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High-Dynamic Range Imaging (HDMI) as Validation and Design Tool in Assessing Daylight Discomfort Glare

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1. ABSTRACT

As glass facades become prevalent in our cities, daylighting -- with the dual goals of energy savings and occupant amenity -- is identified as a major driver. Performance metrics traditionally used to evaluate electrical lighting design, such as illumination levels, are proving to be less useful for evaluating visual comfort performance in a highly glazed situation. Discomfort glare in a daylighted space has a large impact on occupant comfort, but it has been difficult to predict during the design process. A host of glare indices have been developed to address this need, but the validation of these indices for daylighting is still underway. Today, many designers use rules of thumb for luminance ratios. RADIANCE software can predict luminance conditions and produce predicted luminance maps used for visual comfort evaluation. The development of High Dynamic Range photography calibrated for luminance levels can produce similar luminance maps from photographs of existing spaces. This tool closes the loop between prediction and validation. Using recently constructed projects, this paper describes the use of post-occupancy HDRI in the validation of luminance predictions as well as the use of calibrated HDRI and predictive simulations in the design phase.

2. INTRODUCTION

Many contemporary building envelopes for commercial and high-rise residential projects feature high transparency and all-glass facades. The aesthetics of these buildings drive some of this trend; developers find both the exterior view and the views from inside attractive to tenants and owners while architects receive positive press and visibility in architectural publications. The use of the highly-glazed facade has been aided by significant technical advances in glazing, such as low-iron and spectrally selective glass, as well as curtain wall technologies such as thermally-broken frames and accurate fabrication techniques (Green 2011, Selkowitz 2003)

Highly glazed facades have also been encouraged by the growing interest in daylighting related to occupant well-being and productivity, high quality interior environment and a desirable connection to nature. Daylighting is understood to deliver "sustainable performance" including energy savings in building types such as offices that otherwise use 40% of their electrical energy for lighting. Hence we often hear the general assumption that large areas of glass and highly transparent facades deliver not just daylight but "daylighting". There are problems with this simplistic equation and we find push back from many areas including energy codes, occupant thermal comfort and concerns about glare that are surfacing in post-occupancy evaluations of "daylighted" and "green" buildings.

2.1 Energy Codes and Standards.

Energy codes and green building standards take an approach to the building envelope in which glazed areas are seen as thermal miscreants that must be controlled. Glazed areas typically lose more heat in the winter and gain more solar radiation in the summer than insulated opaque envelope. This results in an approach, at least in the prescriptive path, that restricts the percent of wall that can be glazed; the window to wall ratio (WWR). "New versions of energy

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codes and building codes will call for lower window-to-wall ratios: prescriptive requirements in the 2012 version of the IECC (International Energy Conservation Code), for example, call for 30 percent window-to-wall ratio (WWR) and 3 percent skylight area, which is stricter than the 40 percent and 5 percent, respectively, allowed by the 2010 version of ASHRAE 90.1." (ED+C 2013). With questions from the daylighting and architectural community, recent research has started to examine the role of daylighting and its impact on energy use. Daylighting requirements in ASHRAE 90.1 have been examined in one study, although there are concerns about the assumptions used in generating the results (Athalye 2013). Another study brings an optimization strategy to examining the relative contributions of daylighting and thermal performance in building envelope design (Lartigue 2013).

2.2 Thermal Comfort.

Concerns about occupant thermal comfort in highly-glazed facades have also been noted in the professional press: "When I see a fully glazed, floor-to-ceiling commercial or institutional building, I see an energy-consuming nightmare of a building that requires lots of heating and cooling at the perimeter just to maintain comfort.... Although it is well accepted that “green” buildings are above all low energy consumption buildings, there is a mistaken belief, almost a myth, that buildings with large expanses of glass are somehow green." (Straube 2008) Occupants near a 100% glass facade can experience discomfort due to surface temperature variations such as asymmetric radiation, drafts, vertical air temperature difference, and warm or cold floors which then will require specific HVAC solutions that may use more energy to solve the comfort problems. (Green 2011)

2.3 Visual Comfort.

There is also a general concern with potential visual discomfort from glare in highly-glazed buildings (Green 2011, Straube 2008). Beyond anecdotal warnings we can turn to responses from building occupants on satisfaction with lighting quality. The survey conducted by the Center for the Built Environment at University of California, Berkeley has collected enough responses such that they have been able to examine the subset of office buildings (Frontczak 2012). Data from 52,980 occupants in 351 office buildings has been analyzed and provides an understanding of occupant satisfaction with lighting quantity and lighting quality. The most important parameters for workplace satisfaction were not related to lighting, but rather to the amount of space, the noise level and visual privacy experienced by the occupants. On a seven point scale, with 0 being neutral, +3 being very satisfied and -3 being very dissatisfied, satisfaction with amount of light ranged from +1.66 in private offices to +0.9 for those far from a window, and with lighting quality from +1.21 for those in private offices to +0.64 for those far from a window, with low partitions and being close to a window increasing the satisfaction. A separate report of survey results from 21 LEED certified buildings and green buildings indicates occupants in this subset of buildings rated lighting quality consistently neutral or better than neutral, with three clumps of response: neutral, satisfied and very satisfied (Abbaszadeh 2006) The most frequent negative comments about lighting quality included "not enough daylight", "reflections in the computer screen", "too dark" and "too light", but did not identify conditions of discomfort glare as a problem.

As an extension of the CBE survey that also followed up with more detailed questions, HOK performed post-occupancy evaluations of the green and LEED buildings they had designed. "Access to natural light is understood by designers as a universally positive feature; however, we found that user satisfaction requires a true integration of daylighting strategies with the building’s lighting systems. In some of our highly successful daylit buildings, challenges remain with light spill and glare, and results point to operational problems with some occupancy sensors." (Mendler 2007) Other post-occupancy evaluations have focused more specifically on daylight and discomfort glare. Extensive workstation surveys in Brisbane, Australia involved 493 surveys collected from five green buildings. "Discomfort glare was highly prevalent within the green buildings investigated, 49% of occupants surveyed reported some discomfort at the time of survey." (Hirninga 2013)

These concerns indicate that the "glass = daylight = sustainable" equation operating in much facade design is far too simplistic. To deliver energy efficient, daylighted buildings, design professionals must address energy use, thermal comfort and visual comfort in the design phase. Rather than focusing on minimizing glass, we have found that simulations of thermal comfort and energy use, accompanied by robust predictions of daylighting performance can achieve the both energy efficient and high quality interior environments. These robust performance predictions must, necessarily, include an examination of visual comfort or glare.

