The Role of Theory in Lighting Research and Design

First in a series on a more analytical approach

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It is a truism that theory needs to be tested in the laboratory and many lighting experiments remain to be done. Nonetheless, an important question is, "What is the importance of theory in lighting research?"

In recent years, much has been written by historians of science about the role of theory in the development of science and the interplay of theory and experimentation. For instance, in stating that heavy objects fall no faster than light ones, Galileo was not reporting on an experiment in which he dropped a feather and a stone from the Tower of Pisa. He experimented with metal balls rolling down inclined planes. He then made a theoretical statement that extrapolated to the idealized case of objects falling without air resistance.[1] With today's vacuum pumps, one could do the idealized experiment; Galileo could not. If it seems trivial today that gravity and air resistance are separate effects, we can thank Galileo for his theory of falling objects, which lets us move ahead to other problems.

This article does not trace the history of science, but lists some specific reasons that theory is important in lighting research and design. In doing this, I am not promoting a particular comprehensive theory of lighting, but the appropriate use of analytical methods from optics, visual science, and elsewhere.

Theory is what engineers do

It's theory that lets you predict the sum of ac currents at differing phases, pressure under 20 ft of salt water, peak stress in a loaded beam, or the velocity and radius of a geosynchronous orbit. Most calculations that a lighting designer makes have a basis in optical theory, although some design tools such as visual comfort probability and officially recommended illuminances give rule-of-thumb answers with little theoretical basis. Prediction of illuminance on a task involves optical theory, whether calculated by the zonal cavity method or the latest computer model.

Facts without a unifying theory are of little use to an engineer. All questions of lighting quality clearly involve the anatomy and physiology of the eye in some manner. These topics are not mysterious: They are explained in lengthy illustrated textbooks. Yet simply handing such books to a lighting designer helps little. The designer needs a theory, perhaps based only on a tiny fraction of the available facts, that allows prediction of the effects of design by calculation.

An electrical engineer may have thick volumes of data on electrical components and materials; but the books don't make an electrical engineer. Mastery of the theory of simple idealized circuits is necessary. C. P. Steinmetz, an IESNA past-president, invented the profession of electrical engineering by developing its theoretical methods.[2]

Current methods of lighting design involve a mixture of theory and intuition. An important goal of research should be increasing the role of theory and decreasing that of intuition.

It's hard to vary light source size and SPD

Familiar light sources vary greatly in the solid angle they subtend, as seen in **Table 1**. Source area in turn affects veiling reflections, highlights, shading, shadows, and the direct illumination of the eye.

No luminaire in the lighting stores has a switch that an experimenter can turn to vary light source area while holding constant the illuminance on the work. If there were such a variable-size light, the changes in object appearance and contrast that result from adjusting the size would be considered obvious and well-understood. Homeowners could decide how far they wished to go from sparkling to soft and on into washed out. Photometric measurements could quantify the blurring of shadows and the smearing of highlights. Experiments with human subjects could measure performance and assess discomfort as the size knob is adjusted.

Table 1—Light source sizes

Light Source	Area (m^2)	Solid Angle at 2 m Distance (μstr)
Unfrosted 60-W incandescent bulb	2.0×10^{-5}	5
The sun (distance = 93,000,000 mi)	1.5×10^{18}	67
Ordinary frosted incandescent 60-W bulb	3.1×10^{-4}	79
Soft white 60-W incandescent bulb	2.4×10^{-3}	590
F40 T12 fluorescent tube	4.6×10^{-2}	12000
Luminous ceiling extending to ∞ (2π str)	∞	6,300,000 (2π million)

Clearly no such luminaire exists. Tiny and large sources depend on different technologies and differ in other features such as spectral power distribution and the ease with which they can light the working surface uniformly. The theory must come first, to show how source area will affect the contrast in different sorts of objects. In view of the dramatic theoretical results, one can select large and small sources to experiment with, although the problem of controlling other factors may be hard.

