Perception is Reality: Visibility in Architectural Lighting Research

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ABSTRACT: How architects measure light is changing. Human perception of light is ostensibly the reason why spaces are illuminated, yet primary lighting guidelines used by architects measure how much light is falling on a surface, not the distribution of light to the human eye (Cuttle 2011). Recent lighting research related to human visual perception introduces new ideas that, while they challenge the status quo of lighting practice, build on decades of respected prior research. In this paper's case in point, researchers are developing new methodologies and tools to study luminance distribution in built environments (Inanici & Navvab 2006). The concept of studying luminance, or perceived light, instead of only illuminance has long been established in texts by leading lighting designers and researchers (Lam 1977, Boyce 2003, Steffy 2008). This paper aims to provide information on luminance distribution as a factor of emerging importance in the design of quality illuminated environments. To this end, it reviews the use of illuminance and luminance metrics in contemporary architectural lighting practice and research contexts, exposing the objective and subjective aspects of light that these terms measure. It finds that new tools that analyze luminance data from high dynamic range photography and digital simulation models are joined by new lighting knowledge dissemination platforms, together breaking down barriers that prevent architects from designing with luminance concepts. Examination of these research and knowledge tools reveals a shift to a cross-disciplinary, user-centered approach to architectural lighting where realities of human visual perception and surrounding physical contexts enjoy renewed attention.

KEYWORDS: Lighting, perception, practice, luminance, education

INTRODUCTION

Considering architectural lighting research, *visibility* has two concurrent connotations relevant to architectural practice. First, the Illuminating Engineering Society of North America (IESNA) defines visibility as "the quality or state of being perceivable by the eye (IESNA 2003, 192)." Human perception of light is ostensibly the reason why spaces are illuminated, yet primary lighting guidelines used by architects measure how much light is falling on a surface, not the distribution of light to the human eye (Cuttle 2011). Second, visibility in the sense of access to information is a desirable characteristic for the technical knowledge generated by lighting researchers about visibility, perception and related human factors. Many important findings about lighting are isolated in discipline-specific journals that are rarely referenced by architects. At the intersection of these visibility issues is the question of how research about human visual perception is causing innovation across all facets of the lighting design industry and subsequent reform to architectural practices related to lighting. The following discussion aims to emphasize the importance of lighting proficiency for architects, and to begin to explain the underlying split nature of lighting design research as it synthesizes objective and subjective components of light.

1.0 HOW MUCH LIGHT?

> The standards and recommendations that guide general lighting practice bear no sensible relationship to providing for human satisfaction (Cuttle 2011).

1.1 Dual approaches

The simple question architects may have about visibility and perception, "How much light?" begs a complex answer. A status quo or typical architect's response would likely be given objectively in terms of *illuminance* (measured in lux) to accommodate anticipated uses or perhaps in terms of *lighting power density* (watts per square meter), a metric that rectifies minimum illuminance levels with mandates for maximum energy consumption. A change to this line of thinking is afoot, however. Using both books and blogs to transmit the message, author and academic Kit Cuttle addresses a lighting profession that is in transition to a new way of thinking about lighting. The concepts of visibility and perception, so unified in the IESNA definition of visibility in the Introduction are divided when it comes to how different lighting professionals approach lighting design.

Cuttle categorizes two distinct approaches for determining light quantity and distribution as 'best practices' and 'architectural'; he has taught both methods and clearly favors the latter as the way of the future.

The best practices approach sees task visibility as the purpose of lighting. This illuminating engineering method employs the illuminance unit of measurement to quantify the amount of light falling on a workplane. In 1979, IESNA refined the illuminance selection process to respond more to human factors such as knowledge of the space and occupant characteristics when determining target light levels. The Tenth Edition of the Lighting Design Handbook furthered refined the process to have more categories with finer steps while maintaining the emphasis on task visibility (DiLaura et al 2011). This method is most familiar to architects because it is codified in IESNA illuminance guidelines and the metrics of energy codes such as the International Energy Conservation Code (IECC).

