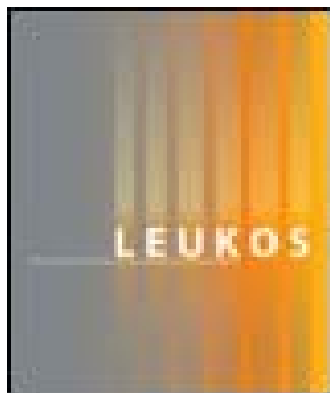




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High Color Rendering Can Enable Better Vision without Requiring More Power

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High Color Rendering Can Enable Better Vision without Requiring More Power

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ABSTRACT For many people, the correct perception of the colors of objects is an important part of life, and today it is being threatened by misinformed policy-making and associated business decisions.

Some conservationists and lamp manufacturers have concluded that the accurate color rendering provided by ordinary incandescent lamps is an unaffordable luxury that good citizens should forgo as we employ more energy-efficient alternatives. Though this is not as extreme as suggesting that we should live in cold darkness, it is in the same general direction of deprivation.

Yet research has shown that color rendering is important to people and high-efficiency lamps can now also provide high color rendering, so there is no longer any need to have lighting that distorts color appearance. This article focuses on the tradeoff between color rendering accuracy and lamp efficiency to show that high color rendering accuracy is appropriate and, contrary to a common misconception, does not intrinsically require greater electrical energy consumption.

KEYWORDS color rendition, economics, energy management, light sources, visual perception

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1. INTRODUCTION

Several programs promoting the use of energy-efficient lighting products have failed to yield widespread market acceptance because they focus on reducing energy and cost at the expense of quality factors that are important to people; a case in point is the introduction of compact fluorescent lamps into the market [Sandahl and others 2006]. These quality factors include lamp color appearance (correlated color temperature [CCT]) [Ohno 2014], color rendering (for example, CIE color rendering index [R_a]) [Houser and others 2015], color consistency among identical products, smoothness and range of dimming response, and absence of flicker and buzzing. This article is focused on color rendering and will use the term R_a to refer specifically to the CIE general color rendering index.¹ We focus on inadequate color rendering, not because it is the only barrier to adoption but because it is an important barrier that, once recognized, can be readily overcome. In terms of lighting application areas, we will be discussing the provision of light for the purpose of general use, recognizing that in certain specialized situations color rendering might be much less important, or much more important, than is typically the case.

Generally, energy efficiency programs will be more successful if they address users' expectations as they promote energy-efficient products [Cowan and Daim 2011]. Although energy and environmental benefits and the promise of reduced energy bills are important, they are not the sole drivers in technology adoption decisions. Cowan and Daim [2011] categorized lighting expectations in three behavioral categories that influence these decisions: performance expectations (outcome expectations; fitness for purpose), effort expectations (ease of use), and social influences (norms and image). The likelihood of adopting a new technology increases in the presence of facilitating conditions, such as high energy prices and product compatibility with relevant standards. Experience has shown that programs that focus only on outcome expectations (for example, lower energy costs or lower maintenance costs) are likely to be unsuccessful in the long run if they ignore other performance expectations. That is a key insight gained from the low adoption rates of compact fluorescent lamps (CFLs).

The importance of reducing energy use for both environmental and economic reasons is clear to all, and with the advent of solid state lighting (SSL) there are new ways to achieve this. This promising alternative to the low adoption rates of CFLs has motivated many SSL programs aimed at accelerating development, demonstrating technologies, and formulating performance standards. There is widespread recognition that only high-quality products will deliver the good experiences that are required for broad adoption of these innovative energy-efficient light sources. However, we contend, and this article aims to show, that color rendering has received much less attention in the development of new SSL products than it deserves, in part because of common misconceptions that this article seeks to dispel. At risk is a valuable, affordable, and traditional human experience—the natural color appearances of objects² enabled by high color rendering light as produced by incandescent lamps.

It is widely expected that efficient lamps using conventional and/or organic light emitting diodes (LEDs and OLEDs) will replace the incandescent lightbulb. These new light sources are revolutionary and have required substantial research and development on the part of industry and governments. Especially given the very long life of these new lamps, it would be understandable for manufacturers to seek the largest possible share of the first wave of lamp replacement, so there is a business incentive to promote these lamps to consumers and to recoup some of the associated investment costs quickly.

Unfortunately, most of the currently available high-efficiency replacement lamps in the market produce significantly poorer color rendering than incandescent lamps because, for reasons explained here, improving luminous efficacy of radiation (LER) and color rendering are, to a degree, conflicting goals. LER, measured in lumens per watt, represents the effectiveness with which a given spectral power distribution stimulates the human retina during typical daytime light levels, and this is indeed an important energy consideration. It would be understandable, but also incorrect, to assume that increasing a lamp's LER is the only way to reduce energy use. Possibly this has led manufacturers to prioritize LER over color rendering. As an example, numerous manufacturers are selling LED lamps that are described as "incandescent replacement" lamps even though they do not provide the high color rendering of incandescent lamps. Energy agencies have supported this trend by setting minimum color quality requirements that allow lamps to produce readily apparent color rendering error (for example, $R_a = 80$ as opposed to $R_a = 100$ for incandescent lamps) [Energy Star 2014]. Lamps with an R_a value of 80 often cause unnatural color appearance of skin, some foods, and other common objects. Some people find the distortion disturbing and it probably bothers many to some extent. We argue that by undervaluing this important aspect of the performance expectation for SSL, this approach, if continued, might not even save energy. Indeed, by impeding the adoption of the most suitable technology, it could cause needless energy waste.³

Of course, if necessary, people could tolerate such inferior lighting, just as they could tolerate, for example, having their homes heated to only 10°C (50°F) in winter. But would that be the best plan? We note that instead of being encouraged to shiver in the winter, consumers are encouraged to insulate their homes to save fuel while also improving comfort. Similarly, it seems reasonable to expect that modern lamps should save energy while also improving the lighting experience. From that perspective, it seems appropriate to critically assess the widespread view that we should now forgo the high color rendering lighting that we have long enjoyed with incandescent lamps.

