THE BLU LIGHT

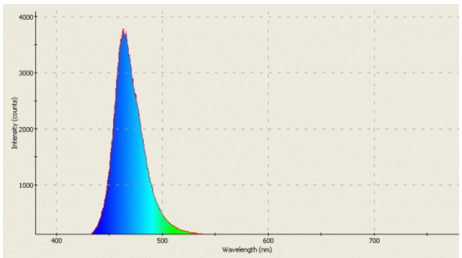
OSCAR SANTILLI
Lighting Designer

Summary
In 2014 the Physics prize was awarded to 3 Japanese researchers, inventors of the technology for the realization of the blue LED. The treatment of the news, especially by the media, did not sufficiently clarify the reasons for the prize. The research aims to illustrate them, with reference to the academic and technical presentation of the experts: the blue LED allowed the creation of the white LED.
The electroluminescent effects of the blue LED were combined with the photoluminescent effects of the phosphors. The research also intends to examine the positive and critical reverberations of both indoor and outdoor applications. The reverberations are above all related to the bio-perceptive modalities of light, to visual comfort and to a redefinition of the parameters that are the basis of the evaluations and design of light, especially in mesopic and scotopic vision, contributing to a more conscious definition of the chromatic connotations of the urban scenes. Furthermore, by combining blue light and phosphors, some applications related to the world of design and dissemination will be illustrated.

Keywords: *Blue light, blue LED, photoluminescence, scotopic and mesopic vision, light drawing, light paintings*

The blue light of the LEDs

Isamu Akasaki, Hiroshi Amano and Shuji Nakamura are the 3 Japanese researchers who were awarded the Nobel Prize in Physics 2014 for the invention of the Blue LED. They were awarded for the tenacity with which they insisted on identifying the technology that would stabilize the emission of blue light in the LED. More than 95% of the researchers were oriented in a different direction from that taken by the three Japanese [1]. The choices of the three were, as seen, winning. The wait was to be able to create the blue LED which then combined with the red and green LED would have allowed the creation of an LED capable of emitting white light. But the greatest expectation was to have a blue light, or a shortwave light with a high energy content; the only one able to excite some specific materials: those containing phosphors. [2].
When the materials are hit by light, they absorb, reflect or transmit the same light. They respond passively. Some materials, on the other hand, those containing phosphors, give a photoluminescent, or active, response. They receive light and then release light. The activating light, however, must be qualified: only the so-called blue light. So-called blue because the shortwave light that can excite the phosphors covers a range that goes from UV rays and goes into the visible up to blue passing through violets.
Phosphors were already known in the 12th century by Arab alchemists. After other experiments and discoveries, in 1800 and 1900 in the centuries of industrial maturity, by fruitfully combining research and application, lamps were conceived that exploited the mixture of short-wave rays and phosphors. The short rays, produced by a magnetic discharge or induction, and the phosphors as a coating of the bulbs [3]. These were the technologies of reference for the stubborn researchers of the blue light of LEDs. But no discharge or induction, but the electroluminescence of the LED (Light Emitting Diode). The first white LEDs were made in 1996 by mixing the light of the blue LED, with a spectrum as in Figure 1, with that of the yellow phosphors, obtaining a spectrum capable of emitting wavelengths extended to almost all visible radiations (see Figure 2)



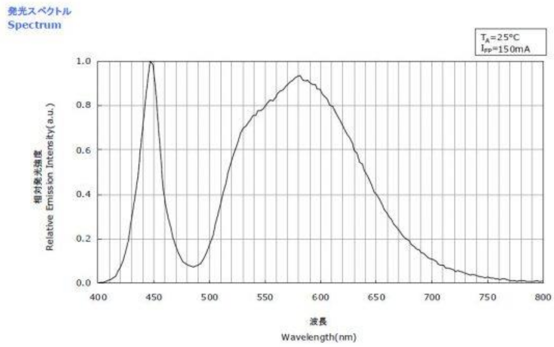


Figure 1: Typical emission spectrum of a BLUE 450 and 473nm InGaN LED (source LED Museum)	Figure 2: Typical emission spectrum of a typical white light emitting LED Ra> 90 (Source Nichia)