The architectural approach focuses on appearance as the purpose of lighting, recognizing the role of human visual perception and room finishes in measuring whether lighting is adequate. It should be noted that many lighting designers follow both code-driven task visibility and individualized architectural methods in an iterative process. But codes and established metrics alone dominate the methods of many lighting decision-makers. Understanding this, Cuttle proposes perceived adequacy of illumination (PAI) as a new criterion, and mean room surface exitance (MRSE) as a metric for evaluating quantities of perceived light. MSRE is the average luminous flux density (lm/m2) from surrounding room surfaces; in other words, it measures how much light reflected from room surfaces is available to the eye. More research using human subjects is needed to validate use of PAI and calibrate the MRSE metric (Cuttle 2012).

The divide in approaches can be further characterized as rational versus phenomenological, or objective versus subjective, keeping in mind that in either methodology it is desirable for light and its perception to be quantifiable and measurable.

Figure 1: An interior where appearance of light has been considered along with the delivery of adequate light to perform a variety of visual tasks. Victoria and Albert Museum, London. Source: (J. Elliot 2009)

1.2 Dual Measures

To achieve well-tempered environments (Banham 1984) architects are required to synthesize quantifiable requirements with qualitative goals for the character and function of a space. *Illuminance* (E) and its partner concept *luminance* (L, measured in candela per square meter) provide the means to quantify light so that guidelines can be set for qualitative goals. The difference between what these interrelated terms measure – simply put, how much light falls on a surface for illuminance and how much light is reflected to the human eye for luminance (IESNA 2009) – hints at lighting's concurrent objective and subjective realities. On one hand, figuring light distribution on a workplane is a relatively simple, objective task. On the other hand, determining how occupants perceive that light is an affair that requires synthesis of knowledge about subjective and objective properties of light, materials, space, and humans.

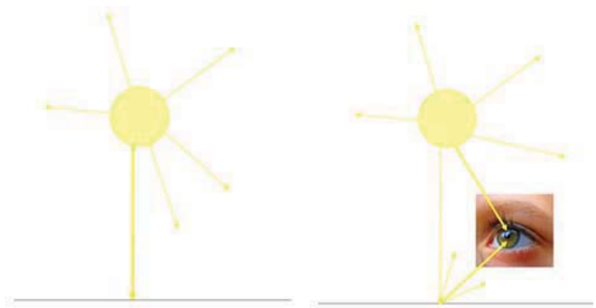

Figure 2: Illuminance (left), the density of luminouse flux received by a surface, relates to a light source’s intensity. Luminance (right) is the intensity of light that is received by the eye of an observer. Luminance is dependent on direction, and takes into account the degree to which material surfaces reflect or transmit light in a space. Source: (Sarawgi 2013)

Calculation and measurement methods for illuminance are accessible to architects, and photometric meters are relatively inexpensive tools for analog measurement of illuminance in built spaces. Calculating luminance requires additional information about material surface reflectance and room interior layout, and is dependant on shifts in viewpoints. Luminance meters have historically been more expensive and less widely used tools. The next section focuses on recent research advancing affordable and accessible tools for measuring luminance distribution in digital and analog settings. But for now, in order to contextualize that research, it is important to provide general information about who is creating and using lighting research, and how lighting research is performed and knowledge disseminated.

2.0 LIGHTING CONTEXTS

2.1 Practice

Lighting practitioners defy simple categorization of their education, training backgrounds and paths of entry into the lighting field. Education may emphasize the roots of the architectural lighting profession in the science and art of theatre lighting, it may present an engineering basis of design, or both aspects may be synthesized. Many start in the lighting field with apprenticeship rather than specialized higher education. Examinations determine professional credentials at a variety of experience levels. Architectural lighting is first and foremost the domain of professional lighting designers. However, because quality lighting is achieved through careful coordination of spaces, materials, electrical systems, budgets and more, responsibility for the achievement of quality lighting regularly falls within the purview of architects, electrical engineers, interior designers and other members of the project team. The architect in the role of coordinator between disciplines and prime communicator with the client regarding project objectives must have sufficient capacity to make and manage lighting decisions. At times when no lighting design consultant is engaged on a project, or when a project uses integrated project delivery model, the need for architects to be knowledgeable about lighting is intensified.

