LIGHTING RESEARCH AND THEORY CAN CREATE BUSINESS PROSPECTS

Opportunities lie in the realm of luminaire design

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The first article in this series listed six reasons for the use of theory in lighting. These reasons all relate to the complexity of lighting and the need to approach it systematically, as a physicist would. The second article addressed the curious fact that theory helps us to deal with things that are obvious. While the lighting engineer can control light source area over a wide range, controlled experiments with a wide variation of obvious lighting features are hard to design. It is easier to design an experiment in which the independent variable is something subtle. In the theoretician's orderly universe, it is normal to state the obvious, to work with it, and to calculate things from it.

The topic of this final article is: What can theory really do for the business of lighting? What benefits can come from a more theoretical approach to lighting research and design? The answer proposed will be this: Better theory can give better lighting system designs and, in particular, new and better luminaires.

The luminance theorem

Let's imagine a lighted room in which the only light sources are some identical unshielded F40 T12 fluorescent tubes. The fact that the lights are fluorescent is not significant, except that such lights present a large area of uniform luminance, which makes it easier to imagine measuring their luminance with a spot photometer. Now imagine that we have a spot photometer and that various shiny objects are scattered around the room. These objects include concave, convex, and flat surfaces, and in every shape there are examples that are silvered as well as ones made of black glass.

Now we aim the spot photometer directly at one of the fluorescent tubes and measure its luminance, and we get a nice round number of 7000 cd/m^2. If we were to aim the spot photometer at any image of a fluorescent tube in one of the silvered objects, the luminance of that image would be slightly lower, say 6500 cd/m^2. The lamp-image luminance would be the same in all of the silvered objects, irrespective of their curvature or how far they are from the light. Of course, the image sizes vary, but not the luminances.

For all the black-glass objects, the image luminances would also be equal, but with a lower value, something like 300 cd/m^2. Again, the object shape and placement do not matter. Well, when the image is viewed far off normal, its luminance will increase, but that's a small point.

A similar conclusion holds if we aim the photometer through plates of glass, lenses, or more elaborate optical systems. The bare lamp's luminance reading would show small losses due to reflection and absorption. Lens power as such would not affect the readings.

The strikingly simple fact that image luminance is independent of the curvature of the optical surfaces involved is a special case of what is known in optics as the radiance theorem. We may attribute these phenomena to the luminance theorem.

Thermodynamics

Luminance can go down but not up. There's no way to make a lens or mirror that amplifies luminance to a value higher than that of the light source. This is something like the second law of thermodynamics which says that a closed system tends toward disorder. Light from a small, high-luminance source is orderly. A simple lens or mirror can make its rays nearly parallel or can focus them back down to a small high-luminance image. Light from a large, low-luminance source is disorderly: You can focus it into a small image, but not a bright image. In fact, the radiance theorem is closely related to the second law of thermodynamics because if you could cheat the radiance theorem, you could squeeze down the radiation from a large warm body to give a small body a higher temperature—in effect making heat run uphill, violating the second law.

The conclusion that luminance always decreases or stays the same applies as well when a diffusing surface is involved. The luminance of a white surface is the average of the luminances received by the surface. The light source will always be the brightest thing in the environment, and the white surface's luminance will be lower than that of the source.

Lighting quality

In earlier articles, I have tried to show some principles of lighting that do not have quite the same simplicity as the radiance theorem. The first of these is that lighting quality issues such as shading, shadows, highlights, veiling reflections, and even color rendering are all really issues of object contrast. The second principle is that, color rendering aside, the other sources of contrast depend on light source area, with increasing area leading in general to lower contrast. A final simple rule is that to be small and yet give the needed illuminance on the work, a light source must have a high luminance: To keep area down, you must keep luminance up. This is intuitive and is easily derived from photometry.[1] **Figure 1** shows how area and luminance relate when the source is circular and the desired illuminance on the work is 1000 lx.[1] It also shows the wide variation in luminance among available sources, with the corresponding size variation. The luminous ceiling is the largest, and therefore the dimmest, source that can give 1000 lx. The sun is the brightest source.

The theoretical issues of lighting quality and the radiance theorem can be related to the business question of what hardware should and can be invented. Lighting quality problems as we know them today were essentially invented when fluorescent lamps were introduced about 50 yrs ago. Previously, when incandescent lamps were the dominant source, the baseline luminance was that of tungsten at 2800–2900 K, which could be reduced over some range with lenses and diffusers. Although this luminance is lower than that of the sun by a factor of as much as 1000, at practical illuminance levels incandescent sources present a visual area comparable to that of the sun. Also, the incandescent source is spectrally similar to the sun low in the sky.

The introduction of fluorescent lamps gave lighting designers the option to choose a source of much lower luminance and much larger area, to choose a source that reduced red-green contrasts, and to choose a source that flickered more strongly than the incandescent lamp. Of course, all these features came in one modern package, the 1.5-inch fluorescent tube. This increased control over the optical features of the light source would seem to call for a more systematic discussion of the optical effects that lighting decisions entail. Even at this date, 50 yrs later, such discussion is sparse. The opportunity remains to improve lighting through changes based on optics.

