A note on the overall efficiency of outdoor lighting systems

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Abstract:

Less than 1 photon out of 22+ million reflected ones is useful for vision, per viewer in the street, in a perfect lighting installation.

This fact calls for additional prudence in the use of artificial light at night, re-evaluating what applications are actually necessary and reducing the overall emissions as much as achievable. It also suggests that all emitted light, not just the one directly sent towards the upper hemisphere or outside the area intended to be lit, should be explicitly accounted for when evaluating the light pollution produced by any outdoor lighting installation.

Main text:

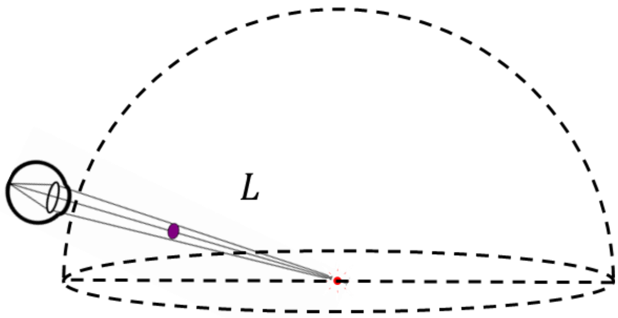
The current urban lighting approach has two main features: all points of the visual scene are lit, and the light reflected from every individual point propagates in all directions. This is a sensible choice. Illuminating all points of the relevant urban scene (sidewalks, roadway pavements, street furniture...) is certainly a reasonable option to ensure the user can foveally fixate anytime on any target of interest, simultaneoulsy getting the peripheral information required for orientation, navigation, and hazard detection. Regarding the second feature, isotropic or Lambertian-like diffuse reflections from urban surfaces also play an important role: they allow seeing the objects from whatever location the viewer may be looking at them. Furthermore, this kind of reflections are easy to obtain, not to say unavoidable, from common building materials for which purely or predominantly specular reflections are the exception rather than the norm.

The overall efficiency of any lighting system is ultimately determined by the fraction of emitted photons reaching their intended target surface, which for visual purposes is arguably the human retina, or, as a practical proxy, the input pupil of the viewer's eye.

The eye can only capture those photons propagating within the narrow solid angle subtended by its pupil from each point of the scene. Assuming a generous D=6 mm pupil diameter and a typical street viewing distance of L=10 m this angle is of order $\Omega = \pi D^2/(2L)^2 = 2.8274\text{x}10^{-7}$ steradian, for foveal fixation. This is a fraction equal to $\Omega/(2\pi) = 4.50\text{x}10^{-8}$ of the total number of photons reflected at that point during any time interval. This means, in practice, that only one out of every 22 million reflected photons are used for vision, per viewer in the street (having two eyes is counterbalanced by missing the photons from the back hemisphere). It is easy to show that this is a conservatively large estimate (*), and that it cannot be increased by improving lighting technology without renouncing to the second essential feature of our present lighting approach.

That 'single photon' out of 22 million is of course of paramount importance for us. Thanks to it (and to its billions fellow companions captured during the temporal summation window of the visual system from this and other points of the scene) we are able to see at nighttime in illuminated spaces. However, its obvious usefulness does not modify a relevant fact: from an environmental perspective, in practical terms, "all" artificial photons reflected outdoors at nighttime are sent to the atmosphere, lost by absorption or sent to locations not intended to be lit, contributing that way to different light pollution manifestations. The few ones we catch make no big difference.

This fact calls for additional prudence in the use of artificial light at night, re-evaluating what applications are actually necessary and reducing the overall emissions as much as achievable. It also suggests that all emitted light, not just that directly sent towards the upper hemisphere or outside the area intended to be lit, should be explicitly accounted for when evaluating the light pollution produced by any outdoor lighting installation.



$$\eta = \frac{S_{pupil}}{S_{hemisph}} = \frac{r_{pupil}^2}{2\,L^2}$$

(*) In the urban nightscape most points of the visual scene (front-facing hemisphere) tend to be at distances larger than 10 m and, consequently, the average fraction of visually useful photons is expected to be even smaller. This number is additionally lowered by the cosine-driven reduction of the elliptical cross-section of the eye pupil for peripheral field rays, an effect not accounted for in the above ratio.

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