It might at first seem unreasonable to suggest that respected regulators and manufacturers should reconsider their views on this matter, but this is actually a surprisingly complex topic. It involves three interconnected performance variables—radiant power density (irradiance), LER, and color rendering (R_a), and each of these has a non-linear effect on lighting benefits. Proper optimization in

the face of such complexity can be challenging, so understandably people have tried to simplify the issue, accepting illuminance as a given (in the form of illuminance recommendations) and valuing luminous efficacy (as the means to deliver the target illuminance with least energy) while assigning no benefit to having R_a exceed a minimum value of, typically, 80. Sometimes such simplifications can be helpful, giving reasonable answers. But other times (and this is one of them) a reasonable-sounding simplification of the design process yields a problematic outcome. In this article, we correct that understandable error and show an encouraging result: As the title of this article suggests, it may now be possible to have high color rendering and thus better vision, without using more power.

This article is intended to accurately cover an important scientific topic using language that is accessible to a wide audience. As such, critics might worry that the treatment is insufficiently technical and does not offer indisputable scientific proof. Indeed it does not—rather, the aim is to offer a strong plausibility argument for a testable hypothesis. We argue that in an important and meaningful way, color rendering is more valuable to people than illuminance, provided that illuminance is greater than the minimum truly required for the task at hand. We further argue that present-day lighting standards are indirectly leading to inadequate color rendering and that this problem can be readily solved without increased energy use. We hope that this article will motivate further research and deliberation on this important topic.

2. HOW LIGHT AFFECTS VISION

To state the obvious, there is no vision without light. Indeed, the definition of light is visual: “radiation that is considered from the point of view of its ability to excite the human visual system” [CIE 2011]. Our system of physical photometry is based on the biological functions of spectral luminous efficacy; this is the only physical quantity in the international system of weights and measures that is derived from human capabilities. In calculating how much light one has, one takes the radiometric intensity (irradiance) measured across the wavelength range of the visible radiation spectrum (typically from 380 to 780 nm) and applies a weighting function (usually V_λ), summing over the spectrum to determine the quantity available to excite a visual sensation [CIE 2004]. This is well known in lighting circles but less well known among the general public. This photometric quantity predicts brightness judgments of white light because it is an average over the

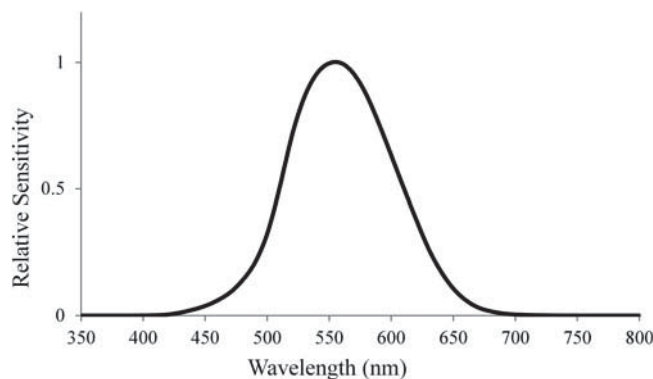


Fig. 1 The relative photopic weighting function, V_λ .

relevant photoreceptors but is not as accurate in predicting brightness judgments of colored light, which require specific information about stimulation of individual photoreceptors [CIE 2004].

The photopic weighting function, V_λ , used to calculate the quantity of light at levels typical for interiors is shown in Fig. 1. In principle, one could obtain a maximum luminous efficacy of 683 lm/W by delivering all of the energy at a wavelength of 555 nm. However, it is well known that such monochromatic (single-wavelength) light (similar to that from low-pressure sodium lamps) yields no color information. A more reasonable approach might seem to be to make a lamp’s spectral power distribution proportional to V_λ . One author calculated that a light source with such an output would have a spectral luminous efficacy of 488 lm/W but an R_a value of only 24 [Murphy 2012]. Neither of these theoretical illuminants would have any market uptake for general lighting because no one wants to live under a green light all of the time. In order for us to perceive the natural color appearance of the objects around us, the light sources we use must deliver radiant power fairly broadly across the visible spectrum. Only those wavelengths emitted by the source and reflected from the surfaces we look at trigger visual responses—although predicting the perceptual response to those wavelengths is more complex than this article can begin to describe [Boyce 2003; Gregory 1998] and is unnecessary in understanding the arguments presented.

As mentioned in the Introduction, the purpose of this article is to present a plausibility argument for the hypothesis that people would be significantly more satisfied by illumination having higher color rendering than the minimum presently required, even with the slight reduction in illuminance required to ensure that there is no increase in power consumption. The argument requires an approximate, but nevertheless quantitative, discussion—this is

about numbers and the numbers matter. The article does not present new quantitative scientific information, nor does it summarize the cited previous quantitative research in scientific detail. Rather, it introduces the general quantitative relationship between illuminance and visual perception on the one hand and color rendering and lamp efficacy on the other.

2.1. Effect of Light Quantity On Visual Performance

Thanks to a century of investigation, we have excellent models of the effect of the quantity of light on achromatic visual performance. That is, we know quantitatively how our ability to see details will improve if we increase the amount of light available to the eye; the size and contrast of the target also are important parameters [Boyce and Rea 1987; Rea and Ouellette 1991]. These models put numbers to our everyday experience, showing that we can better see objects when they are larger, have greater contrast, and/or have a greater quantity of light falling on them. Importantly, over the range of illuminance levels commonly experienced in interiors, small changes in the quantity of light have very little effect on relative visual performance. The relationship depends somewhat on the target size and contrast and will differ slightly from one normal observer to another, but overall these results provide reliable guidance in setting illuminance recommendations that are high enough to support our visual needs without being wasteful [DiLaura, Harrold, and others 2011].

Figure 2 shows, very approximately, how human angular resolution for a high-contrast target varies with the intensity of illumination for the average person. The primary reference [Shlaer 1937] used to create Fig. 2 is an early experiment in which subjects viewed screens with black and white bars having varying visual angular spacing. The size of the finest visible spacing was determined for a wide range of light levels. Although this particular experiment used only a small number of subjects, it has the advantage of spanning the full relevant range of light levels for this article, and it uses a very general vision task. Similar information is available in more recent studies [Van Ness and Bouman 1966]. The y -axis of Fig. 2 represents the angular size, from the position of the subject, of the finest visible spacing.

