How Light Meters Can Fool Us

A primer on why bluer white light looks brighter to us and how it can help save the planet

Imagine two identical rooms artificially illuminated with exactly the same amount of white light. A light meter confirms that the two rooms have equal light levels. In fact, everything about the rooms is the same except for one important detail: The light in one room has a little more blue in it than the other room. Why, then, does the room with the bluer light seem so much brighter? (See Fig. 1.)

For decades this effect has created more than a little controversy among vision scientists, with many dismissing it as nothing more than an illusion. But recent advances in vision science now support the view that this is a real effect. The room with the bluer light does appear brighter to the human eye — a fact that can help reduce lighting costs by as much as 40% or more. To understand why, we need to know a little more about the history of why light meters are calibrated the way they are and how our eyes react to light.

Figure 1: The shopping center above was initially lighted by fluorescent lamps having a color temperature of 4100K (left photo). The fluorescents were replaced by LEDs with a color temperature of 6000K (right photo). Even though the LED lamps use less electricity, the area still looks brighter because LED lighting is more efficient, but also because the higher color temperature creates a bluer white light that looks brighter to us.

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Day Vision, Night Vision, and Light Meters

Way back in 1924, the International Commission on Illumination (CIE) established a standard way to measure the eye's visual response based on photometric studies that were done between 1912 and 1923 (1). Using the results of this earlier work, the CIE defined a sensitivity curve for the eye called the photopic luminous efficiency function, or V(λ) for short. The function plots the perceived brightness (luminous intensity) of a light source against its color (wavelength), and it reveals that our eyes respond differently to various colors (see Fig. 2). Green light, for example, appears much brighter to us than red light of the same intensity because the eye is more sensitive to green. In brightly lighted environments, our eyes respond best to yellow-green light with a wavelength of 555 nanometers (nm), which defines the peak of the V(λ) function. The entire V(λ) curve (the green plot in Fig. 2) defines photopic vision.

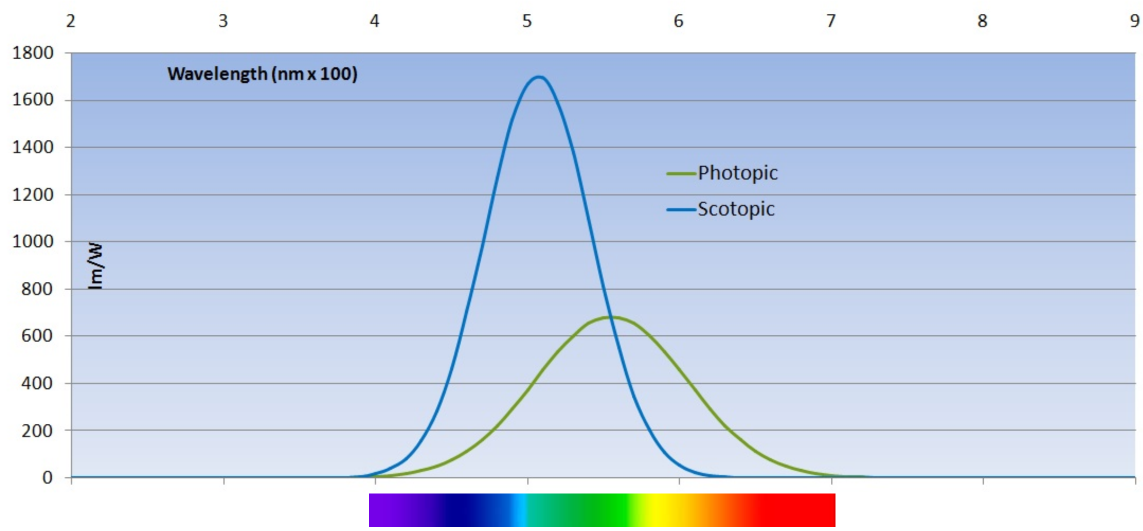

Figure 3: Our eyes react to light differently under bright and dim conditions. In bright light, the photopic response dominates with a peak sensitivity of 683 lm/W at a wavelength of 555 nm (green plot). In dim scotopic conditions (blue plot), the eye is more sensitive to bluer colors and has a higher peak response of 1,700 lm/W at 507 nm. (Note: Both plots are depicted here as bell curves.)