3. GLARE AND DAYLIGTING PERFORMANCE

For over a hundred years, the metric for lighting performance has been illumination levels delivered by the lighting system, whether electric or daylight. Illumination levels appropriate for task and occupant conditions are still are the dominant metric for lighting performance and therefore daylighting performance, whether in guidelines, standards or in codes. Illumination levels can be easily and inexpensively measured in the field and therefore work well for standards and codes. They can also be accurately predicted using a wide range of tools, from hand calculations to physical models to simulation software. These advantages overcome general agreement that illumination levels are relative and standards have often been set based on industry interests and available technology rather than scientific data (Osterhaus 1993).

Beyond standards and codes that demand performance in terms of illumination levels, lighting controls that reduce electrical lighting use when daylight is available effectively estimate the illumination level that must be supplemented by electrical lighting. To control the electrical lighting output, these controls use a measurement of either available illuminance from the sky (open loop) or use a type of luminance sensor to estimate illumination levels on a task surface (closed loop) to control the electrical lighting levels. Therefore daylighting design is locked into a metric of delivered illumination levels in order to deliver energy savings.

3.1 Beyond Task Visibility

In looking for additional measures of "good lighting" and "good daylighting", one finds a long history of lighting designers arguing against illumination levels as the sole criteria for lighting design. In 1949, the famed lighting designer Richard Kelly proposed three design functions for light: "emphasis, or the organization of visual design; comfort, the fulfillment of the needs of seeing; and character, or the feeling of a space." (Neumann 2010) Kelly followed this in 1952 with his description of three types of light: focal glow, ambient luminescence, and the play of brilliants, but also included six additional qualities of light: intensity, brightness, diffusion, spectral color, direction and movement. Only a small part of this proposal for lighting performance involves illumination of a task. Twenty-five years later, Bill Lam proposed that lighting fulfills biological needs and published his twenty-three principals or "Rules of Thumb" for lighting that included no quantitative metrics (Lam 1992). As he wrote: "Knowing what information one wishes the luminous environment to convey is therefore far more important than specifying arbitrary general light levels. The eye adapts to light levels automatically; the *mind* responds to *information*."

Kelly and Lam considered the appearance of a space as the key to lighting performance, rather than providing for visibility , as Cuttle (2013) notes in a recent paper: "Lighting regulations made with the best of intentions – resources management, environment protection, and sustainability – follow the pattern set by the 'visibility' camp in that the provision of illumination is assessed in terms of illuminance values measured on 'visual task planes', which is almost invariably interpreted as referring to the horizontal work plane."

As an example of this, standards that include daylighting as a sustainable design strategy have responded to the concern for over-lighted rooms and discomfort glare with new metrics that are nevertheless based on illumination levels. The USGBC LEED system has followed the Collaborative for High Performance Schools (CHPS) in focusing on uniformity of illumination levels within a space, bounding both upper and lower illumination levels in order to disallow extreme light and dark areas in a daylighted space. "IEQ C8.1 – Daylight and Views – Daylight. Demonstrate through simulation that 75% or more of all regularly occupied spaces achieve daylight illuminance levels between 25-500 footcandles for a clear sky condition on September 21 at 9am and 3pm." The top cap on illumination levels in a space typically will not allow direct sun, thus requiring the use of sun control to increase visual comfort (LEED 2009).

3.2 Measuring Visual Discomfort

From the perspective of the design professions, the available metrics for discomfort glare have been an alphabet soup, and seen as more successful as a research topic than something that can be used in practice. There are a number of brief but informative histories of glare metrics available (Osterhaus 2005, Jakubiec 2011). For this paper it is sufficient to note that, starting in the 1920's, lighting researchers attempted to develop a method of quantitatively describing the phenomenon of discomfort glare. Their work was focused on the problem of visual discomfort from electrical luminaires that can present small areas of extremely high luminance in the visual field. Visual Comfort Probability (VCP), the British glare index (BGP also known as the IES glare index) and the European Glare Limiting Method, were developed to measure and predict discomfort glare from electrical sources. The CIE glare index (CGI) attempted to combine previous indices and was succeeded by the Unified Glare Rating (UGR). Non of these addressed conditions of large area sources of high luminance such as introduced with daylighting apertures.

In 1972, Hopkinson proposed the Daylight Glare Index (DGI) that accounted for large glare sources, such as sky seen through a window (Hopkinson 1966). This was combined with successive research to generate the Cornell Formula. These glare indices relied on equations, geometrical analysis, nomographs, and look-up tables to predict a single number (the Glare Index) that could then be matched against recommendations. More recently, the Daylight Glare Probability (DGP) index has been proposed which calculates glare as a function of the vertical eye illuminance as well as the glare source luminance, its solid angle and its position index (Weinhold 2006). Using computer simulation and analysis, the DGP and now other metrics can be calculated with a luminance map of a space under specific daylight conditions rather than the more tedious hand calculation methods involved previously.

The intent of these glare indices is to provide a single number that characterizes visual discomfort due to highly luminous sources within the visual field. Two critical questions arise if these are to be used in practice: are these glare metrics accurate in predicting occupant visual discomfort and are they useful in predicting occupant visual discomfort?

3.4 Accuracy of Glare Indices

There are highly mixed conclusions as to the accuracy of the various glare indices. Clear's remarkable study of multiple glare indices concluded that "We do not have a theoretical understanding of discomfort glare, and every formula evaluates glare differently." (Clear 2012) In 2005, before the DGP was proposed, Osterhaus reviewed studies of the predictive ability of glare indices compared with subjective responses and concluded that " All of the above observations appear to suggest that the current daylight glare index is at best unreliable, if not misleading." (Osterhaus 2005)

Jakubiec and Reinhart (2011) are more sanguine on results comparing the DGP to four other glare metrics: "Experimental results in three spaces utilizing individual Radiance simulations for each sky condition and space showed that of five tested glare metrics DGP, daylight glare probability, is the most robust metric and least prone to produce misleading or inaccurate glare predictions under a variety of analyzed solar conditions."