After a couple of years of great excitement for the availability of a new light source, with expectations favored by enthusiasm [4], critical issues emerged. Some are still ongoing.
The peak of the presence of blue light, acute and intense, has aroused articulate and heated debates. The most important critical issue arose in the adoption of white LED light to allow the fulfilment of visual tasks, especially in the workplace. The IRC or CRI, or the index of the ability to return colours, of the white LED does not reach the value of 100, as in incandescent lamps. The eye and the biological processes of image postproduction are a much more refined and demanding means of evaluation than the regulatory protocols for the evaluation of the IRC. These protocols are rough and rather lenient. It was thought that it was enough to increase the value of Ra9 (dark red), but it was not enough. The belief has also spread that it was enough to lower the color temperature to 2700 K to balance the strong presence of blues with the yellow-reds. It was also mistakenly led to believe that T solved the problem of poor IRC. T and IRC have no binding relationship. Two sources with the same T value (among other things, T on the chromaticity diagram is not a point but a segment) can have completely different spectral compositions and therefore the ability to return colours in an equally different way. The eye does not have the ability to discreetly detect the presence of colours by observing the source directly. It can detect its presence through the chromatic response (or non-response) of the surfaces.

The blue light of the day and the blue light of the night
The sun is a white star. Its rays impact our atmosphere. Sir John William Rayleigh explains that the particles suspended in the upper part of the atmosphere are so small that they can interfere with shorter than visible waves, the waves of blues. The waves are diffracted, the atmospheric blanket is therefore blue, the sky is blue. The white sun, deprived of its blue component, takes on the yellow colour. Yellow is the complement of blue. White surfaces on earth can appear white when exposed to the additive synthesis of the yellow of direct sunlight and the blue of the soft light of the sky. The parts that cannot be illuminated directly or indirectly, by reflection, by the yellow light of the sun, will receive only the omnidirectional light of the blue sky and will appear blue. The shadows in daylight are blue, the phenomenon is very evident on the snow. White surfaces can reflect all radiation and cannot receive other contributions from other reflective surfaces (see Figure 3).
The phenomenon is less visible on other surfaces in other contexts and times of day, but it is (see Figure 4). It is visible to the artists who have magnified its presence and, as always, have invited us to deepen our observation skills. See in Figure 4 Der Blaue Reiter (The Blue Rider) by Wassily Kandinsky.

Figure 3: Shaded surfaces are blue. They only receive the light of the celestial sky.

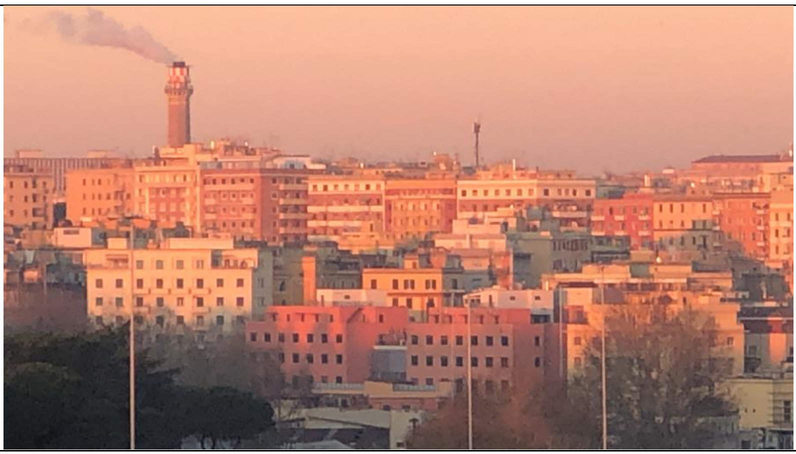


Figure 4: Sunrise, the sun is low. Shaded surfaces are blue. They only receive the light of the celestial sky.