Photopic vision is the full-color daylight response of the eye. It is our day vision, and it results entirely from the stimulation of photoreceptors in the retina called cones. The retina contains about 7 million cones, many of which reside exclusively in a tiny central region called the foveola. The foveola is only about 0.3 mm in diameter, but it is densely packed with nothing but cones, and there are three kinds of cones: L, M, and S. Each responds differently to long-, medium-, and short-wavelength light to create our sensation of color (see Fig. 3). The relative populations of these three cone types vary among individuals, but almost all of them are either "red" L-cones or "green" M-cones.

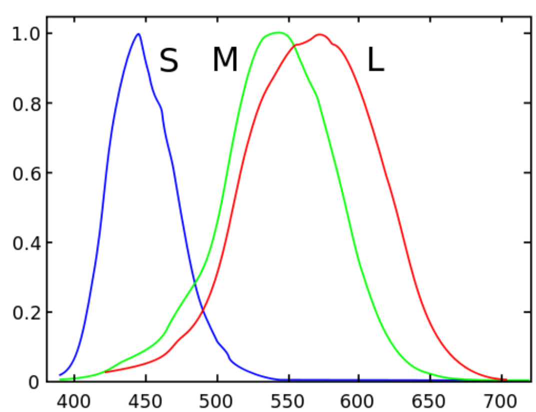

Figure 2: Normalized response curves of S-, M-, and L-cones reveal their selective sensitivity to color (17).

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Only about 2-4% of the cones in the retina are blue-sensitive S-cones, and nearly all of those lie outside of the foveola.
The sensitivity, density, and distribution of cones in the foveal area of the eye strongly influence the photopic V(λ) function, because the tests used to define the function intentionally restrict the viewing angle to just 2° or less. With such a narrow viewing angle, light can illuminate only the cone-rich fovea. But in natural surroundings, our eyes can sense light and movement at angles as high as 95° in some directions. Besides, the retina contains other important photoreceptors that contribute to our sight. Photopic vision, therefore, is only one part of the picture.

For example, about 120 million rods also populate the retina, outnumbering cones by nearly 20 to 1. (See Fig. 4 for an illustration of the relative density and distribution of retinal cones and rods.) There is only one kind of rod, so the brain cannot use them for color processing like cones, but rods are much more responsive to light than cones. In fact, when light levels fall to near total darkness, rod response soars 200x to 1000x higher than cones (2). In addition, the peak sensitivity shifts toward the blue, maximizing at a wavelength of 507 nm. This defines scotopic vision, which is how we see in the dark.

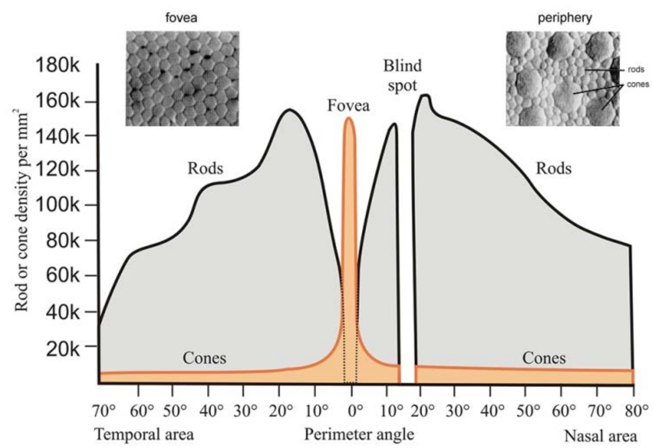

Figure 4: Cone density (orange area) is very high in the foveal region of the eye, trailing off sharply toward the periphery. But rod density (gray areas) is very low in the fovea and high in the peripheral area. Note the higher number of rods, too. (19)

It wasn't until 1951 that the CIE formally adopted a photometric standard for scotopic vision (see the blue curve in Fig. 2). The scotopic luminous efficiency function, as it is formally known, is usually symbolized as V'(λ), and it measures the eye's response to low light levels at wider viewing angles up to 20° horizontally and 15° vertically. This is the realm of night vision, where our eyes become hypersensitive to light. In this state, vision is mediated exclusively by the rods, enabling us to see at night even when the sky is overcast (about ten-millionths of a foot-candle).