If comparative studies of glare metrics are, at least so far, inconclusive, perhaps post occupancy surveys can reveal more about the accuracy of the predictive metrics compared to occupant satisfaction. In a first round of post-occupancy studies of green buildings in Brisbane, Australia 64 office workers were surveyed. "The study used a specially tailored post-occupancy evaluation (POE) survey to help assess discomfort glare. Luminance maps extracted from High Dynamic Range (HDR) images were used to capture the luminous environment of the occupants. These were analyzed using participant data and the program Evalglare. The physical results indicated no correlation with other developed glare metrics for daylight within these open plan green buildings, including the recently developed Daylight Glare Probability (DGP) Index." (Hirning 2013) Occupant studies that looked at the impact of view on visual discomfort ratings found that a bright window with an interesting view seems to cause less discomfort than a similarly luminous window with a less interesting view (Tuaycharoen 2007). The conclusion, that "a good view tends to reduce the DGI by several points" further brings the accuracy of glare indices into question.

3.5 Rules of Thumb: Luminance Ratios

Between these mixed conclusions as to accuracy and the difficulty in using any of these indices (with the possible exception of DGP), many design professionals have returned to rules of thumb that are widely promulgated through professional references (Daylight 2000, Baker 1993, DiLaura 2011).

- variation in luminance across the immediate task should be kept to a maximum of 3:1;
- variation in luminance between the task and background is permitted typically 3:1;
- greater variation is permitted between the task and remote surfaces typically 10:1
- variation in a daylighted space should be kept to 20:1
- maximum contrast allowed is 40:1
- highlighting objects for emphasis 50:1

A study by Sutter (2006) of spaces where the occupants were satisfied with their luminous environments showed that while there was some variation from the above ratios, they might serve as well or better than a glare index in the design process: "... luminances were in a 1:3:10 ratio as long as no source of daylight was visible in the user's visual field. If a window was part of the worker field of view, the analysis of the data showed that luminances were in a 1:6:20 ratio, rather than 1:3:10. In this case it was observed that a tolerance up to 1:50 could occur if the patch of bright luminance remained fairly small (about 5% of the whole field of view)."

4. LUMINANCE PREDICTIONS AS VISUAL COMFORT DESIGN TOOL

Our search as a design and consulting practice was for a reliable and robust method to consider visual comfort during the design process. Little has been published about how glare is handled in the design process on real building projects. Thompson (2011) is one of the few but demonstrates a simplified example. Luminance ratios offer a ball-park visual comfort evaluation strategy, but still require quantitative luminance information. In the years of physical modeling, this was hard to generate during the design phase and one was left with the glare indices to calculate. Most often, no glare analysis was attempted except visual examination of the model or model photographs. More recently, RADIANCE software has enabled design professionals to predict luminance conditions in a design space under the full range of sky conditions that the built space will experience. Once simulation software was capable of predicting luminance values, the luminance map of a room became our primary tool to assess potential discomfort glare and disabling glare. Luminance ratio rules of thumb became a useful secondary tool for interpreting the luminance maps to architects, owners and users.

As part of developing a daylighting design, we simulate the illuminance of a space under varied sky conditions identified in the TMY data for the project site. These simulations are used to understand the range and spatial distribution of light levels, the potential impact of shading, the necessity of controlling direct sun, the electrical lighting control zones and performance relative to standards such as LEED, CHPS and client standards that typically specify recommended illumination levels.

4.1 Luminance Maps

In many projects the visual comfort of the daylighting design is a more critical performance issue than achieving specified illumination levels. Luminance maps describe the luminance conditions of the visual field viewed from a specific location both visually and quantitatively. They include the task area, the near surround and the far areas of the visual field. Depending on the detail of the model and the simulation, the luminance map accurately includes apertures, computer monitors, and light fixtures on/off or dimmed to specified levels. To look at luminance ratios and check potential discomfort glare, one can use the false color scale for quick estimates or call out the value of an individual pixel in nits or candelas per meter squared. It is also possible to look at the character of the overall visual field that in ways address the goals of the "appearance" advocates; is this room generally bright or dim, is there an evenness or a large gradation of luminance, does the visual field convey orientation and hierarchy consistent with the use and architectural intention.

Luminance maps also assist with understanding visual performance of design components or alternate schemes. This is especially true in understanding the performance of shading. Shading devices such as horizontal louvers, interior light shelves, exterior overhangs and fins, venetian blinds and diffuse roller shades are often crucial for occupant visual comfort. They are also typically on the chopping block during budget discussions such as Value Engineering because they are not integral to the existence of the building (as the structural system is) and they typically have a line item cost that can be identified. Shading devices, moreover, rarely if ever can pay for themselves over time through energy savings. Being able to explain the crucial visual comfort contribution through luminance maps is often the most convincing method for keeping shading in a building. In Figures 1 and 2, the simulation of visual conditions presented in luminance maps makes the case that visual comfort will be increased through shading.

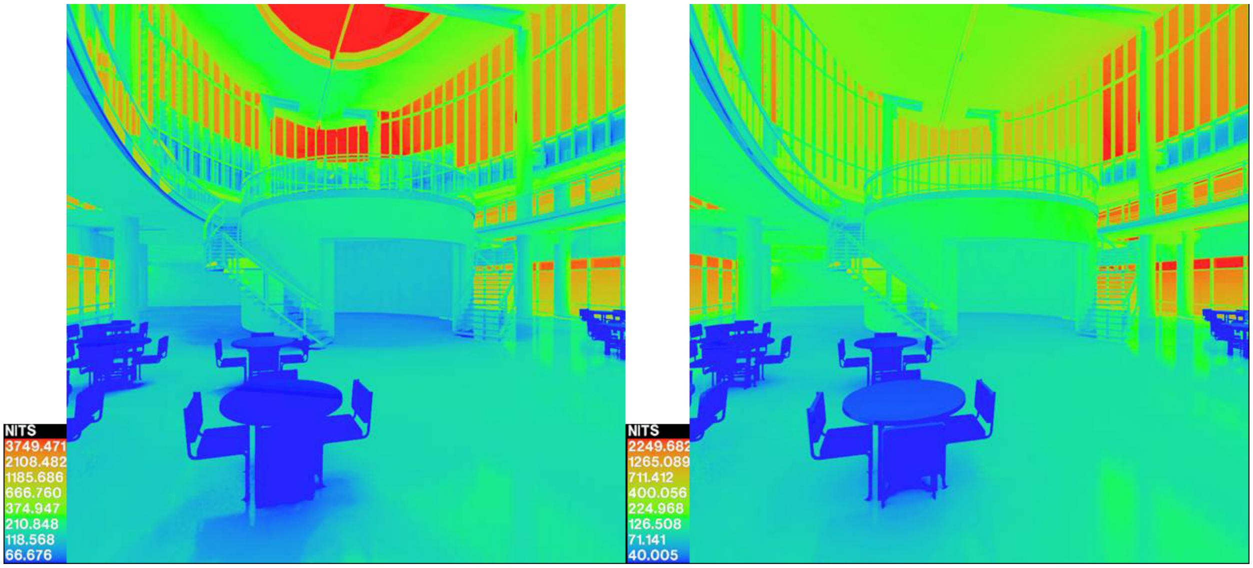

Figure 1a (left) Radiance simulation showing luminance map of executive dining room in Dallas, Texas view to south. Figure 1b (right). Same view with shades deployed