Figure 5: Wassily Kandinsky, 1903, *The Blue Rider* (*Der Blaue Reiter*), oil on canvas, 52.1 x 54.6 cm, Stiftung Sammlung E.G. Bührle, Zurich

At sunrise, sunset and related twilights, the sun's rays penetrate the parts of the atmosphere closest to the earth's crust where the particles are coarser and, explains Sir Rayleigh, are able to interfere with longer waves. The sky illuminated by direct sunlight turns yellow and red. A hint of the colors of the night for low altitudes, under the blue of the sky (see Figures 6 and 7).

Figure 6: Twilight (civil) of dawn. On the right, the blue color of the night that is about to end

Figure 7: Twilight (civil) of sunset. On the left, the blue color of the night that is about to begin.

Photopic, mesopic and scotopic vision

The eye and the processing of vision have been structured over the millennia in relation to the offer of natural lights, those of the day and those of the night. Vision process researchers identified these processes, qualified them, measured them, and produced tables and graphs. In relation to the eye response to the levels (cd/m^2) of ambient luminance (L), three phases have been identified:

1. Photopic vision: L$\geq$ 3 cd/m^2
2. Mesopic vision: 3 cd/m^2 $\leq$ L $\geq$ 0,001 cd/m^2
3. Scotopic vision: L$\leq$ 0,001 cd/m^2

In fact, they are the phases that develop from day (photopic) to night (scotopic) passing through the crepuscular (mesopic) phase. The graph and the values representing the visibility of the light frequencies in the photopic and scotopic phase are those illustrated and indicated in Figure 8 and Figure 9.

The adaptation time of the eye for the transition from the photopic to the scotopic phase, and vice versa, is in fact that of the twilight. About 20 minutes to 1 hour [5].