By the time the CIE officially recognized scotopic vision, however, photopic vision was well-established in the lighting sciences and industry. The photopic V(λ) function had become the standard by which nearly every light meter was calibrated. In fact, it is still the standard used to calibrate light meters. And those who questioned this status quo quickly discovered just how hard old habits die.

Singing the Blues

Despite clear evidence early on that V(λ) was seriously flawed at the blue end of the spectrum (1), most vision scientists did not believe that blue-sensitive rods had anything to do with it because rods stop functioning in brighter photopic conditions. This occurs when the rod's photopigment, rhodopsin, bleaches out in stronger light, allowing the cone's photopigment, photopsin, to dominate completely.

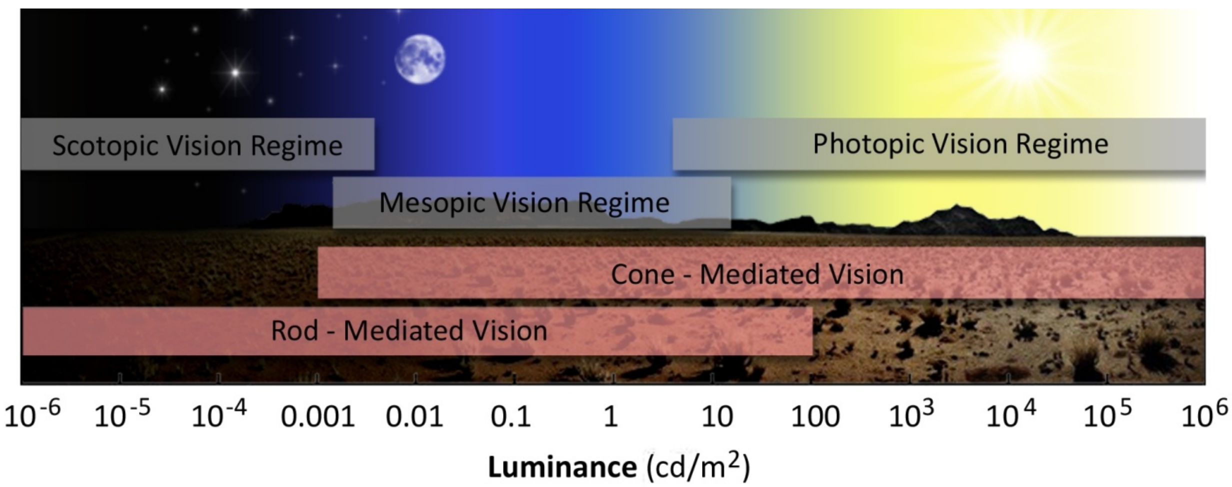

Figure 5: Together, rods and cones endow us with an enormous sensitivity range divided into three vision regimes: Scotopic, Mesopic, and Photopic, from totally dark (10-6 cd/m2) to blazing bright (106 cd/m2).

Human vision, therefore, became neatly divided into two mutually exclusive camps: blue-sensitive rods for night vision and green-sensitive cones for day vision. Officially, the scotopic range of night vision is defined in units of luminance from 0.000001 to 0.03 cd/m2, while photopic day vision characterizes luminances between 3.4 and 1,000,000 cd/m2. The twilight zone between the two is unofficially called mesopic vision. (See Fig. 5.)

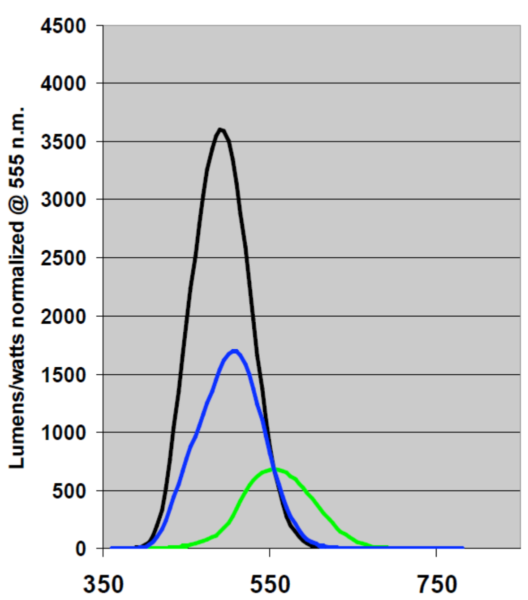

Figure 6: Three spectral sensitivity curves show the relative responses of ipRGC (black), rods (blue), and cones (green) when normalized to the standard lumen of 683 lm/W at 555 nm (18).