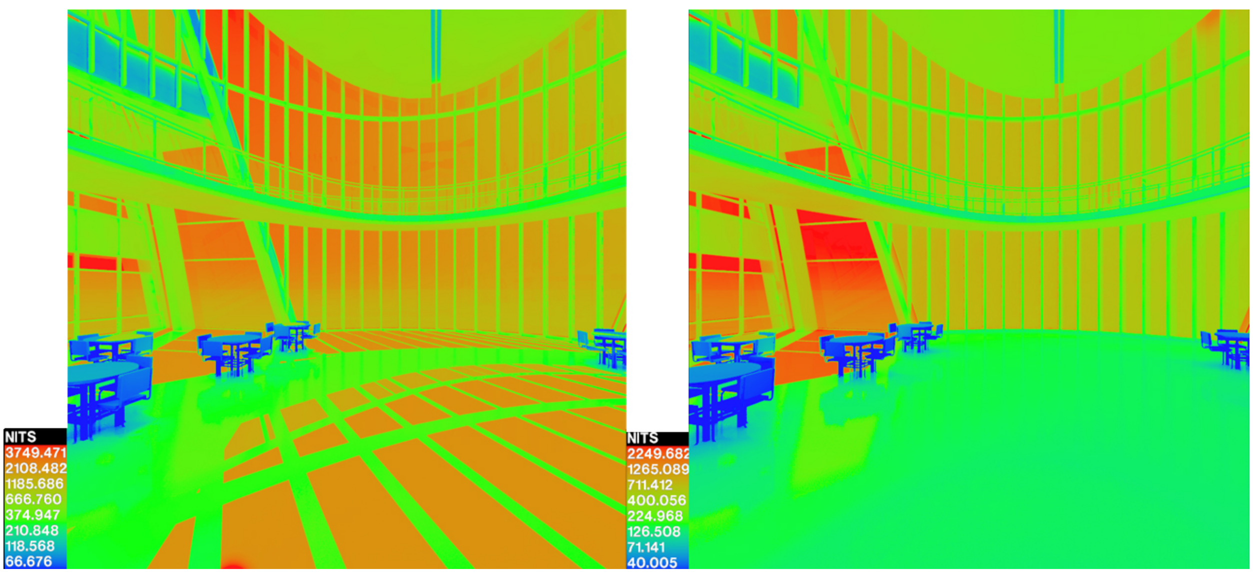

Figure 2a (left) Radiance simulation showing luminance map of executive dining room in Dallas, Texas view to north. Figure 2b (right). Same view with shades deployed.

Luminance maps can also be informative for the task of coordinating space planning with and curtain wall design. Typically the architect, mechanical engineer, curtain wall and daylighting consultants will develop the glazing and shading strategies for a design while the interior designer and workplace consultant will select the finishes and furniture systems. There is often little if any communication between these two groups as to the intentions and performance assumptions of the curtain wall and visual comfort. Often it is simply the orientation of the computer, and therefore the view from a workstation, that can make a difference in discomfort glare for the occupant. In Figure 3a the workstation was modeled as designed, with the occupant looking directly toward a fully glazed curtain wall with high visible transmission glass at an hour when the sun is directly entering the glazing (a). We then looked at the effect of turning the workspace 90 degrees so the occupant is looking parallel to the curtain wall. The images make clear the improvement effected by a simple space planning change, while still identifying potential discomfort glare in the visual field. The luminance ratio in the second set of images is approximately 1:10 in the periphery of the visual field but is still not ideal. the images also reveal the location and character of the problem. In this case, well-designed shading and perhaps less transmissive glass is required to deliver visual comfort when the occupant is facing the window while less aggressive shading and/or darker workstation surfaces can mitigate the discomfort glare in the second images.

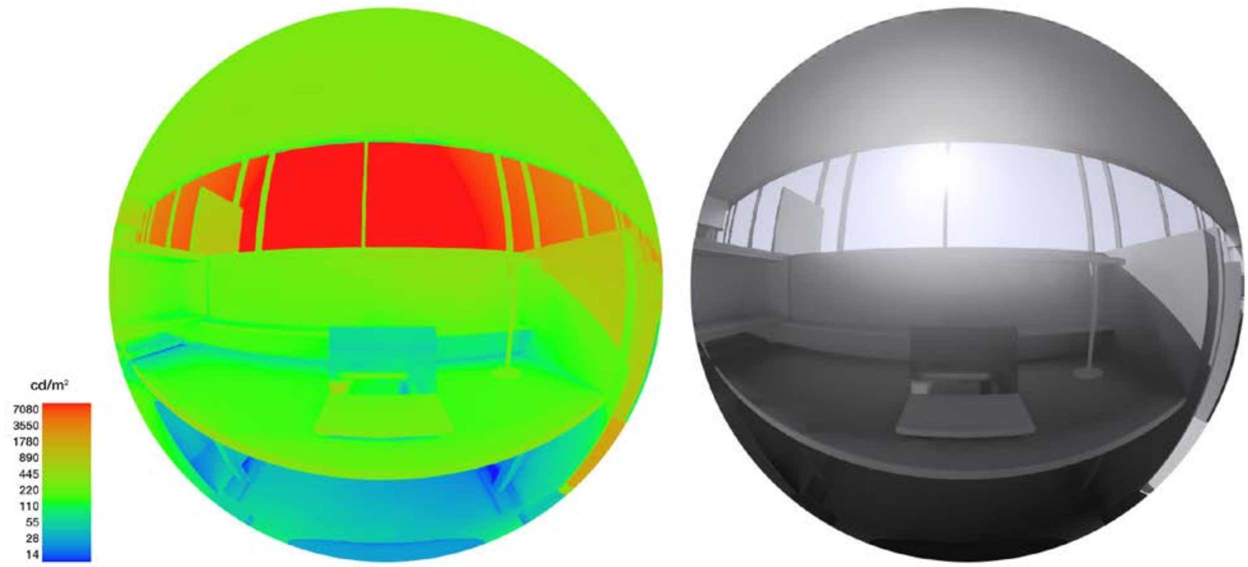

Figure 3a. Simulation of view from workspace with desks facing curtain wall. Luminance map showing nits in false color. DGP=1.00