Conclusions

For most situations, smaller luminaires of higher luminance, using sources that reveal color contrasts, give higher object contrasts. Because the luminance theorem does not permit a fixture to have a luminance higher than its light bulb, taking control of luminaire luminance means using sources that have a luminance higher than that of the T-12 fluorescent tube. This means, in effect, new sources that have a higher efficiency than incandescent lamps and give good color contrast and have a luminance at the level of soft white incandescent or higher. Although I would not want to make assertions about the color rendering of particular products on the market, it is clear that metal halide lamps, tungsten-halogen lamps, and compact fluorescent lamps have the potential to meet these requirements. Tri-phosphor fluorescents have the potential to give color contrasts as high or higher than those in daylight. In short, the theoretical analysis says that some optically excellent lamps are either on the market or are well within the state of the art.

The opportunities, then, lie particularly in the area of luminaire design. Fixtures must be designed to exploit the high-luminance, good color-rendering sources. In particular, the luminance must be maintained by the use of specular reflecting surfaces. This is consistent with directionality of the

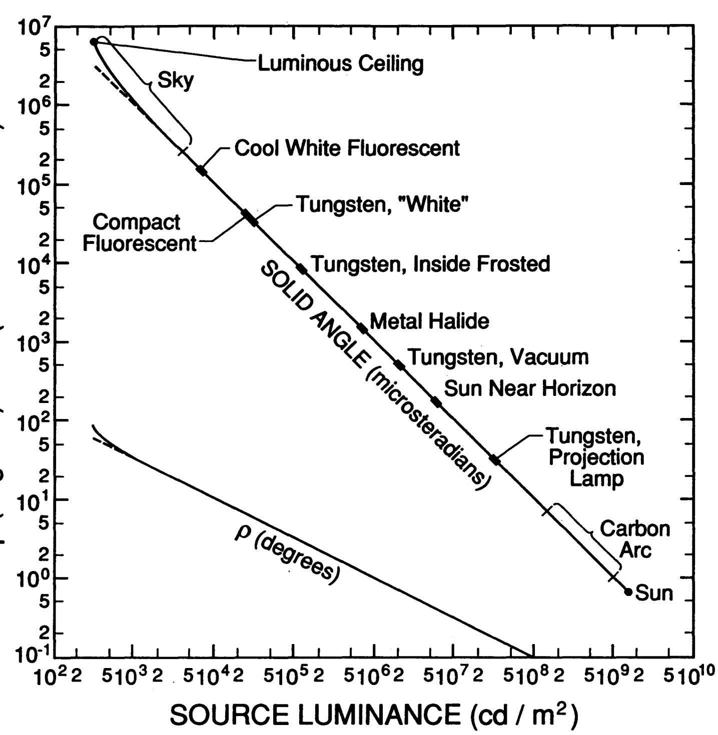

Figure 1—Light source size as a function of luminance, with the constraint that illuminance on the work is 1000 lx. The source is assumed to be a uniform Lambertian emitter, in the form of a circular cap of a sphere. Its size can be expressed either by its semi-subtense (ϱ) or its solid angle (Ω). In each case, the solid curve represents the luminance-size tradeoff exactly, whereas the dashed line is the appropriate small-angle approximation. The labeled points on the graph of solid angle are placed according to the luminances of the sources indicated. Thus, the points do not indicate the solid angle that a source actually subtends, but the solid angle that would be needed to give 1000 lx at the given luminance.

source, needed to avoid shining the light into the eye. Specular reflectors are also consistent with efficient utilization of light.

Alert readers have noted that I have advocated, in effect, heavy use of triphosphor fluorescent floodlights, a product that is actually on the market. However, I have not said by any means that the existing fluorescent floodlights are ideal. They would need to be evaluated by detailed application of theory, measurement, and experiment.

Let me now propose a luminaire idea that clearly goes beyond what is on the market. The idea was suggested by the theoretical discussion that daylight is advantageous because the optical properties of daylight tend to give good object contrast and not for mystical aesthetic reasons. Recognizing this, we might ask if daylight enhances contrast in any other way, beyond color rendering and the small subtense of the sun's disk. The answer is decidedly yes; daylight presents a sky dome that varies in color as well as luminance. To put it simply, the directional, yellowish rays from the sun combine with the diffuse bluish light from the sky to shade objects in color as well as in lightness. At dusk, the colors of the sky paint objects pink on the west side, fading to bluish on the east side.

It would be consistent with the luminance theorem to design luminaires that combine a highly directional beam with a limited amount of less directional spill to the sides. The spill should be bluish and the directional beam slightly yellowish. In addition to improving object contrast, this would answer the objection that downlighting systems make the ceiling dark and gloomy. Because of the high chromatic brightness of blue light, a little blue spill would go a long way toward brightening the ceiling without undermining the directional nature of the lighting system.

In short, it is desirable to imitate daylight more closely than any existing artificial lighting system does. The luminance theorem says that this can never be done with T-12 fluorescent tubes, but such a goal may be within reach if available higher-luminance sources are used.

Parting shot

Some readers may feel that I have said many simple things that they knew intuitively. Also, I am advocating changes consistent with current trends. The key point, however, is that thoughtful use of optics in the present marketplace could enable a shrewd luminaire manufacturer to jump ahead of the trends.

References

1. Worthey, J.A. 1990. Lighting quality and light source size. *J of the IES* 19(no. 2):142–148.

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