But then in 1962, the Dutch vision scientist Herman Bouma was investigating how the eye's iris reacts to light of different colors and discovered that blue light at 490 nm produced the strongest pupil contraction under full-field viewing conditions (3). More sophisticated experiments conducted 30 years later by Sam Berman and others (4) confirmed Bouma's discovery, leading some to suspect that retinal rods must play a more important role in our perception of brightness and light after all. At the very least, these studies strongly hinted that some physical mechanism must lie behind the effect that bluer light looks brighter to us. That mechanism may finally have been isolated.

Through a series of elegant experiments performed in 2002, a new retinal photoreceptor was discovered and given the unfortunately long name of "intrinsically photosensitive retinal ganglion cells," or ipRGC for short (5). The experiments revealed that ipRGC's photopigment, called melanopsin, directly stimulates regions of the brain that control circadian rhythm and pupil size. More importantly, these same ipRGC photoreceptors lie outside of the fovea, like rods, but also respond to bright light, like cones.

In addition, the sensitivity of these new photoreceptors peaks at 491 nm (6) (7), which matches the peak pupil response and is very close to the peak response of rods. Berman has suggested that the new photoreceptor's spectral sensitivity be called cirtopic vision, because of its correlation with circadian regulation. Figure 6 plots the response of ipRGC against the scotopic and photopic reactions of rods and cones.

Saving Energy with Spectrally Enhanced Lighting

Although the discovery of ipRGC photoreceptors and their function has reignited the ongoing debate over photopic vision, scotopic vision, and light-meter calibration, no one really disputes the fact that bluer lighting enhances visual acuity. The effect has been empirically verified and measured in several scientific studies (8) (9) (10) (11). Bluer light makes our pupils contract more, and as any photographer will tell you, a smaller aperture yields sharper images and better depth of field. The Department of Energy (DOE) has already realized significant energy savings throughout the United States by exploiting this effect. The DOE's Spectrally Enhanced Lighting (SEL) program has achieved energy savings of 40% and more by advocating the use of bluer lighting in commercial and municipal buildings (12).
The SEL program simply recommends that existing lamps be replaced with lower-wattage lamps having a higher correlated color temperature (CCT). Lamps with higher CCTs naturally emit more light in the blue part of the spectrum. The Los Angeles Public Library, for example, cut its energy consumption by nearly 40% at its 538,000-square-foot downtown facility by replacing the fluorescent lamps in 8,900 fixtures with lower-wattage, higher-CCT fluorescents (13). The retrofit now saves the library $100,000 a year in lighting expenses. Had the library retrofitted their building with higher-CCT LEDs, not only would it save even more in energy costs, but the longer lifetimes of LEDs would cut maintenance costs by two to three times. In fact, the library did realize some energy savings this way by replacing its 400 exit signs with highly efficient LEDs.

Glossary

CCT: Correlated Color Temperature, specified in Kelvin (K), is a general indicator of the "warmth" or "coolness" of a lamp's appearance. Higher color temperatures yield "cooler," bluer light.

CIE: International Commission on Illumination.

Cones: A photoreceptor of the eye responsible for our daytime color vision.

Foveola: The centermost area of the *fovea*, which is exclusively populated by *cones*.

Illuminance: A measure of the amount of visible light delivered to an area, usually measured in foot candles (lm/ft^2) or lux (lm/m^2).

ipRGC: Newly discovered photoreceptor of the eye responsible for circadian regulation and pupil reaction.

Lumen (lm)*:* A measured quantity of visible light energy from a source. At 555 nm, 1 W of light is defined as 683 lm. A photopic lumen is defined solely by the response of retinal cones.

Luminance (cd/m^2): A measure of the amount of light emitted or reflected from a source in a certain direction.

Melanopsin: Photopigment of *ipRGC*.

Photopic Vision: The spectral sensitivity of our daytime vision.

Photopsin: Photopigment of *cones*.