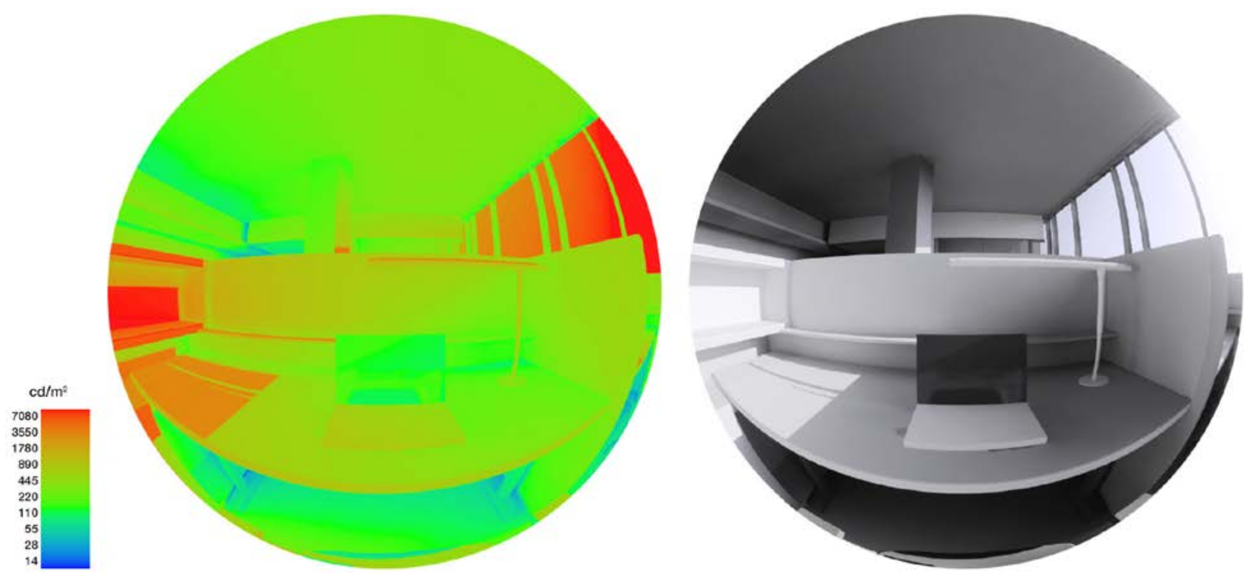

Figure 3b. Simulation of view from workspace with desks turned 90 degress. Luminance map showing nits in false color DGP=0.71

4.2 Why not use a glare index instead?

If the DGP is developed from the luminance maps, why not simply use the single number glare index rather than the full visual map to evaluate and explain glare? In general, a single number that predicts visual discomfort in a space seems very attractive: it sounds definitive, it delivers the weight of research, it is quantitative and brooks little argument. In this respect it can be understood a similar to the Color Rendering Index (CRI) which is widely used in lighting design.

We have started generating the DGP index for luminance maps, but at this point find the single number far less useful than the image itself for our understanding and for communicating with the design team and the owner. In looking at the workstation orientation in Figure 3, we find that the DGP of 1.00 in the first instance looking directly into the disc of the sun and a reduced DGP of 0.71, which indicates a slightly better visual situation. However, it is vastly worse than an "imperceptible" discomfort glare indicated by an average DGP of 0.33 or even an "intolerable" condition indicated by a DGP upper limit of 0.59 in testing. Essentially, the issue is that a DGP index tells whether a problem might exist, and to some extent the intensity of the problem, but cannot tell us much about how to solve the problem. We also recognize that results of DGP validation are varied in the literature and are likely to undergo more investigation in the near future (Jakubiec 2011, Cantin 2011, Mardaljevic 2012).

More importantly, questions in daylighting design are usually about an integrated spatial and luminous experience that needs to be characterized with a grain of performance data unsatisfied by a single number. A designer wants to know not just if there is a problem, but if so, what is causing it and how to fix it. To answer these questions, the glare analysis needs to identify what and how various components of a designed space contribute to the visual field as alleviate that discomfort. the information must be generative of action in a design sense, not just a judgment.

This is where the luminance maps are profoundly informative to the design team. The visual field mapped spatially in luminance values explains the situation in terms that a design team can understand almost intuitively and can use to identify a range of corrective design alternatives. By looking at a luminance map, the design team can quickly identify the contrast ratios that are *probably* too great for visual comfort and which aspects of the design (glazing, wall, monitor, ceiling, etc) are creating these conditions. This can then be checked against varying sky conditions (is there a problem on a clear day but not an overcast day, or vice versa?) and also against alternative designs (for example, different glazing specifications, alternative space plans that change the view directions) and potential remediation (deploying diffusing shades, adding exterior shading louvers).

In the skylight design for a below-grade library reading room, the specification of the glass became crucial for the thermal and the visual performance of the space below (see Figure 4). In discussions with the mechanical engineer and architect, the glass needed to keep a high visual transmission for daylighting the underground room, but have a low solar heat gain coefficient (SHGC) to control heat gain from solar radiation. The first study examined the visual performance of two glass types; Figure 3a shows the luminance map for a glass with 63% Tvis and 0.27 SHGC on the left and 19% Tvis with 0.15 SUGC on the right under clear sky conditions in June. Noting the extreme luminance ratios between the deep patches of direct beam radiation on the left of the space and the darker seminar rooms on the right, the design team was satisfied with the 19% Tvis glass.