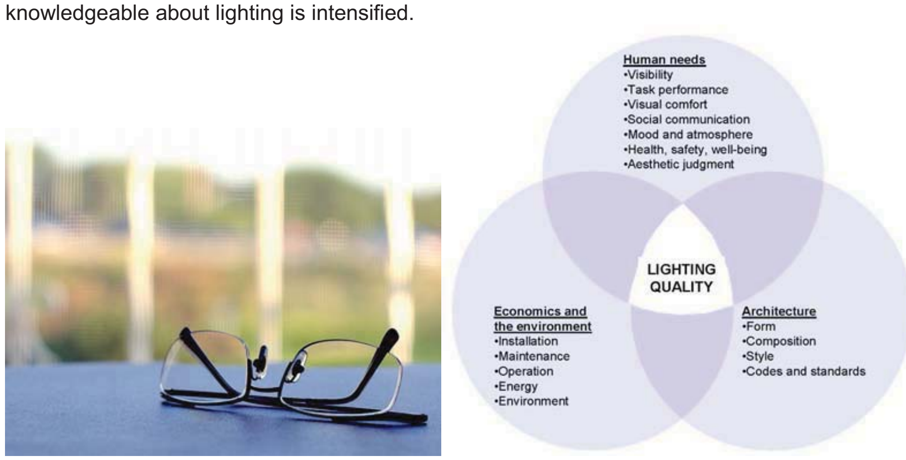

Figure 3: Quality lighting balances human needs with economic, environmental and architectural concerns. Source: (Left: Dori 2006; Right: IES lighting quality diagram by Ardra Zinkon, 2011)

2.2 Research

Lighting researchers fall into as many categories as the practitioners described above; add to these researchers having a non-construction human or natural sciences background. Lighting researchers are expanding and refining knowledge on nearly every aspect of lighting, from creating new lamp technologies to studying human circadian system response to light. Architects that perform lighting research in university research settings are specially positioned to introduce new ideas, develop technology and question current practices in ways that are relevant and accessible to other architects. Researchers with architectural training can be found in university research centers, government research laboratories, private research consortiums, manufacturing industries, and lighting design or architectural/engineering (A/E) consulting firms. Cooperative efforts between these groups are common.

2.3 Knowledge

How is lighting knowledge disseminated? Lighting design research journals such as *Leukos*, the journal of the Illuminating Engineering Society and *Lighting Research and Technology*, a Sage publications journal, have a diverse but limited readership of individuals including practitioners, researchers and manufacturers. Trade publications with a focus on lighting applications (*e.g. Lighting Design and Application* and *Architectural Record Lighting*) spread research findings to a large audience, but do so in a selective manner in less technical detail. Many important findings about lighting are isolated in discipline-specific journals that are rarely referenced by the many disciplines involved in lighting.

Books that encapsulate practical application of the lighting field's most influential research form a basis from which to observe established lighting design practices. This paper references the following texts aimed at an architectural audience: *Perception and Lighting as Formgivers for Architecture* (Lam, 1977) and *Architectural Lighting Design* (Gary Steffy 2001, 2008). Additional seminal and influential texts are too numerous to mention in this study.

How lighting knowledge is transmitted to an architect has great variation. A National Architectural Accreditation Board (NAAB) required building systems course in an architectural degree program might address lighting for only a few weeks or for an entire semester. An advanced course in lighting may or may not be offered. Lighting courses may or may not emphasize specific lighting facets such as physical properties of light, calculation methods, integration of daylighting with electrical lighting, controls, energy conservation, codes, human factors, integration with material and furniture layouts, etc. With such a vast range of topics to be addressed, some aspects are sure to be omitted. Naturally, architects will gain more comprehensive knowledge in architectural lighting in the field through ongoing project experiences. But it may not be sufficient any longer to rely on incremental, empirical knowledge to achieve 'good enough' lighting. There is increasing demand for environments to deliver higher levels of energy conservation, visual comfort and health for occupants, on time and on budget. It is time for architects as project team leaders to have capability to confidently participate in both objective and subjective aspects of architectural lighting.