The x -axis spans the million-fold range of illuminance values over which human vision works well. At illuminance levels typically found in offices (often between 500 lx and

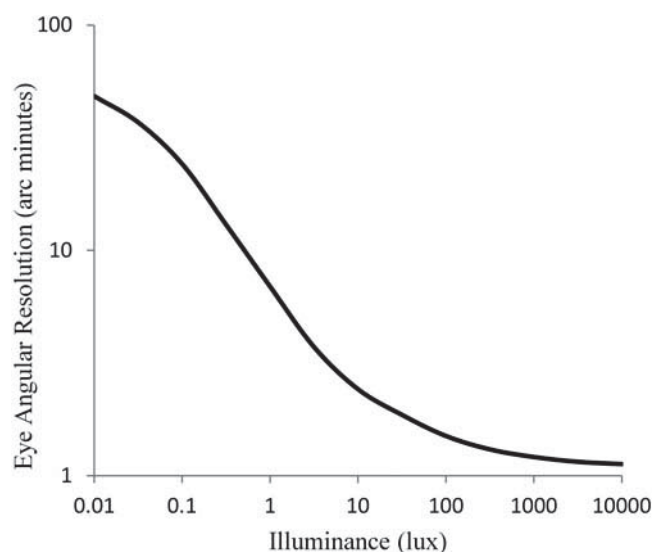


Fig. 2 Log-log plot of human eye angular resolution (y -axis) vs. illuminance (x -axis).

1000 lx), human angular resolution is approaching its minimum value of about 2 arc minutes, which corresponds to excellent vision. The chart shows that the eye angular resolution grows as illumination diminishes, but this happens very gradually—as the illumination decreases by a factor of a thousand, the angular resolution increases by only a factor of 10.

2.2. Color Rendering and Visual Performance

The human visual system also differentiates between spectral channels in the radiant energy it detects. We describe these perceptions as colors. Most humans are able to distinguish very fine color appearance differences [Wyszecki and Stiles 1982]. Artists and designers understand that the nuances of color appearance are a really important part of life. Indeed, considering how much time, effort, and money are devoted to color perception in areas such as clothing, paints, inks, cosmetics, foods, ornaments, and visual media, it is clear that color perception matters a great deal to many people. Put another way, color perception is an important component of visual perception overall.

It is interesting to consider why humans may have evolved such a sharp sense of color. Biologists generally believe that wavelength sensitivity evolved for basic survival reasons [Pinker 1997]. Color vision would have helped our ancestors to choose nonpoisonous berries, fresher food, and cleaner water and to recognize fertile soil, a clear sky, a healthy mate, and so on. Perhaps it is not surprising that today, the emotional impact of color appearance and its

design are, for many of us, an extremely important part of life [Gibson 1977; Mollon 2003; Palmer and Schloss 2010].

Of course, it would be incorrect to assume that under all circumstances people prefer illumination that produces natural color appearance in objects. An obvious counterexample is theatrical lighting, which is often used to create unnatural color appearances for dramatic effect. In addition, it has been observed that more subtle distortions of color appearance, in which color saturation is mildly increased, are sometimes chosen in certain comparisons. Nevertheless, the fact remains that color perception has the practical purpose of providing us with useful information about some properties of illuminated objects, by comparison to previous observations. For that to work well, it is important that the illumination present during previous observations rendered colors in the same way as the current illumination does, which is more or less the definition of high color rendering.⁴

Furthermore, researchers have recently begun to examine the additional contribution that color perception makes to visual performance [O'Donnell and Colombo 2008; O'Donnell and others 2010]; previously, it was generally assumed that at typical interior luminance levels, color perception would have little effect on visual performance. However, recent research suggests that this is only partly true [O'Donnell and others 2011]. When luminance contrast is high (greater than $\sim 60\%$), chromatic information adds little to visual performance. However, when luminance contrast is very low (below $\sim 20\%$), color perception makes visual performance possible; otherwise, it would approach zero. This effect depends on the chromatic characteristics of the stimuli. In between 20% and 60% luminance contrast, both luminance and chromatic contrast contribute to visual performance. Although the specifics of this model await independent validation, the empirical evidence is clear: chromatic information matters. It might matter particularly to people with certain visual aberrations, such as those that reduce luminance contrast (for example, cataracts), in which case ensuring good color rendering could be especially beneficial.

2.3. Color Vision and Illuminance

Another important consideration is the illumination level dependence of color vision sensitivity; that is, the ability to detect color appearance differences between objects. There is surprisingly little research on this well-known effect, but at least two experimental studies show that

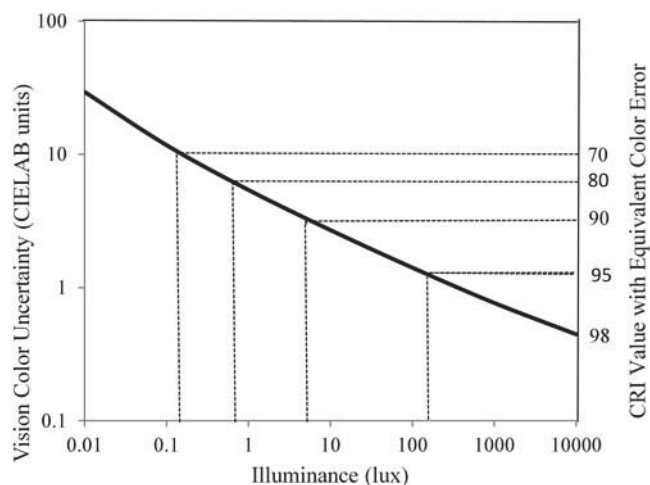


Fig. 3 Log-log plot of visual color uncertainty (left y -axis) and R_a value with equivalent color error (right y -axis) vs. illuminance (x -axis).

observers can detect smaller color appearance differences at higher illuminance levels [Baah and others 2012; Huang and others 2011]. This effect is depicted in Fig. 3, which shows the approximate dependence of color appearance uncertainty on illuminance. Color appearance uncertainty (left y -axis) is the size of color appearance difference of two nearby objects that is required to ensure that the average observer would be able to perceive that they do not have the same color appearance, expressed in CIELAB [Fairchild 2005] units. Also shown, on the right y -axis, are related values for the CIE general color rendering index value, R_a .

The values in Fig. 3 were estimated by means of CIECAM02 [Fairchild 2005], the most recent widely adopted color appearance model approved by the CIE, and calculated using a publicly available CIECAM02 spreadsheet calculator [Fairchild 2008]. CIECAM02 was designed to match a wide range of color appearance data, including the Hunt effect [Fairchild 2008], whereby the nonlinear response characteristics of retinal photoreceptors cause a reduction in color sensitivity as illuminance is decreased. At the various illuminance levels in Fig. 3, the CIECAM02 calculator was used to determine how large a color appearance change in CIELAB space was required to cause a one-unit change in CIECAM02, which is approximately a just noticeable difference in that space. Due to the Hunt effect, this value increases as illuminance decreases. The right y -axis of Fig. 3 depicts the R_a values for which the mean color rendering error associated with that value matches the color observation error shown on the left y -axis. The current R_a model is based on a slightly different measure of color difference than CIELAB, but an

approximate connection can be derived from recent studies [Davis and Ohno 2005], showing that the R_a value is approximately 100 minus 3 times the mean CIELAB color error. This is the basis upon which the right y -axis values have been matched with those on the left y -axis.