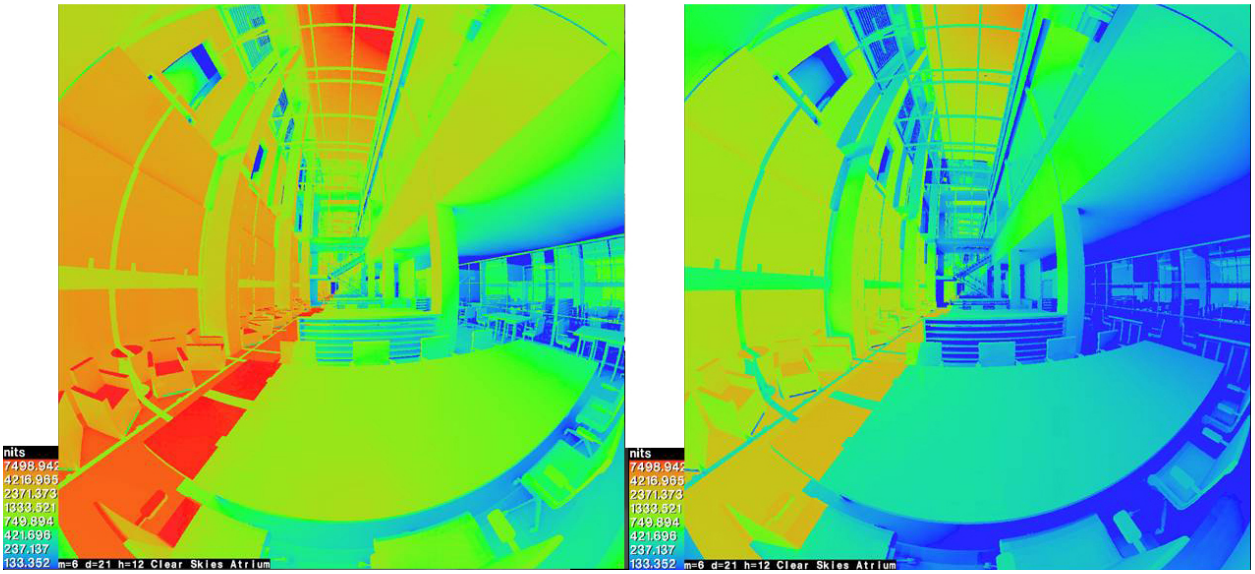

Figure 4a. UC Berkeley Law Library South Addition glazing studies. False color luminance maps illustrate visual conditions with high transmission and low transmission glazing alternatives under clear skies.

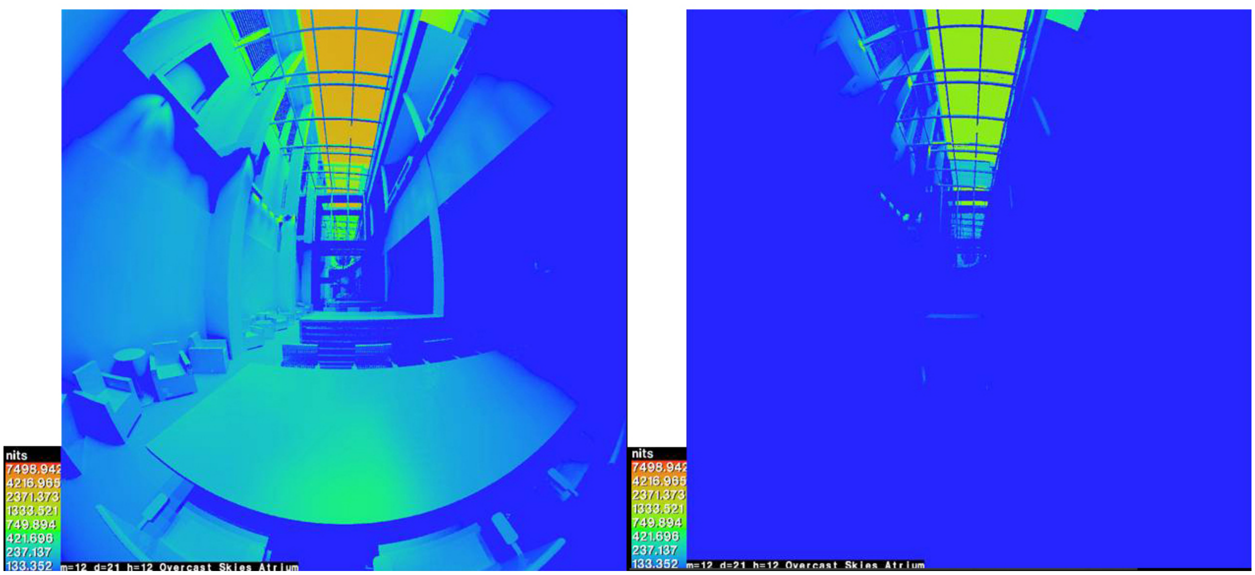

Figure 4b. UC Berkeley Law Library South Addition glazing studies. False color luminance maps illustrate visual conditions with high transmission and low transmission glazing alternatives under overcast skies.

Concerned about performance under overcast skies, which occur about 50% of the time in this location and are much darker than the clear sky condition, we developed a similar comparison for the same glass selections under a December noon overcast sky (Figure 4b). The luminance map helped the design team understand that this reduced Tvis created an undesirable lack of detail and contrast in the visual field under these conditions. A glass with a mid-range of Tvis (43%) and a still very good SHGC (0.19) was selected for a better balance between visual goals and thermal goals in this space.

As Bill Lam wrote (1992), "Traditional lighting research has tried to evaluate the relative comfort and discomfort of various environments by attempting to define the borderline between comfort and discomfort in terms of abstract mathematical indices. The basis of this rather negativistic approach is that if one could define the limits of discomfort, and then surpass them, one would have comfortable spaces. The conceptual poverty of the idea is rather disappointing: in effect, it says that the way to design good space is to avoid the positively objectionable. That seems a rather unambitious objective!"

5. POST OCCUPANCY USE OF HDRI

It is well established that HDR photography can be calibrated for luminance measurements (Inanici 2004 and 2006, Bellia 2009). Recent and current research is adding levels of detail and accuracy to the use and interpretation of the HDR images, but in general do not raise red flags about the accuracy of the luminance calibration for use in design and post-occupancy evaluation (Borisuit 2010, Cai 2011, Lim 2014). From a practice standpoint, this is a remarkable development, in that it closes the loop between prediction and validation that is so useful and necessary with design tools.