Rhodopsin: Photopigment of *rods*.

Rods: A photoreceptor of the eye responsible for nighttime vision.

The energy savings made possible by SEL rely on a lighting concept called visual equivalence, which assigns each light source a weighted ratio of scotopic and photopic lumen outputs. First proposed by Berman (14), the S/P ratio allows a comparison to be made between light sources based on their capacity to improve visual acuity. A 32-watt lamp with a CCT of 6000K, for example, will have more blue light in its spectrum than a 32-watt lamp at 3000K. As a result, the 6000K source will emit more scotopic lumens, which translates into smaller pupil size and higher visual acuity. To achieve the same acuity, either the 3000K source must be made brighter by ramping up the input power, or the 6000K lamp must be made dimmer by dialing back the power. For lower energy consumption, the choice is obvious.

Glossary (cont.)

Scotopic Vision: The spectral sensitivity of our nighttime vision.

SEL: Spectrally Enhanced Lighting uses bluer lighting to stimulate higher visual acuity and reduce energy consumption.

S/P Ratio: Proportion of scotopic to photopic lumens from a source.

Visual Acuity: A measure of visual clarity based on tests such as the Snellen optometry chart.

Visual *Equivalence*: The concept of equalizing visual acuity by adjusting the scotopic and photopic outputs of a light source.

For the U.S. Navy the choice was obvious, too. At Port Hueneme, Calif., the Navy replaced 2,300 fluorescent ceiling lamps inside a 67,000-square-foot office building with higher-CCT fluorescents powered at a reduced ballast factor of 0.71. The retrofit lowered photopic lumen output by 15%, but scotopic lumens remained unchanged. The facility now enjoys an annual savings of $9,250 in lighting expenses, representing a 21% reduction (15).

Each light source, then, has an S/P ratio associated with its color temperature that helps classify its effectiveness for SEL. The higher the ratio, the more scotopic lumens are produced at a given CCT. However, there is no one S/P ratio that applies equally to all lighting applications, so Berman and others have proposed using the following formula to establish visual equivalence for various situations: P x (S/P)n, where n is a value between 0 and 1. Each activity has a recommended n value related to it. For tasks such as document reading, for example, the recommended value for n is 0.78. For this particular task, then, a lamp with a photopic luminous intensity of 2,000 lm and an S/P ratio of 1.5 would yield an apparent output of 2,744 lm—a 37% improvement. More efficient sources with higher S/P ratios, such as LEDs, would yield even better results.

Bluer Skies Ahead

In 2010, the United States consumed 700 billion kilowatt-hours (kWh) of electricity for lighting alone, which amounts to about 18% of all the electricity used in this country (16). Generating 700 billion kWh of electricity creates 532 million tons of CO2 that spews into our atmosphere, which is why energy-saving methods such as SEL and LED lighting are so critical to our economic and ecological future.

It is important to recognize that each lighting application has unique requirements. Not every space can be retrofitted successfully or economically. However, the potential cost and energy savings of high-efficiency lighting solutions such as LEDs and SEL are enormous.

Ironically, the sensation of brightness that many vision scientists had once dismissed as a phantom of our imaginations has turned out to be an energy-saving bonanza with a significant environmental impact and a brighter, greener outlook for all.

About Revolution Lighting, Inc.

Revolution Lighting Technologies, Inc. is a leader in the design, manufacture, marketing, and sale of LED lighting solutions focusing on the industrial, commercial and government markets in the United States, Canada, and internationally. Through advanced LED technologies, Revolution Lighting has created an innovative lighting company that offers a comprehensive advanced product platform of high-quality interior and exterior LED lamps and fixtures, including signage and control systems. Revolution Lighting is uniquely positioned to act as an expert partner, offering full service lighting solutions through our operating divisions including Energy Source, Value Lighting, Tri-State LED, E-Lighting, All-Around Lighting and TNT Energy to transform lighting into a source of superior energy savings, quality light and well-being. Revolution Lighting Technologies markets and distributes its products through a network of regional and national independent sales representatives and distributors, as well as through energy savings companies and national accounts. Revolution Lighting Technologies trades on the NASDAQ under the ticker RVLT. For more information, please visit http://www.rvlti.com/ and connect with the Company on Twitter, LinkedIn and Facebook.

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