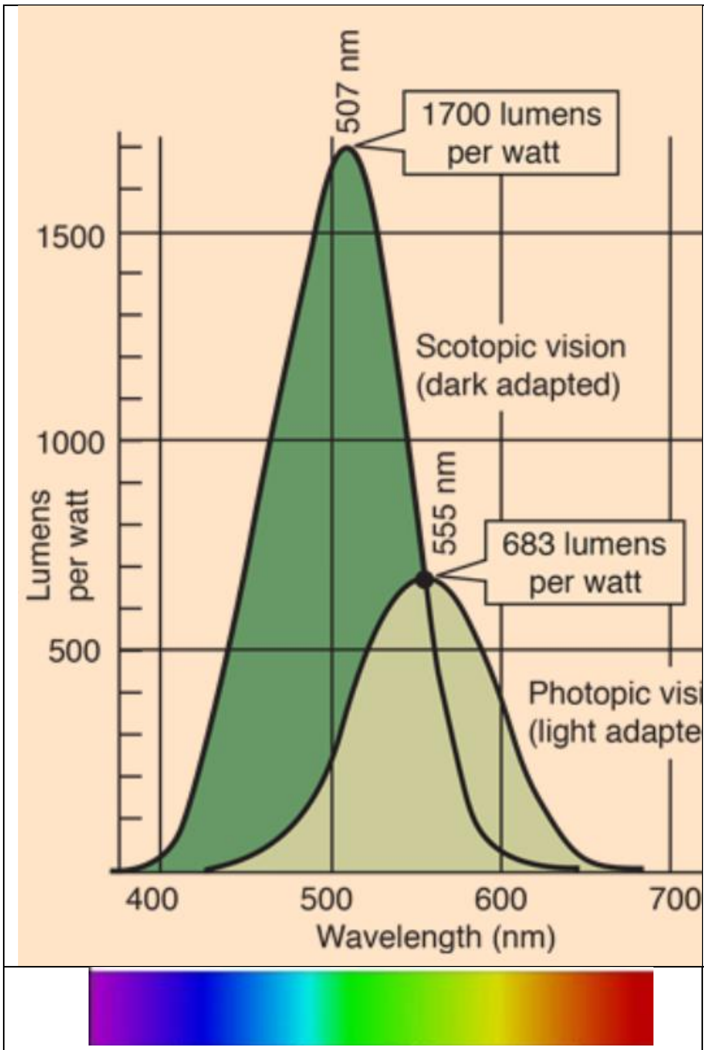


Figure 8: Eye sensitivity curves in photopic and scotopic vision

8

Wavelength λ (nm)	Photopic Luminous Efficacy V_λ	Photopic Conversion lm/W	Scotopic Luminous Efficacy V'_λ	Scotopic Conversion lm/W
380	0.000039	0.027	0.000589	1.001
390	0.000120	0.082	0.002209	3.755
390	0.000120	0.082	0.002209	3.755
400	0.000396	0.270	0.009290	15.793
410	0.001210	0.826	0.034840	59.228
420	0.004000	2.732	0.096600	164.220
430	0.011600	7.923	0.199800	339.660
440	0.023000	15.709	0.328100	557.770
450	0.038000	25.954	0.455000	773.500
460	0.060000	40.980	0.567000	963.900
470	0.090980	62.139	0.676000	1149.200
480	0.139020	94.951	0.793000	1348.100
490	0.208020	142.078	0.904000	1536.800
500	0.323000	220.609	0.982000	1669.400
507	0.444310	303.464	1.000000	1700.000
510	0.503000	343.549	0.997000	1694.900
520	0.710000	484.930	0.935000	1589.500
530	0.862000	588.746	0.811000	1378.700
540	0.954000	651.582	0.655000	1105.000
550	0.994950	679.551	0.481000	817.700
555	1.000000	683.000	0.402000	683.000
560	0.995000	679.585	0.328800	558.960
570	0.952000	650.216	0.207600	352.920

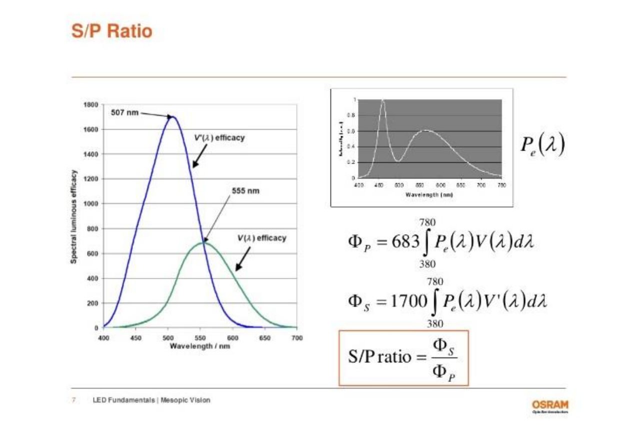
Source: Table 6-1 of Williamson & Cummins, Light and Color in Nature and Art, Wiley, 1983. The Photopic conversion (lm/W) is obtained by multiplying V_λ by 683 and the Scotopic conversion is obtained by multiplying V'_λ by 1700 as suggested by those authors.

Figure 9: Normalized tabular values of the eye visibility curves in photopic and scotopic vision with indication of the maximums.

The photopic phase is the one considered most important. It is that of sunlight. It is the one that allows the fulfilment of functional visual tasks in exteriors and interiors. She is the one who informed the values of the evaluation parameters of the light sources and lighting fixtures: quantity of emitted luminous flux, luminous efficiency of the sources and therefore performance of the fixtures, photometric curves, CRI (Color Rendering Index) and UGR (Unified Glare Rating - glare ratings). He informed the methodologies of calculation and lighting engineering verification. The scotopic and mesopic phases, known by the connoisseurs of light, first the Czech researcher J.E. Purkynje, have so far received little consideration by light manipulators: lighting designers, architects, engineers, etc. However, they are experienced by all living beings at least once a day. As can be seen from the graph in Figure 8, the differences between the two phases are astonishing: both from a qualitative and a quantitative point of view. The photoreceptors of the "dark" (the rods) have considerably