3. LIGHT SOURCE COLOR AND COLOR RENDERING

As lighting professionals know, both the color appearance of a light source itself and its color rendering quality depend on its spectral power distribution (which is the relative amount of radiation at each wavelength of the visible radiation spectrum) and, importantly, they depend on it very differently. Because of this different dependence, two light sources can have the exact same light color, yet very different color rendering properties. Figure 4 shows the spectral power distributions of two familiar white light sources that appear to have the same light color. The incandescent source has an R_a value of 100. The compact fluorescent lamp has a very different R_a value of 80. Despite their matching light color, the different spectral power distributions produce quite different color appearances for some of the objects they illuminate [CIE 1995].

This distinction may be important to the adoption of new lighting technologies because people generally prefer light sources that give their surroundings the appearance they have come to value and expect. Surprisingly, only one study seems to have examined consumers' beliefs about light source color rendering as an influence on CFL uptake: Beckstead and Boyce [1992, p. 196] found that people who

believed that “fluorescent lighting makes your skin look an unnatural or funny color” were less likely to adopt CFLs. Recent utility surveys and consumer focus group studies concerning SSL uptake [Sandahl and others 2006] have focused on the light source color and its consistency from one product to another (lack of color consistency is a barrier to adoption) but have not questioned people as to whether their décor, their food, or their faces have a natural color appearance under various light sources.

4. RELATIVE IMPORTANCE OF ILLUMINANCE AND COLOR RENDERING

We have the opportunity today to choose from an almost unlimited range of possible light source spectral power distributions, and the associated optimization problem actually has been familiar to manufacturers for decades [Schanda 1981]. Put simply, there is a fundamental trade-off between the color rendering and LER for a light source. This is because, as shown in Fig. 1, the sensitivity of the human eye decreases for wavelengths near either end of the visible spectrum (blue and red). As a result, lamps that emit little power at those extreme wavelengths produce more lumens per watt. However, using such lamps also causes color distortion because of the missing wavelengths; that is, they have lower color rendering. An R_a value of 80 might seem like a good choice, because such a lamp typically has a 15% higher LER value than a light source with an R_a of, say, 95 (that is, for the same power it provides 15% more visible light). Though this might at first seem like a sensible choice, the arguments below indicate otherwise.

The appendix explains, in simple terms, how oversimplified decision making often leads to poor optimization decisions and describes a commonsense approach for avoiding this. Anyone who feels unsure about this is encouraged to read that appendix. Its main point is that in order to make good decisions, it is important to assign the appropriate relative importance to the various desirable features. For illumination, the key issue is the relative importance of luminous efficacy and color rendering, from the perspective satisfying human needs. We provide a simple example here to illustrate the point.

Consider a room with good lighting for almost any visual task—an illuminance of 1000 lx and a CIE color rendering index value R_a of 100 (that is, perfect color rendering). The information in Figs. 2 and 3 shows that this condition gives ideal visual acuity and color discrimination. A subject spends about half an hour doing some visual

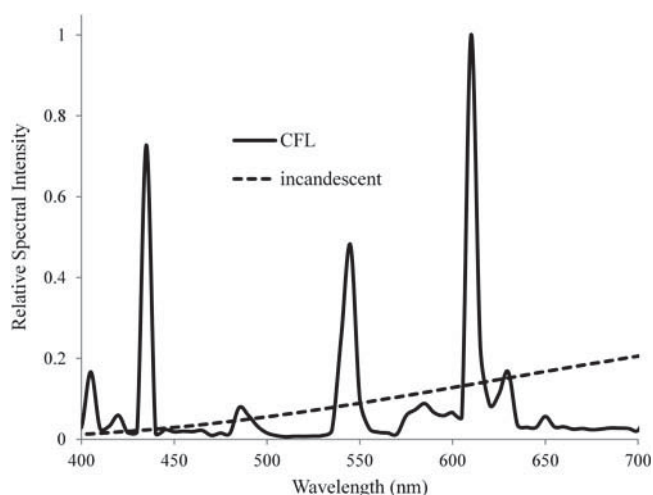


Fig. 4 Spectral power distributions of an incandescent and a compact fluorescent lamp.

tasks in the room, then walks outdoors for a while and returns to continue with the same tasks. While away, unbeknownst to the subject, either the illuminance or the color rendering of the light is reduced. How sensitive would you expect a subject to be to such changes in the lighting of a room? The answers, which are well known to lighting designers, reveal the relative importance of illuminance and color rendering in terms of human perception. First, consider changes of illuminance, with the color rendering index R_a value kept at 100.

4.1. Decreasing Illuminance

If, between observations, the illuminance is reduced 20% (from 1000 lx to 800 lx), almost no one will notice the difference and it would be virtually impossible to measure any decrease in visual acuity or color discrimination. If reduced 60% (to 400 lx), few will notice and almost no one will care. If reduced 80% (to 200 lx), most people will notice and care slightly, and it could be possible to measure a small decrease in visual acuity [Rea and Ouellette 1991] and color discrimination [Baah and others 2012; Boyce and Simons 1977; Huang and others 2011]. The widely observed truth is that such large decreases in illuminance cause only very slight reductions in visual acuity and color acuity, to the extent that they are often very difficult to observe at all. This is consistent with Figs. 2 and 3, which show that big illuminance changes cause only modest changes in vision. Put simply, people are remarkably insensitive to changes in illuminance levels. Next, consider the very different situation in which illuminance is held at 1000 lx and the color rendering index R_a value is reduced.

4.2. Decreasing Color Rendering

If, between observations, the R_a value has been reduced 20 points (from 100 to 80), some may say the lighting is less pleasant, and for almost all observers it will be possible to measure increased color discrimination errors [Boyce 1977]. If reduced 60 points (to 40), almost everyone will be uncomfortable and some will feel very uncomfortable. Under such light, people look like corpses, food looks rotten, and essentially only shades of grey look normal. This shows that, in stark contrast to our weak sensitivity to illumination levels, we are very sensitive to color distortion. This makes sense from an evolutionary perspective—typically natural light has a highly variable illuminance level but fairly constant high color rendering,

so our highly sensitive sense of color, combined with our great tolerance of illuminance changes, would have been quite advantageous.

