of both natural and electric light installations. It also includes concerns over maintaining or even enhancing the psychological well-being of building users, their productivity, and the optimization of tasks and processes they undertake. These considerations have become central targets in current lighting technology developments [22]. This change in the perspective of lighting is not just a fashion but a major paradigm shift in the reformulation of principles made possible by the recent and new understanding of physiological mechanisms like the non-visual paths of melatonin and cortisol, which were known but not fully understood until very recently. In fact, there are still open points like the potential determination of a melanopic spectral sensitivity curve, which, if it were possible to determine and manage, would provide the most powerful tool for working on the effects of light on people.

In this promising framework, very simple uses of lighting have been somewhat ignored precisely because their deepest implications could not be understood without the abovementioned advances in non-visual effects of light. One of these facts is the nature of the light we receive every morning. The importance of spending the first 20 or 30 min under natural light just after waking up can determine performance and well-being during the rest of the day.

In this framework, the use of light pipes to introduce natural light in indoor installations is mainly limited to working spaces like offices, factories, and schools. Even when light pipes were used in residential buildings, bathrooms were not considered as a priority because their relatively low occupation did not require high consumptions. However, bathrooms are key spaces in houses due to several particularities. The first exposure to light in the day is received in the bathroom. The first minutes of lighting exposure are critical because of their deep impact on hormonal releases (mainly cortisol) or inhibition (mainly melatonin). Cortisol release and melatonin inhibition are strongly influenced by the received irradiance and the spectral distribution of the received light. In this sense, natural light is rich in short wavelengths to stop melatonin release and start cortisol secretion as demanded in the early morning to start daily activity. Furthermore, the excellent chromatic reproduction of daylight is ideal for the tasks to be carried out in the bathroom, especially in the early morning, such as applying makeup, shaving, checking the general aspects of and detecting potential disorders of the facial tone and spots in the skin, etc. All these factors make natural light much more accurate than artificial light, even if it has accurate intensity and good chromatic reproduction.

In this work, the performance of two systems of light pipes with different apertures on similar roofs, introducing natural light in bathrooms of a typical house, has been carefully analysed through measurements. These measurements provided consistent results that show that it is possible to profit from the required levels of natural illuminance even in the cloudy and dark winter mornings of the UK climate.

Furthermore, two types of light pipes have been compared in order to determine which aperture system is better: flat glass or crystal dome with a prismatic effect. According to our results, the crystal dome allows the injection of a higher luminous flux, which can exceed that of the flat glass by almost 100% in the winter months and shows a better performance in general after one year of operation, when the effects of weathering and pollution start to interfere. The better performance of the glass dome, surely due to a higher collecting surface and its capacity to capture low incident light, means a higher maintenance factor. This makes this type of aperture cheaper in the long term, leading to less reliance on electrical lighting and fewer maintenance operations to change the light collecting device when its performance has been affected by weathering and pollution.

In summary, this paper provides strong evidence of the advantages of using a crystal glass dome aperture for a light pipe instead of a flat glass aperture as the system allows more light to penetrate the

spaces in the winter months and in the long term. The paper has also highlighted the fact that certain types of rooms (such as bathrooms in residential settings) with low time occupation by the residents, but very important in terms of the type of tasks performed in them, and their impact on human well-being and performance, must be a priority from the perspective of lighting and architectural design. Techniques like light pipes that introduce natural light with its benefits through both visual and non-visual paths are a reality that must still be optimised as presented in this work.

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Conflicts of Interest: The authors declare no conflict of interest.

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