higher sensitivity than the photopic photoreceptors (the cones). For example, for each Watt of radiation at the wavelength of 507 nm in photopic vision the eye can perceive 303 lumens, while in scotopic vision it perceives 1700 lumens. About 5.6 times more! As can be seen, the wavelength of 507 nm can be classified as belonging to the chromatic segment of blue. Blue is the colour of the night. Seeing the night light well means perceiving the blue colour well and vice versa. From the diagrams of Figure 8 and Figure 9 it is clear how the eye perceives with difficulty all the wavelengths to the right of 555 nm (the maximum visibility in the photopic phase); the penalized colours are the yellows and the reds or the colours of the twilight. They are the chromatic memories of the day that has passed, and they are the opening colours of the day that arrives.
During the day (photopic vision) colours other than those of the night are enhanced. The day is predominantly yellow (photopic vision - red and green photoreceptors) and the night is blue.

The sources and devices to illuminate the night
The luminous fluxes emitted by the sources, that is the lumens, the visible Watts of the radiation, are measured in photopic vision. In mesopic and scotopic views, these fluxes could decrease or increase (with the same absorbed power) according to the emission spectra of the sources.
The values of the numerical ratio, S / P ratio, which expresses this increase or reduction, in relation to the sources, in scotopic vision are shown in Figure 10



Some Typical S/P Ratios

Lamp Type	Typical S/P Ratio
Low-pressure sodium	0.25
High-pressure sodium	0.66
Halogen headlamp	1.43
Linear fluorescent	1.3 to 2.3
Metal halide	1.26 to 2.1
Warm white LED	1.21
Cool white LED	2.04

More detailed tables are available (e.g., IES TM-12-12)

LED Fundamentals | Mesopic Vision OSRAM

Figure 10: Method for evaluating the S / P ratio in scotopic vision and the values relating to some sources (Source OSRAM)

The luminance levels required by the standards for the illumination of outdoor environments place the design in the mesopic context, that is, between the photopic and the scotopic. Another parameter was then processed: ELF (Effective Luminance Factor). This parameter considers the gain or loss of the efficiency of the sources and devices in relation to the ambient luminance levels (mesopic), required by the standards or in any case design.
Sources that have a strong blue component perform better. In the phase of design evaluation of illuminances and luminances, by having fluxes amplified by visual perception, important energy savings can be obtained.
The exteriors to be illuminated are various. It is not difficult to agree on the lighting of streets, parking lots, etc., which are exquisitely functional places. Instead, it is more complex to illuminate urban areas with multiple and complex functions. Lighting the cities has allowed the expansion of the times of use. Where people circulate money circulates. Light contributes to GDP growth. The movement of people must be encouraged by ensuring safety and enjoyment. The luminaires with their own sources are objects that together with the wings of buildings, plantings, monuments, etc. contribute to the formation of the urban scene. Above, the blue sky.

Observing the light means observing the colours and the colours of the night are not those of the day. The project must verify the balance and make the story meaningful through light. In a static and dynamic way.
For multiple and well-founded reasons (longevity, immediate switching on and off, luminous efficiency) there is a rather widespread tendency to replace lighting devices equipped with discharge lamps (iodides, mercury, sodium) with LED devices. It is necessary, however, to make some reflections.
As shown in Figure 11, the frequencies of the blue of the spectrum of the white LED are placed in an important way within the scotopic and mesopic curves. In the same figure we see how the yellows and the reds are mortified.