2.4 Process changes

Over thirty years ago, lighting design principal and author William M.C. Lam articulated the need for an "all in" team approach to achieve lighting excellence:

> A closer cooperation will be required among all the members of the design team at all stages of the design process, with more emphasis on the formulation and achievement of perceptual rather than numerical objectives (Lam 1977, 83).

Fortunately for the task of quality lighting, projects increasingly employ integrated project design and delivery (IPDD) process models.

> The integrated design process is a method of intervention in early stages of the design process that supports the development and design team to avoid sub-optimal design solutions (Larsson 2009).

IPPD has advanced in use in part due to its role in helping projects to achieve higher performance in sustainable and energy-efficient design, efforts that require close coordination between disciplines. The process can also help deliver higher performing illuminated environments by facilitating teams to establish and meet shared objectives through cross-disciplinary planning.

Professional lighting design methodologies clearly distinguish between objective, rational properties of light and subjective, experiential qualities of illuminated environments, yet synthesize these aspects into working paradigms. This is in contrast to everyday lighting practices of other professionals such as architects or electrical engineers who respond directly to numerical code requirements in a way that is disconnected from or contradictory to strategies they may employ to achieve desired experiential qualities in a space. To work together effectively, professionals will need to at a minimum understand the mindset and work processes of their collaborating team members. Teams would be even more effective if shared methodologies could be established such as the human-centered design criteria promoted by Cuttle. Recent lighting research related to visual perception is being driven by this slow but sure sea change in attitudes.

3.0 RESEARCH ADVANCING THE LUMINANCE CONCEPT

> In an interior space, the visible surfaces and the way in which they are illuminated are the design. They define space and its perceived meaning (Lam 1977).

3.1 Evolving methods

Lighting researchers are introducing new ideas that, while they challenge the status quo of lighting practice, build on decades of respected prior research. In this paper's case in point, researchers are developing new methodologies and tools to study luminance distribution in built environments. The concept of studying *luminance*, or perceived light, instead of only *illuminance* is itself preceded in texts by leading lighting designers and researchers.

Luminance, or measured brightness as it used to be called, is a powerful metric for human-centered lighting design. Being the product of illuminance and surface reflectance or transmittance, it captures the intensity and formal characteristics of a light source as it is experienced in an applied context. Building on the ideas of Lam and others, lighting designer and educator Gary Steffy has articulated a cogent understanding of luminance and procedures for the use of the luminance metric. While full exploration of Steffy's recommendations for lighting designers is outside the scope of this study, several of the book's sections related to human psychological and physiological factors serve to illustrate why designing with luminances is advantageous.

"Lighting is all about planning and maintaining luminances (Steffy 2008, 107)." Alone, for a given point in space, a luminance value is discrete and quantifiable. It does little to describe the quality of the light, or how it is perceived. In combination however, multiple luminance values describe the qualities of light in a space. Steffy articulates how luminances can be distributed to create visual hierarchy and visual attraction (focal centers). Two adjacent areas of luminance, such as a focal object and its background, can be quantified with a luminance contrast ratio. Drawing from John E. Flynn's work on the psychology of lighting (Flynn, 1973, 1979), Steffy ranks luminance contrasts in terms of their 'attraction power'. For example, a 2:1 focal-to-background ratio is considered to have 'negligible' attraction power, with the effect of providing a 'barely recognizable focal' whereas a 10:1 ratio would have 'marginal' attraction power setting a 'minimum meaningful focal.' Creation of a 'strong significant centerpiece' effect, the contrast between the focal luminance and its background could approach 100:1. In addition to varying the intensities of the luminances as described above, chromatic contrast through manipulation of light source color and receiving surface material color can establish visual hierarchy and attraction (Steffy 2008).

Variations in luminance uniformity, location, and intensity also influence how occupants feel about a space. Again drawing from the research of Flynn and others, Steffy categorizes five impressions of space: visual clarity, spaciousness, preference, relaxation, and privacy (Steffy 2008).