The results in these two cases are not particularly surprising, considering that the value of R_a is calculated by subtracting, from 100, a measure proportional to average color rendering error [CIE 1995]. This means that an R_a value of 60 (that is, 40 points below 100) corresponds to twice the color distortion present with an R_a value of 80 (which is only 20 points below 100). Similarly, an R_a value of 40 has three times the color distortion present for an R_a value of 80. Often people are surprised to learn that R_a is calculated in this way, perhaps because of the common misconception that the R_a value represents a percentage of something, which it most certainly does not.

There is also an intriguing connection between color rendering and spatial perception research. Both spatial and temporal luminance patterns can cause discomfort and, in susceptible individuals, can provoke migraine and epileptic seizures [Wilkins 1995]. Fourier analysis of images shows that the spatial frequency pattern of natural images follows a $1/f$ function of higher amplitudes at lower spatial frequencies. Uncomfortable images show disproportionately high amplitude at spatial frequencies, peaking somewhere between 1 and 3 cycles/° [Fernandez and Wilkins 2008; O'Hare and Hibbard 2011]. This work has been extended to confirm that visual discomfort increases when one looks at an image whose statistics deviate from those of natural images in terms of both luminance and color contrast [Juricevic and others 2010]. Although to our knowledge, this work has not been extended to include distortions in color appearance associated with light source color rendering, the evidence that there are perceptual preferences for naturally occurring images leads to the inference that we should tread cautiously in planning widespread application of long-life light sources that would immerse the population in potentially uncomfortable circumstances.

To summarize, the key point is that fairly large fractional decreases in light level are insignificant to most people, yet fairly modest decreases in color rendering may be quite disturbing. Roughly speaking, we estimate that a decrease in R_a from 100 to 80 (20 points) is about as significant as a decrease in illuminance from 1000 lx to 400 lx (60%), based on the comparison of the information in Figs. 2 and 3. This shows that, generally, changes in color rendering are much more important to people than changes in illuminance. Let us now consider how to apply this type of thinking to make the best trade-off, for people, between efficiency and color rendering.

5. QUANTIFYING THE EFFICIENCY VERSUS COLOR RENDERING TRADE-OFF

Figure 5 shows the R_a , LER combinations for a number of light sources available today [Y. Ohno, National Institute of Standards and Technology, personal communication, Oct. 15, 2009], along with the theoretical limit for possible future sources [Hung and Tsao 2013]. Two of those light sources have been selected to demonstrate a typical trade-off in R_a and LER between them. One of the light sources (A) has an R_a value of about 94 and LER of about 308 lm/W. The other light source (B) has an R_a value of about 84 and an LER of about 362 lm/W.

Lamp B produces about 17% more light per watt of radiation than lamp A, at the cost of a 10-point reduction in R_a , corresponding to a 2.7-fold increase in color distortion. Based on the preceding discussion of the relative importance of color rendering, it is likely, in this example, that people will find lighting based on lamp type A preferable to using the same amount of power with lamp type B to produce a little more illuminance with much lower quality.

It is important to emphasize that in this comparison the energy use for the two lamp types is identical; no more energy is used with lamp type A. For the same amount of radiant power, lamp type A will give 17% fewer lumens—a difference no one can notice—while reducing color error by a factor of 2.7, which many will value. Put simply, when people prefer something (such as in this example lamp type A), it is generally because it provides more overall human value. In this sense, lamp A provides more human value for the energy than does lamp type B. From this

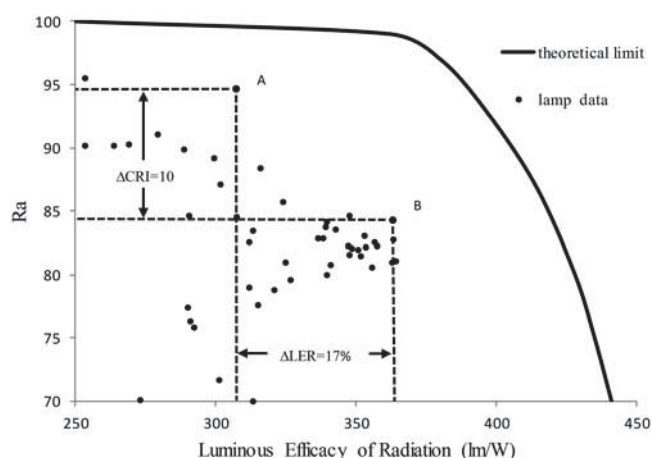


Fig. 5 CRI R_a value vs. luminous efficacy of radiation (LER).

perspective, choosing the seemingly more efficient lamp B would actually be wasteful.

6. OVERCOMING OBJECTIONS TO HIGH-QUALITY COLOR

The aim of this article has been to make the conclusions seem reasonable and straightforward. For readers who agree with this reasoning, it may seem puzzling that some well-intentioned people cannot seem to accept any argument for using a lamp with an R_a of 95, when a lamp with an R_a of 80, from one perspective, is more “efficient” and when many people are not consciously aware of the poorer color rendering at an R_a of 80. But this argument is no different than concluding that office light levels should be only 100 lx, not 500 lx, because people can easily work at that lower illuminance level and many would not be bothered by the reduced illuminance. Both of those design approaches would fail to maximize human value. To properly optimize lighting design, it might be best for society and/or consumers to first decide how much power should be used for electric lighting in a given situation and, subject to that constraint, determine what form of light will provide most value, overall, for people. From this perspective, the question “What is the most appropriate CRI R_a value?” is absolutely not an energy issue—it is a human value issue. The only meaningful question is, “What CRI R_a value enables people to get the greatest *overall* value from their lighting expenditure?”

In this regard, another objection to properly valuing color rendering is that the current method for evaluating it (the CIE color rendering index) is not perfectly accurate, and improvements are in the process of being made. However, for the fairly high color rendering lamps that are the topic of this article, the errors in question are small and they therefore do not detract from the overall reasoning. (To hold back for this reason would be somewhat like eliminating automotive speed limits because speedometers are not perfectly accurate.) The CRI is sufficiently accurate to support the arguments presented in this article and, in any event, the anticipated improvements should be available soon [Smet and others 2013]. Another article in this *Leukos* issue provides more information about the CIE color rendering index and its future [Smet and others 2015].