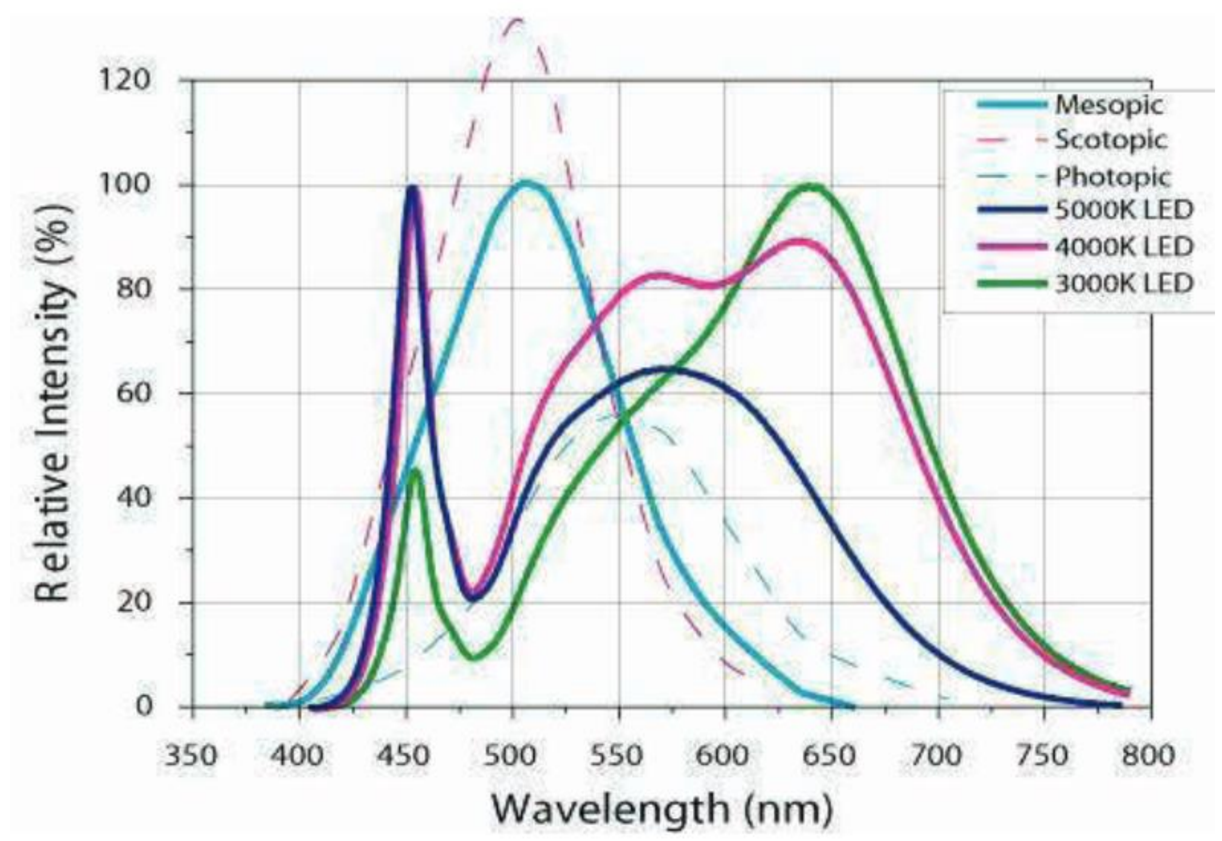


Figure 11: The mesopic and scotopic curves "ignore" the yellow-reds and enhance the blues (Source see note [6])

Urban scenes lit by white LEDs will inevitably have a blue color cast. This dominant hysterically combines with the diffracted blue of the sky. The eye is offered an overdose of blue. The eye sees syncretically, it is unable to discern the chromatic components; but all the devices of the postproduction of the image are aware of presences and absences (see Figure 12). The photoreceptors of the eye are nourished in their entirety, and each intends to perform its function.
If the scenes did not offer all photoreceptors the opportunity to perform their function, the eye and its bio-neuro-collaborators would express discomfort with some discomfort. One could take the example of an orchestra where not all the orchestrants called are offered the opportunity to play. This would not make sense!