Steffy also recommends studying luminance values for the role they play in "how we see, react to, and accomplish tasks (Steffy 2008, 130)." In general, luminance values on tasks should be high enough for tasks to be performed accurately, yet low enough for visual comfort issues such as avoiding glare. How high or low depends on the surrounding context. Steffy explains why the 'three lighting layers' of ambient, task, and accent or architectural are important: Ambient lighting levels affect overall subjective impressions of a space; accent lighting draws attention to special architectural elements or artwork; task lighting is localized specific to light task areas (Steffy 2008).

The ideas of Steffy and Cuttle are presented as indicators that the luminance concept is gaining renewed importance in the design of quality illuminated environments. The importance revolves around the fact that luminance concepts discussed here - luminance distribution, luminance contrast ratios, and mean room surface exitance – all take human visual perception and surrounding physical contexts into account. The emergence of this lighting trend is not isolated, however, for the synthesis of lighting with building envelope and interior room finish design can lead to optimization of those building components in ways that serve a number of sustainability objectives. Lighting joins with daylighting harvesting, balancing of thermal inertia, solar control, acoustics, and desirable views to create successful high performance 'whole buildings'.

3.2 Evolving tools

Researchers are seeking ways to support the needs of lighting designers and other professionals through developments in lighting simulation technology. This work can help merge subjective and objective analysis within a rigorous design process. Lighting researcher Mehlika Inanici and collaborators have developed new visual perception-based lighting analysis methods and tools in a project for Lawrence Berkeley National Laboratory (LBNL) titled “Lighting Measurement, Simulation, and Analysis Toolbox” (Inanici 2005).

> The project demonstrates several techniques for analyzing luminance distribution patterns, luminance ratios, adaptation luminance, and glare assessment. The techniques are the synthesis of current practices in lighting design and the unique practices that can be done with per-pixel availability. Demonstrated analysis techniques are applicable to both computer-generated and digitally-captured images (physically-based rendering and High Dynamic Range photographs) (Inanici 2005, 2).

Per-pixel luminance data analysis uses photography and digital modeling with post-processing. The RGB data in each high dynamic range (HDR) image is converted into CIE (International Commission on Illumination) XYZ data using the CIE 1931 Standard Colorimetric Observer Functions (Inanci and Galvin, 2004; Inanici and Navvab 2006). HDR imagery captures a scene in high resolution, covering the total human vision range from starlight to sunlight within a large visual field of view mimicking human vision capabilities. Inanici’s team developed the Virtual Lighting Laboratory^{TM} (VLL). Through this computational methodology and tool, any HDR photograph originating from either digital camera photograph of a physical scene or an image produce by a lighting software program like Radiance^{TM} can be imported and analyzed in fine, per-pixel detail (Inanici 2005).

Digital HDR photography is a relatively low cost and accessible solution for capturing luminance values. Web-based software has potential to demonstrate light distribution phenomena without mastery of programs like Radiance. The Radiance Image Database pilot developed by Inanici and other LBNL researchers allows users to select images from an image bank, change design and context parameters, and view the corresponding changes in luminous performance data (Inanici 2005). Sample images from the Radiance Image Database in Figure 4 use per-pixel data to reveal luminous distribution in a number of display modes:

> Each image is available in four display modes: camera exposure, based on average luminance (top left), camera exposure with superimposed iso-contour lines of luminance or illuminance (top right), human exposure, based on the sensitivity and adaptation of the human eye (bottom left), and false color mode, showing magnitude of luminance or illuminance (bottom right) (LBNL 2002, 3)