As a practice, we have found it important to validate the tools we use and the way in which we use them by comparing the actual buildings with our predictive simulations (Ubbelohde 1998 and 2005). This improves our ability to trust the simulations we produce and to understand ways in which the final building is likely to deviate from the predictive work. For example, when we compared our predictive simulations for an early Apple Store to on site measurements and photographs, the measured light levels were very close to the predicted, but we were startled by the lack of accuracy in the rendering of the glass stair. We realized that more recently developed Bidirectional Transmission Distribution Function (BTDF) descriptions for glazing were essential to more accurate simulations (Kampf 2011, Thanachareonkit 2010, Reinhart 2006)

Figure 5a and b. Apple Store LA - Simulation vs photograph from second floor

As we increasingly use luminance maps in the design process to design for visual comfort and shading, we are equally interested in how these luminance predictions compare to post-occupancy calibrated HDR images. Much as we could for many years predict illumination levels with physical models and then check them after construction with a light meter, we now can predict luminance levels with simulations and check them after construction not only with a spot luminance meter, but with a calibrated luminance map.

A later sequence of studies for the skylighted reading room design examined the performance of the selected glass (Tvis 43% and SHGC = 0.19) under clear sky conditions when shading would be used to reduce the illuminance of the daylighted space. Horizontal diffusing shaes with an openness of 3% were measured with a 15% Tvis. This was then modeled with an illumination rendering and luminance map (Figure 5a). The luminance ratios are within visual comfort (a maximum of 1:6 between the diffuse sun patch on the floor and the direct sun on the floor), as compared to performance of the initial glass selection (1:15) on a clear June noon (Figure 4a).

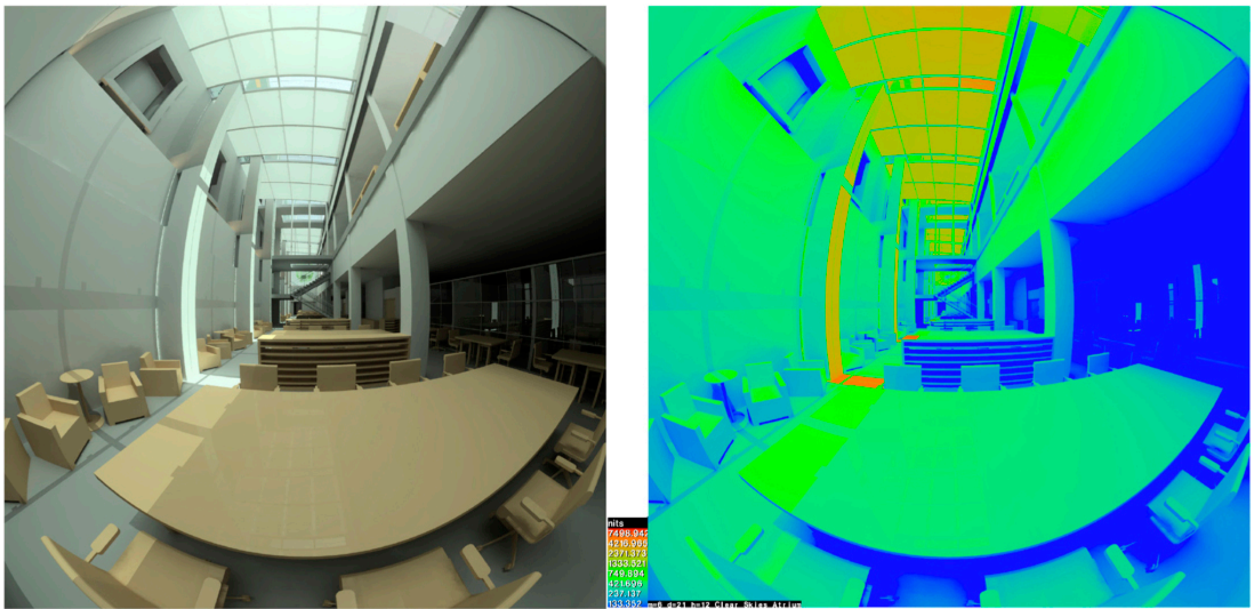

Figure 5a. UC Berkeley Law Library South Addition. Illumination and false color luminance simulations of reading room under June 21st, 12 noon clear sky conditions, glazing Tvis = 43% with shades deployed

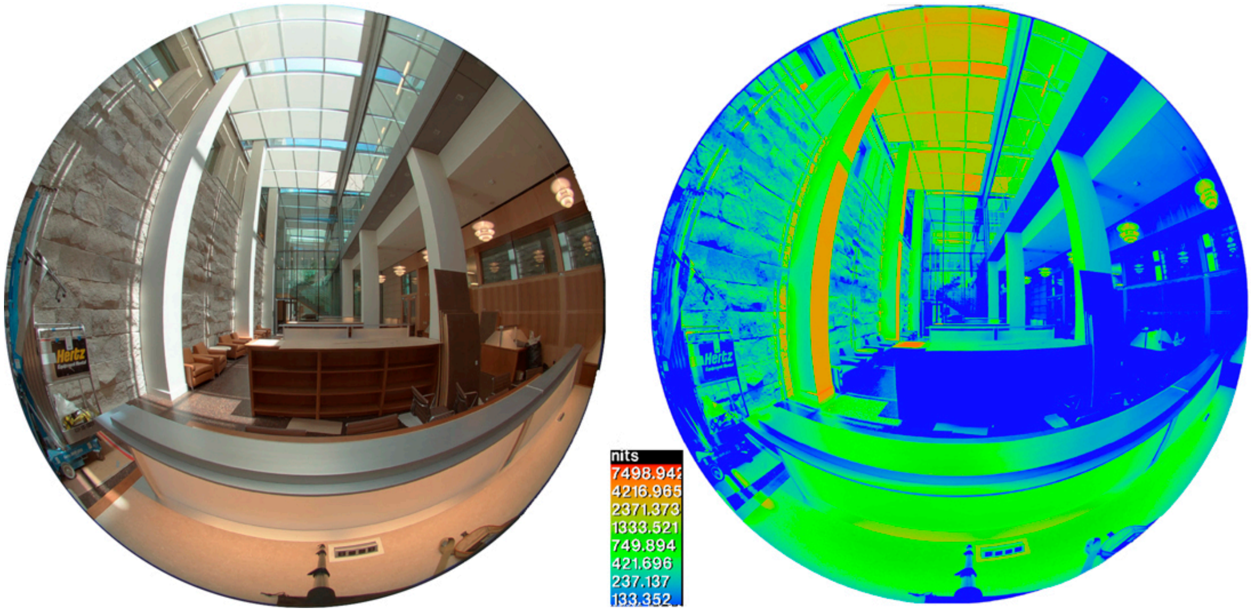

Figure 5b. UC Berkeley Law Library South Addition. HDR photograph and calibrated false color luminance map of reading room under June 21st, 12 noon clear sky conditions, glazing Tvis = 43% with shades deployed

Following construction, we photographed the same space (Figure 5b) under clear skies at noon on June 21st and produced a calibrated HDR luminance map of the real space for comparison. The substantial similarities of the predictive luminance map and the photographed luminance map provide evidence that the predictive luminance maps are giving us satisfactory information about visual performance during the design phase of a project.