Probably the only way to fully resolve these issues to everyone’s satisfaction will be to carry out exhaustive experiments in which people compare equal power options

ranging from higher illuminance levels with poorer color rendering to lower light levels with better color rendering, to determine what point along the trade-off they value most. An international collaboration is now preparing to commence this long-overdue research and, based on the kinds of preliminary observations described above, certain results are anticipated with high confidence. One of these is that the level of illuminance matters. At higher illuminance levels, which are used when visual tasks demand them, as shown in Fig. 3, people are more sensitive to color error, so color rendering will matter more and therefore the optimal value for R_a will be higher. For offices and bright regions in homes, with illuminance values around 500 lx, the authors of this article anticipate that the preferred value for R_a will be about 95. For bright nighttime outdoor lighting, with an illuminance of about 20 lx, it is expected to be about 85, and for dim nighttime outdoor lighting, with an illuminance of about 5 lx, probably about 80 will be an optimal value.

The adoption of such R_a values need not cause any power consumption increase in most settings compared to present-day practices; indeed, there is the possibility of power savings. In office settings, illuminance preferences with fluorescent lamps have been found to be lower when color rendering is greater [Boyce 1977; Fotios and Levermore 1997]. Already, the outdoor lighting standard in the UK permits an illuminance reduction when the light source has $R_a > 60$ [Fotios and Goodman 2012]. Again, this is intrinsically a power-neutral decision, and the resultant increased satisfaction will likely accelerate adoption of LED technology, thereby accelerating energy savings that are badly needed.

There is one additional possible argument against high color rendering lighting—that it might cost more. However, new entries in the marketplace are indicating otherwise. For example, the California Energy Commission recently set a minimum R_a requirement of 90 for LED lamps to qualify for energy rebates [California Energy Commission 2013], and recently at least three omnidirectional commercial lamps are listed in that R_a range [U.S. Department of Energy 2013] in the same general price range as lower CRI lamps.

Above all, it is critical to understand that higher color rendering does not intrinsically require more power, because higher color rendering lamps produce light that works better for people, and therefore fewer lumens are needed to achieve the same human value. To incentivize such proper design, lighting codes should call

for both appropriate power densities and the optimal combination of color quality and luminous efficacy. This could include setting slightly reduced illuminance requirements for higher color rendering light, to ensure that the resultant significant improvement in lighting value can be achieved without increasing power consumption.

7. CONCLUSION

Overall, it is clear there is now no significant barrier preventing the use of truly high-quality, energy-efficient LED lighting in our homes, offices, schools, stores, streets, or factories. Therefore, it is time to urge regulators and manufacturers to pursue excellent human value in lighting as the best way forward for both human well-being and energy efficiency. Likely, regulators will respond favorably to further research firmly establishing this idea; such work is strongly recommended. In the long run, everyone will benefit from high color rendering standards for our light, just as we have already benefited from high quality standards for our food, water, and air.

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NOTES

1. Very often the term CRI is used to mean R_a but that slightly confusing practice will not be followed here, where only R_a will be used to represent the CIE general color rendering index numerical measure for color rendering.
2. Throughout this article, when discussing color appearance, the word "natural" will be used to describe color appearances of known objects that match the expectation of most observers. More precisely, the CIE employs the concept of color rendering, as quantified by the CIE color rendering index, to compare the color appearances of objects under a test illuminant to those under a reference illuminant that is deemed to be the standard for color appearance. The reference illuminant is either a blackbody radiator (similar to incandescent lamps) or a phase of daylight, depending on the source spectral characteristics. Because people are very familiar with the color appearance of objects under these common (and natural) standard illuminants, they often describe these color appearances under these illuminants as natural.
3. To be clear, setting a minimum R_a value of 80 does not directly require that such a low value be provided. However it may often indirectly have that effect, because consumers often may not understand the difference, and lighting designers who are trying to minimize energy use while attaining fixed illuminance requirements may feel obligated to use the most efficient lamps, which have lower R_a . Of course, there are some settings where, for special effects, low R_a values may be preferred, but the topic for this article is general lighting. Requiring a somewhat higher R_a value for general lighting need not prevent the use of lower values for special purposes.
4. There may be specialized circumstances where an important object property may best be studied using a very low CRI lamp that distorts colors in a way that makes a distinction more obvious. In such cases, the same low CRI lamp would also be used to obtain the reference information that would guide the comparison. The value of high CRI lighting is that we can use, as reference information, a great deal of previous color observations that occurred in the context of high color rendering incandescent lighting.

REFERENCES

Baah KF, Green PJ, Pointer MR. 2012. Proceedings of Color Imaging XVII: Displaying, Processing, Hardcopy, and Applications; 2012 Jan 24-26. Burlingame, CA.

Beckstead JW, Boyce PR. 1992. Structural equation modeling in lighting research: an application to residential acceptance of new fluorescent lighting. *Lighting Res Technol*. 24:189-201.

Boyce PR. 1977. Investigations of the subjective balance between illuminance and lamp colour properties. *Lighting Res Technol*. 9(1):11-24.

Boyce PR. 2003. Human factors in lighting. London (UK): Taylor and Francis. 434 p.

Boyce PR, Rea MS. 1987. Plateau and escarpment—the shape of visual performance. Proceedings of the 21st Session of the Commission Internationale de l'Eclairage; 1987 June 17-25; Venice, Italy.

Boyce PR, Simons RH. 1977. Hue discrimination and light sources. *Lighting Res Technol*. 9(3):125-140.

California Energy Commission. 2013. 2013 JA FINAL.pdf Appendix JA-8 Paragraph d. <http://www.energy.ca.gov/title24/2013standards/rulemaking/documents/final_rulemaking_documents/44_Final_Express_Terms> Accessed 2014 May 1.

[CIE] Commission Internationale de l'Eclairage. 1995. Method of measuring and specifying colour rendering properties of light sources. Vienna (Austria): CIE. Publication No. CIE 13.3-1995. 16 p.

[CIE] Commission Internationale de l'Eclairage. 2004. Photometry—the CIE system of physical photometry. Vienna (Austria): CIE.

[CIE] Commission Internationale de l'Eclairage. 2011. ILV: International lighting vocabulary. <<http://eilv.cie.co.at/term/659>> Accessed 2015 Jan 29.