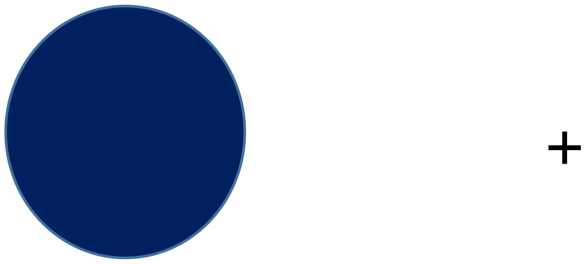


Figure 12: The blue color and its complement (amber yellow). Observe the cross after observing the blue circle for 30 seconds; a yellow circle will appear.

The complexities at the basis of a design of light in urban scenes cannot be exhausted, with the chromatic denotations of the blue of the night and the yellow of the sources. Good designers and artists (See Figures 13 and 14) make up all the factors, natural and artificial, to enrich the so-called collective imagination, according to an effective and exciting narrative.

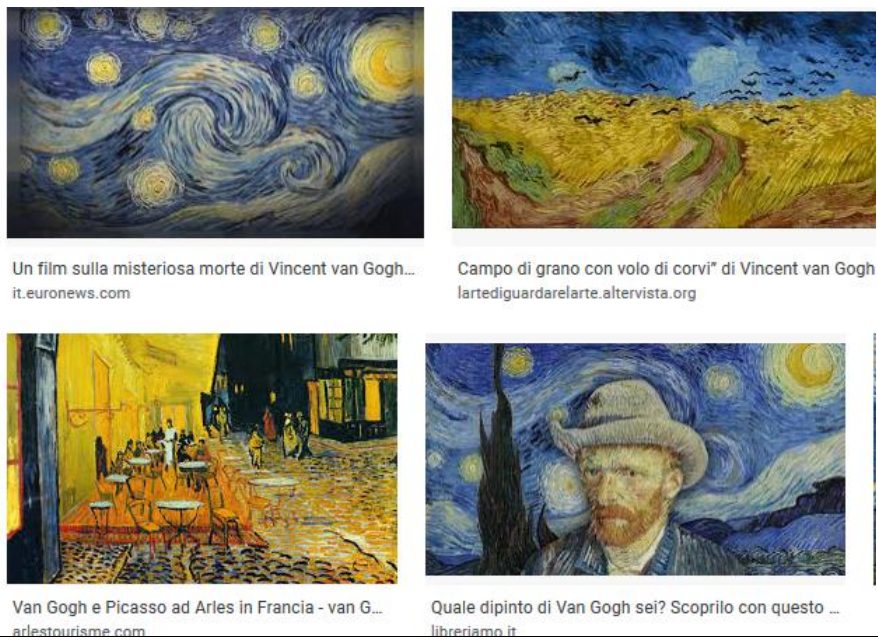


Figure 13: Van Gogh - the use of the color blue and its complementary yellow (From a Van Gogh image search with Google)

Figure 14: An example of effective storytelling where the elements of good prose and poetry are modulated by composing the "warm" (facade surfaces) and "cold" (pastorals' globes) colors in respect of the prevailing monument illuminated by the white light of the LEDs - Piazza del Duomo Milan

Paraphrasing E.A. Poe, we can therefore argue that: “Those who see at night know things that escape those who see only during the day!”.

A spin off for design and for the culture of light as an expression of energy

By exploiting the powers of blue light, performances have been created such as writing and drawing on photoluminescent surfaces. Using this beautiful property, small tables of different shapes and colors have been designed .Whit blue light projectors the light can be modulated through the design, offering graphic messages and environmental suggestions (see Figure 15)