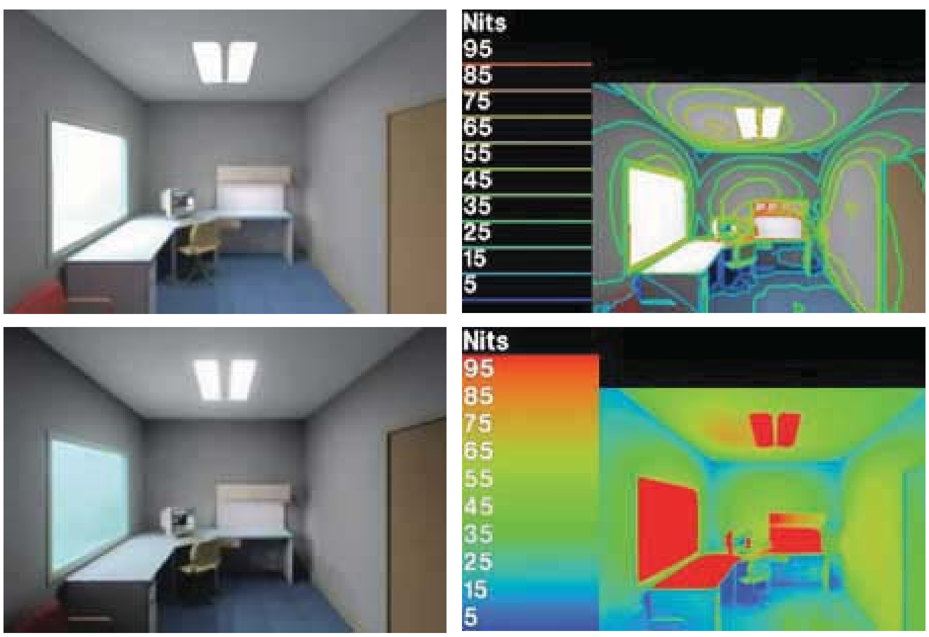

Figure 4. Images from the Radiance Image Database reveal luminous distribution. Source: (Lawrence Berkeley Laboratory Environmental Energy Technologies Division News 2002)

3.3 Barriers to use of luminance concepts

Barriers to architects’ use of luminance and other lighting concepts have persisted for some time, signifying a weakening of architects’ capacity to manage and achieve lighting goals. These include lack of familiarity with the meaning of lighting terminology, for example the difference between illuminance and luminance. Luminance is always defined and discussed in lighting texts aimed at architects, but educational courses will rarely actively calculate or promote use of luminance-based metrics. Energy codes and the IESNA guidelines most commonly used by architects refer to illuminance rather than luminance, leaving only a sector of lighting designers to employ luminance as part of their individualized design processes. Certainly, the lack of readily available tools to measure luminance has played a part in its marginalization. HDR technology has great potential to erase process barriers. Still, educational and knowledge transmission barriers must be addressed.

3.4 Shifts in education and dissemination of knowledge

Advances in lighting design practice are generally revealed to architects indirectly through updates to building industry codes, standards, and guidelines. Publications featuring cutting-edge lighting research are generally written for a readership of lighting or engineering professionals. A preferable situation would find knowledge about lighting best practices being transmitted directly to architects. This points to the need for enhanced education and cross-disciplinary discourse on the topic of lighting. Fortunately, lighting knowledge is becoming easier to access through Internet and digital technologies as evidenced through the Radiance Image Database described above.

Several websites have been developed through government and private sponsorship that aim to broadly educate architects and other professionals on lighting topics. The New Buildings Institute (NBI), a non-profit organization, is the developer of the Advanced Buildings suite of web-based tools including the Advanced Building's Core Performance Guide in use since 2007 followed by the 2010 Lighting and 2011 Daylighting Pattern Guides (NBI 2013). NBI's Advanced Lighting Guidelines is platform through which accepted new best practices can be broadly and effectively transmitted. The National Institute of Building Sciences (NIBS), another non-profit organization, is developer of the Whole Building Design Guide (WBDG 2013) which addresses lighting best practices in the whole building context. The US Department of Energy's Energy Efficiency and Renewable Energy division High Performance Buildings Database (US DOE 2013) is another resource for lighting best practices.

In the education sector, several interactive websites have been created that seek to spread lighting knowledge to broader audiences. The website created by educator Tina Sarawgi of the University of North Carolina, Greensboro, has been in use since 2009:

> E-light is an interactive exploratory interface designed to enable one to draw connections between lighting design software programs and lighting design concepts (E-light 2013).

The site links concepts and metrics of lighting, including luminance, with software design and visualization techniques. By connecting inherently quantitative software back to lighting concepts, students or professionals using the site can better bridge the gap between lighting's objective and subjective characteristics. For example, daylight or electric light sources in a three-dimensional model can be simulated in terms of illuminance or luminance spatial distribution with a simple command.