Cowan KR, Daim TU. 2011. Understanding adoption of energy efficiency technologies: applying behavioral theories of technology acceptance & use to understand the case of LED lighting for commercial, residential, and industrial end-users. Proceedings of Technology Management in the Energy-Smart World, PICMET'11. Portland (OR): Portland International Center for Management of Engineering and Technology. In D. F. Kocaoglu, T. R. Anderson, T. U. Daim, A. Jetter & C. M. Weber (Eds.), pp. Article number 6017904.

Davis W, Ohno Y. 2005. Toward an improved color rendering metric. *Proc SPIE*. 5941: 59411G-1 - 59411G-8.

DiLaura DL, Harrold RM, Houser KW, Mistrick RG, Steffy GR. 2011. A procedure for determining target illuminances. *LEUKOS*. 7(3):145-158.

Energy Star. 2014. <http://www.energystar.gov/index.cfm?c=lamps.pr_crit_lamps> Accessed 2015 Jan 29.

Fairchild MD. 2005. Color and image appearance models. New York (NY): John Wiley and Sons. 472 p.

Fairchild MD. 2008. Example calculations. <<http://www.cis.rit.edu/fairchild/CAM.html>> Accessed 2014 May 1.

Fernandez D, Wilkins AJ. 2008. Uncomfortable images in art and nature. *Perception*. 37(7):1098-1113.

Fotios SA, Goodman T. 2012. Proposed UK guidance for lighting in residential roads. *Lighting Res Technol*. 44(1):69-83.

Fotios SA, Levermore GJ. 1997. Perception of electric light sources of different colour properties. *Lighting Res Technol*. 29(3):161-171.

Gibson JJ. 1977. The theory of affordances In: Shaw R, Bransford J, editors. Perceiving, acting, and knowing: toward an ecological psychology. Hillsdale (NJ): Lawrence Erlbaum. p. 67-82.

Gregory RL. 1998. Eye and brain: the psychology of seeing. Oxford (UK): Oxford University Press. 269 p.

Houser KW, Mossman MA, Smet KAG, Whitehead L. 2015. Tutorial: color rendering and its applications in lighting. *LEUKOS*. DOI:10.1080/15502724.2014.989802

Huang M, Liu H, Cui G, Luo MR. 2011. The impact of different viewing light illuminance on cross-media color reproduction. *Adv Mat Res*. 174:81-84.

Hung PC, Tsao JY. 2013. Maximum white luminous efficacy of radiation versus color rendering index and color temperature: exact results and a useful analytic expression. *J Disp Technol*. 9(6):405-412.

Juricevic I, Land L, Wilkins AJ, Webster MA. 2010. Visual discomfort and natural image statistics. *Perception*. 39(7):884-899.

Mollon J. 2003. In: Shevell S, editor. The origins of modern color science. In: The science of color. 2nd ed. Oxford (UK): Elsevier. pp. 1-39.

Murphy TW Jr. 2012. Maximum spectral luminous efficacy of white light. *J Appl Phys*. 111(10):104909-1-6.

O'Donnell BM, Barraza JF, Colombo EM. 2010. The effect of chromatic and luminance information on reaction times. *Visual Neurosci*. 27(3-4):119-129.

O'Donnell BM, Colombo EM. 2008. Simple reaction times to chromatic stimuli: luminance and chromatic contrast. *Lighting Res Technol*. 40(4):359-371.

O'Donnell BM, Colombo EM, Boyce PR. 2011. Colour information improves relative visual performance. *Lighting Res Technol*. 43(4):423-438.

O'Hare L, Hibbard PB. 2011. Spatial frequency and visual discomfort. *Vision Res*. 51(15):1767-1777.

Ohno Y. 2014. Practical use and calculation of CCT and Duv. *LEUKOS*. 10(1):47-55.

Palmer SE, Schloss KB. 2010. An ecological valence theory of human color preference. *P Natl Acad Sci*. 107(19):8877-8882.

Pinker S. 1997. How the mind works. New York (NY): Norton. 672 p.

Rea MS, Ouellette MJ. 1991. Relative visual performance: a basis for application. *Lighting Res Technol*. 23(3):135-144.

Sandahl LJ, Gilbride TL, Ledbetter MR, Steward HE, Calwell C. 2006. Compact fluorescent lighting in America: Lessons learned on the way to market. Richland (WA): Pacific Northwest National Laboratory. <<http://www.pnl.gov/publications/abstracts.asp?report=217678>> Accessed 2015 Jan 29.

Schanda JD. 1981. Implications of vision research on luminescence investigation. *J Lumin* 24-25(Part 2):851-860.

- Shlaer S. 1937. The relation between visual acuity and illumination. *J Gen Physiol.* 21(2):165-188.
- Smet K, Schanda J, Whitehead L, Luo R. 2013. CRI2012: a proposal for updating the CIE colour rendering index. *Lighting Res Technol.* 45(6):689-709.
- Smet K, Whitehead L, Schanda J, Luo RM. 2015. Toward a replacement of the CIE color rendering index for white light source. *LEUKOS.* DOI:10.1080/15502724.2014.994747
- U.S. Department of Energy. 2013. U.S. Department of Energy lighting facts publication. <<http://www.lightingfacts.com/>> Accessed 2014 May 1.
- Van Nes FL, Bouman AB. 1967. Spatial modulation in the human eye. *J Opt Soc Am.* 57(3):401-406.
- Wilkins AJ. 1995. *Visual stress.* Oxford (UK): Oxford University Press. 216 p.
- Wyszecki G, Stiles WS. 1982. *Color science: concepts and methods, quantitative data and formulae.* 2nd ed. New York (NY): John Wiley and Sons. 968 p.

APPENDIX: MAKING OPTIMAL TRADE-OFF DECISIONS

This appendix describes the conceptual issues present in decisions that involve tradeoffs between two or more performance parameters. Non-experts and experts alike make common, but avoidable, mistakes in such matters. The issues are similar for all such trade-off decisions, so we begin with a familiar everyday example: A person has decided to spend a certain fixed amount of money to buy a house. For simplicity, imagine that there are just two factors that matter to this purchaser in this case. They are (1) the size of the house and (2) the number of useful services close to it. There is a trade-off between those two factors, because with the fixed amount of money available, it is possible to buy a large home in a remote suburb with few services nearby or a small house in a very well-served neighborhood, but the combination of the two is unaffordable. Thus, there is a need to compromise between these extremes and the key question is how to determine the best compromise.