Theory also plays a key role in the study of color rendering. There is no convenient source whose spectral power distribution can be arbitrarily adjusted. William Thornton is able to produce his demonstrations of dramatically good and bad color contrast only because he started with a deep theoretical analysis. The retinex experiments, originated by Land, use a controllable light from the superimposed beams of three projectors containing color filters. Increasing the number of projectors to four could produce a variable-color-rendering light; however, such an experiment has never been done.

In short, spectral power distribution is like light source area. There is no easy way to vary it systematically. In fact, the situation with SPD is even more extreme, because a fairly elaborate theory is needed just to say what systematic variation should mean. The official color rendering index calculation is certainly an elaborate use of theory.

Optics is not controversial

The term theory is legitimately applied to ideas and calculations that are speculative, and to others which are reliable and noncontroversial. In recent articles, I have tried to emphasize data from reference books and new measurements, and calculations based on elementary optics. It is not controversial that F40 T12 fluorescent tubes are 4 ft long and 1.5 inches in diameter, or that the sun and moon each subtend about 30 min of arc. It is not a daring idea that mirrors and other shiny objects exist, along with matte ones, not to mention the important mixed category of matte dielectric objects with shiny surfaces. It is not controversial how the laws of optics will apply in idealized examples.

Simple examples show the range of possible effects, if nothing else. In sunlight on a clear day, highlights in black glass can have well over 1000 times the luminance of a diffuse white surface. Under a luminous ceiling highlights do not exist; the image of the ceiling in black glass is much dimmer than a diffuse white surface.

The conservation-of-luminance theorem in optics tells us that the luminance of a highlight in a truly shiny surface is independent of the surface's radius of curvature. With this powerful insight, and some simple calculations, one could make a few interesting measurements of highlights in daylight without aiming the photometer at the sun, or struggling to measure the tiny highlights in highly curved surfaces. The measurements could then be interpreted as measuring the detailed effects of sky luminance distribution and surface properties.

Theories have a place

Suppose that one wishes to get far beyond simplified examples and use some type of electronic imaging to measure luminance at thousands or millions of points, then analyze the data to assess the effect of light source size and other variables in realistic situations. It will be important to know that when the source is small, highlights can have luminances far higher than those of white diffuse surfaces. Since sampling millions of points is what the eye does, it will be important for theoretical ideas from visual science to guide the data analysis.

A good theoretician tries to explain as much as possible from freshman physics and simple assumptions. That is the fun of it, to do much with little. Still, not all of nature is freshman physics. Complicated problems also need a theoretical approach: First to work out the part of the problem that is simple physics, and second to explain and summarize the messy facts as simply as possible.

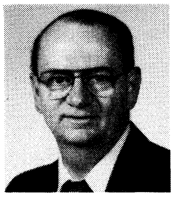
Consider the puzzle of discomfort glare. The traditional approaches make assumptions of good light vs bad light. Light that reaches the eye directly from a luminaire is bad, while light that takes a bounce is good. Yet, if a movie screen or a Christmas tree is the brightest thing in the room, people may willingly look right at it. Is a blank white wall more like a Christmas tree or more like a diffused fluorescent fixture? A scientific theory of discomfort glare would not walk away from these questions, but might use mathematical methods to distinguish a sparkling scene from a bright-but-blank one. Such a theory could be developed from established concepts in visual science, but would still be speculative at the start. Testing it would require new experiments.

Summary

Lighting decisions affect the optical interactions between sources and objects, which in turn affect the contrasts presented to the eye. In this inherently complicated situation, simple optical theory provides needed guidance for design and experimentation. More complicated problems may require more speculative theories.

References

1. Marion, J. B. and Hornyak, W.F. 1984. *Principles of physics* New York: College Publishing.
2. Gillispie, C.C., ed. 1976. *Dictionary of scientific biography* New York: Scribner.



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