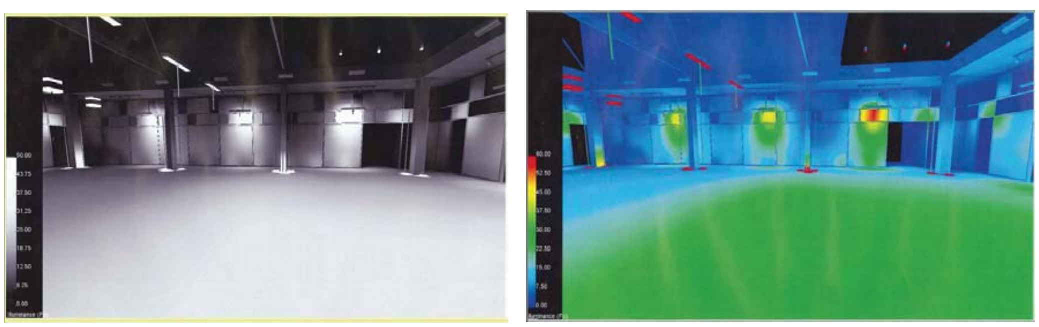

Figure 5: Lighting software can visualize illuminance distribution (left, using grayscale visualization) or luminance distribution (right, using pseudocolor visualization) within a space. Source: (Author and Elizabeth Nahrup 2012)

The author is a contributor to another web resource initiated by educator Katherine Ankerson of Kansas State University:

> The idea underpinning "Lighting Across the [Design] Curriculum" is that lighting is so critical to all aspects of design, that the conversation must be initiated early in a student's design education and carried throughout the design educational process with multiple topics. Comprised of seven interactive modules (and applicable to architecture, interior design, and landscape architecture as well as to architectural engineering), content, examples, definitions, and educator resources are provided, supplemented with animations, audio, and other interactive features (Ankerson et al 2012).

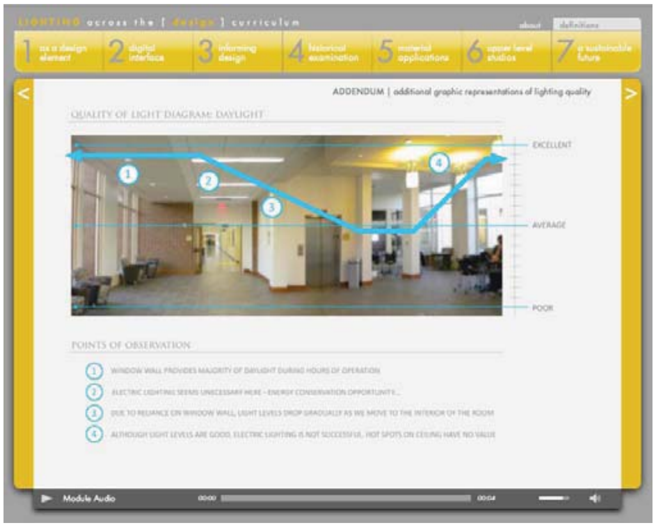

Figure 6: Lighting Across the Design Curriculum seven learning modules. Source: (Author and J. Brice Hamill 2012)

The seven modules are pictured in the sample web page shown in Figure 6. The Lighting Across the Design Curriculum resource received funding from the Nuckolls Fund for Lighting Education.

4.0 CONCLUSION

This study aims to provide information about the potential of designing with luminances to an architectural audience. To this end, it reviews the use of illuminance and luminance metrics in architectural lighting, exposing the objective and subjective aspects of light that these terms measure. This paper addresses only a thin slice of the broad spectrum of lighting design research that is underway. The variety and volume of current research reveals a shift to a cross-disciplinary, user-centered way of thinking about architectural lighting, in opposition to the numerically centered 'watts and footcandles' counting approach often left by the architect to be handled by the project's engineer. The way forward is to promote a blending of engineering 'best practices' and 'architectural' approaches as society continuously refines what it means to have an architecture featuring well-tempered, well-lit, environments.

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