To find this, it is necessary to understand how the purchaser's overall enjoyment of a house will depend on these two desirable features. Ideally, the purchaser would have a chance to try out various affordable combinations of these features, in order to find the most appealing available combination. Failing that, one could study and take into account the experiences others have had in making such decisions. These would be reasonable approaches, but trying out many combinations is impractical for most individuals, and obtaining the information about a range of other people's experiences is difficult.

Consequently, people often use a method that is much simpler but that has significant shortcomings. One could

call this the "sequential choices" method, and it comes in two equivalent approaches, each being the reverse of the other. In this example they are as follows:

1. The purchaser first chooses the smallest house size he can tolerate living in and then purchases such a house in the best-served neighborhood in which that house size is affordable.
2. The purchaser first chooses the least-served neighborhood he thinks he can tolerate living in, and then within that neighborhood he purchases the largest house he can afford.

Both of these sequential choices are easy to follow because they are methodical and fast. That is, first you choose the required minimum value for one of the two desirable factors, significantly reducing the number of possibilities to consider, and then from that smaller set you choose the option that is best according to the second desirable factor. Unfortunately, as depicted in Fig. A1, this easy method generally yields poor decisions. One way to see this is that approaches 1 and 2 almost always give different answers. Worse, there are usually significantly better choices that are overlooked by this simplistic approach. Unfortunately, as described below, it is precisely the method that was used in the past for making the luminous efficacy and color rendering trade-off decision.

The curved line in Fig. A1 depicts the "boundary of affordability"—houses above and to the right of it are priced beyond your reach. The lighter gray zone contains

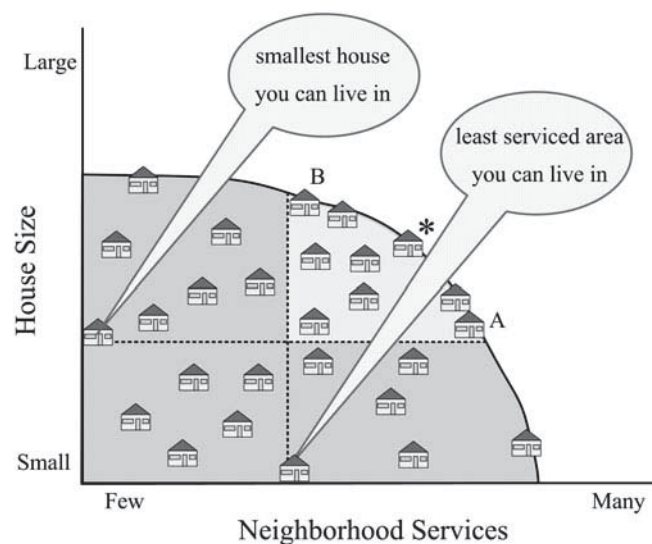


Fig. A1 This graph plots houses you can afford according to the size of the house (y-axis) and the number of nearby services (x-axis).

houses that would be tolerable for you, because they exceed your minimum required size and also your minimal services requirement. The question is which house is the *best* choice for you. Using method 1 you would first choose the smallest house size you can tolerate living in and then find the best serviced neighborhood where houses that size are affordable, yielding the house marked “A” in Fig. A1. Alternatively, using method 2 you would first choose the least well-served neighborhood you can tolerate living in and then finding the largest house you can afford in that neighborhood, yielding the house marked “B” in Fig. A1. Likely, neither is the house in which you would be happiest—the optimal choice is probably somewhere in between, such as the house denoted with a star in Fig. A1.

Consider another example involving decision making while designing a car. It is desirable for a car to be both attractive and inexpensive. Following the sequential choices approach described above, one could first determine a “reasonable minimum level of attractiveness” and then design the least expensive car based on that constraint. The result might look like the car in Fig. A2a. Instead, if a manufacturer explores the range of possible combinations of attractiveness and cost, it is usually found that with a very modest added cost, a much more attractive design is possible, resulting in greater overall value for the consumer, as depicted in Fig. A2b.

In our society, the free market has ensured that manufacturers who take the more enlightened optimization approach stay in business. As a result, cars look more like Fig. A2b than Fig. A2a, which is more reminiscent of vehicles that were produced in communist or fascist countries where human preference was not usually considered an important factor (for example, the Ladas produced in the 1980s in the USSR).

For good reasons, free market forces do not entirely apply to lightbulbs; energy regulators are empowered to make certain design decisions on our behalf. Unfortunately for everyone, energy regulators might not make the

optimal choice for overall well-being, if by using the sequential choices method they prioritize one dimension of the decision (in this case, LER) over the other (CRI). To help make this clearer, consider two fictional examples where energy regulators could inadvertently make the sequential choices mistake:

1. People drink a lot of soda pop, which often contains a lot of sugar made from corn, and corn farming consumes a lot of fuel. Production of artificial sweeteners requires less fuel. Imagine how citizens would feel if regulators banned sugar in pop, requiring instead that manufacturers use only artificial sweeteners, in order to reduce farm fuel use. Their justification might be that “most people say artificial sweetener tastes OK.”
2. Consider the use of power in home audio systems. It is well known that people are less sensitive to low bass and high treble tones. Imagine regulators banning such frequencies, in the hopes of marginally reducing home audio power consumption. The justification would be “only musicians and sound studios really need to hear low bass and high treble.”

Of course those examples sound absurd, but they demonstrate the fallacy of sequential choices optimization. Unfortunately, it seems that this sort of simplistic reasoning has been applied to the trade-off between efficiency and color rendering for light sources.

On that topic, a compromise approach could be to average these two extreme approaches: First, identify the minimum value for R_a that most people will tolerate in their homes and then, based on that value (about 84), design the spectral distribution function that has maximum LER subject to that constraint. Second, and no less reasonably, identify, for a standard electrical power budget, how low a value of LER (and hence lower illuminance) people will generally tolerate, and within that constraint, maximize R_a , which would give a result close to 100. Just as in the house purchase example above, these two approaches yield different answers and both would fail to provide people with the best compromise. However, the average of these two approaches could be close to the optimum—suggesting an R_a value of 92. We hope that upcoming research will be able to establish this unequivocally.

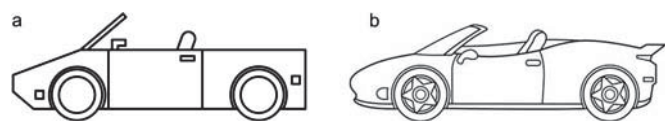


Fig. A2 Cars with (a) lowest acceptable attractiveness and (b) highest overall human value per dollar.