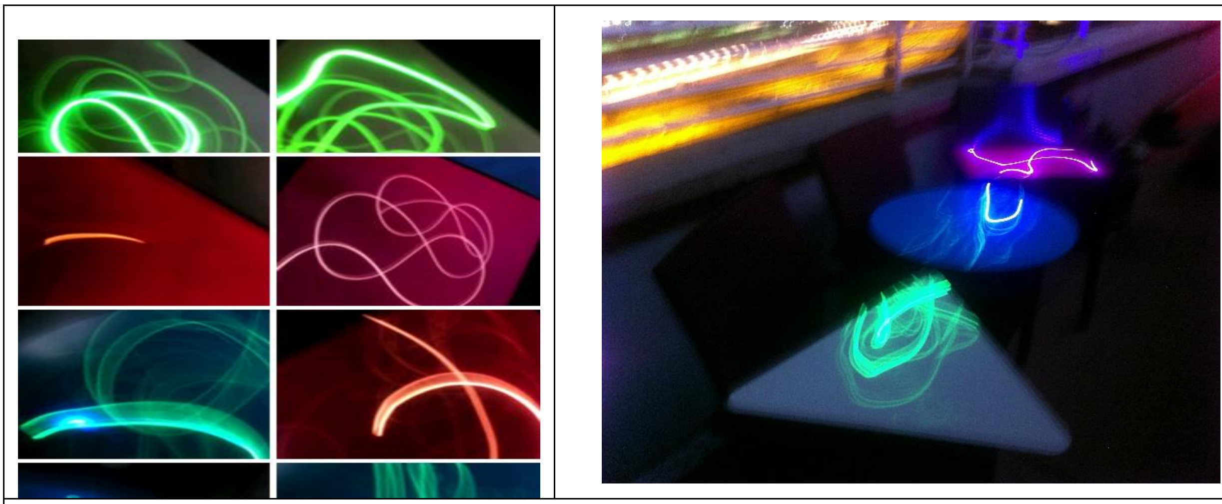


Figure 15: Design objects (tables) on which to draw with light (blue), in a mesopic environment.

In addition, to support the dissertation and importance of blue light, an installation called "Light at Km Zero" was designed and built. The first installation was made in 2015 at the Luiss in Rome as part of a contest, organic to a TedTalk event, on environmental issues. It was then replicated in other contexts. The installation has artistic and informative purposes. The themes developed are those of the relationship between energy (Human Power) and light (blue light) (see Figure 16).
The metaphors are many and the suggestions as many. Both have the dignity and substance of a specific research.

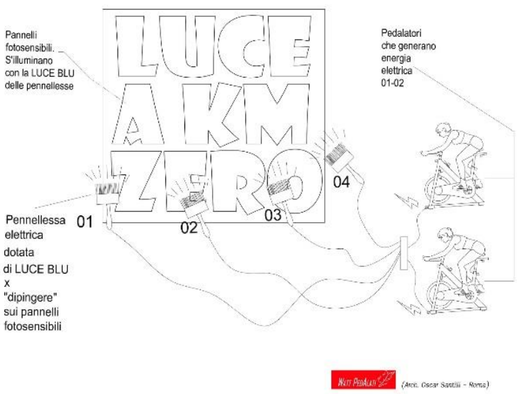


Figure 16: "Light at Km Zero" installation illustrates the relationship between energy and light. Pedalers (Human Power) consciously produce (there is an electric meter with display) the energy to power the blue LEDs inserted inside flat brushes. The brushes allow light painting on photoluminescent panels.

Notes and bibliographic references

[1] Shuji Nakamura Nobel Prize in Physics in 2014: Lectio Magistralis Convegno CIRIAF, University di Perugia, 2019

[2] Conference for the presentation of the Nobel Prize in Physics - Stockholm, 2014 https://www.youtube.com/watch?v=jhAwH4fqDb8

[3] The discharge lamps were presented by N. Tesla and G. Westinghouse at the 1893 Chicago World Exposition

[4] After about 2 years from 1996, or after about 20,000 hours, the people involved in the advertising and trade of LEDs, claimed that the new sources would have a life of about 100,000 hours, at least 11 year

[5] Description and excel table of the times of light, night and twilight times. http://wave.surfreport.it/almanacco_calendario_solare_calcolo_online_alba_tramonto.php

[6] https://www.emerson.com/documents/automation/white-paper-methods-for-comparing-visual-illumination-between-hid-led-luminaires-to-optimize-visual-performance-in-low-light-environments-appleton-en-5071338.pdf