Predictive modeling for another part of the same project, the cafe, is shown in Figure 6a. In this case, the design team had questions about the potential glare from a large south-facing window wall with a screen of ceramic "baguettes" on the exterior of the glass and a set of trees intended for the street edge. Our rendering and luminance map describe a visual condition in which the ceramic shades provide a bit of transition, but the trees are crucial in providing lower luminance ratios than delivered by the bright sky beyond (seen as red and yellow, indicating more than 1500 nits or candelas per square meter of luminance.

Figure 6a. UC Berkeley Law Library Cafe. Illumination and false color luminance of cafe under June 21st, noon clear skies.

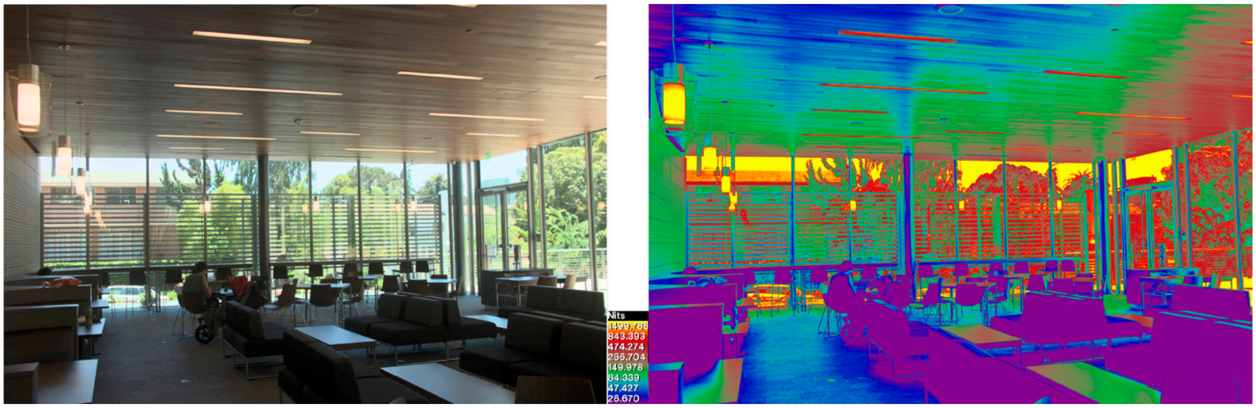

Figure 6b. UC Berkeley Law Library Cafe. HDR photograph and calibrated false color luminance map of cafe under June 21st, noon clear skies.

In the post-occupancy period, the HDR photographs of the cafe under the same sky conditions and time provide an interesting set of lessons. The lighting controls were not yet commissioned, causing all electrical lighting to be on. The change of the ceiling from white plaster to a medium-dark wood finish creates a much more less gradual luminance gradient with the outside sky than in the modeling, and the slow growth of the new trees expands the view of the bright sky beyond that modeled. Darker furniture adds to the increased luminance ratios and the darker surfaces that create a harsher luminance gradient throughout the space from inside to glazing.

6. DESIGN PHASE HDRI AND LUMINANCE MAP COMPARISONS

6.1 Mock-Ups of Building Components

As our work began to involve mock-ups of lighting components such as luminaires and skylights, we expanded our use of HDRI to evaluate the luminance characteristics of the mock-up in order to evaluate visual comfort and relative luminance values of the component while these could still be modified. We found this a successful method for communicating more than the visually apparent performance of the component. Illustrated in Figure 7a and 7b is the mock-up and the final installation of a luminous stair for a building the UC Berkeley campus. In this case, the high level of luminance was part of the design goal for the stair, which climbs from the lobby through six floors of casual working rooms, stitching a large laboratory building together vertically.

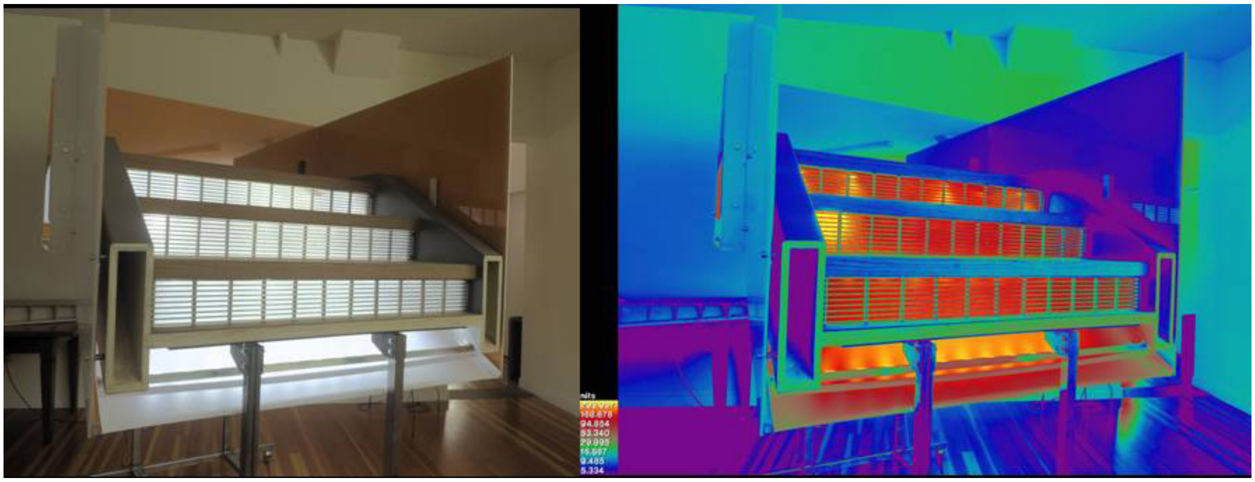

Figure 7a. Luminous Stair for Energy Biosciences Building, UC Berkeley, SmithGroup JJR Architects. MockUp to test LED installation with photograph and false color HDRI. View of treads.

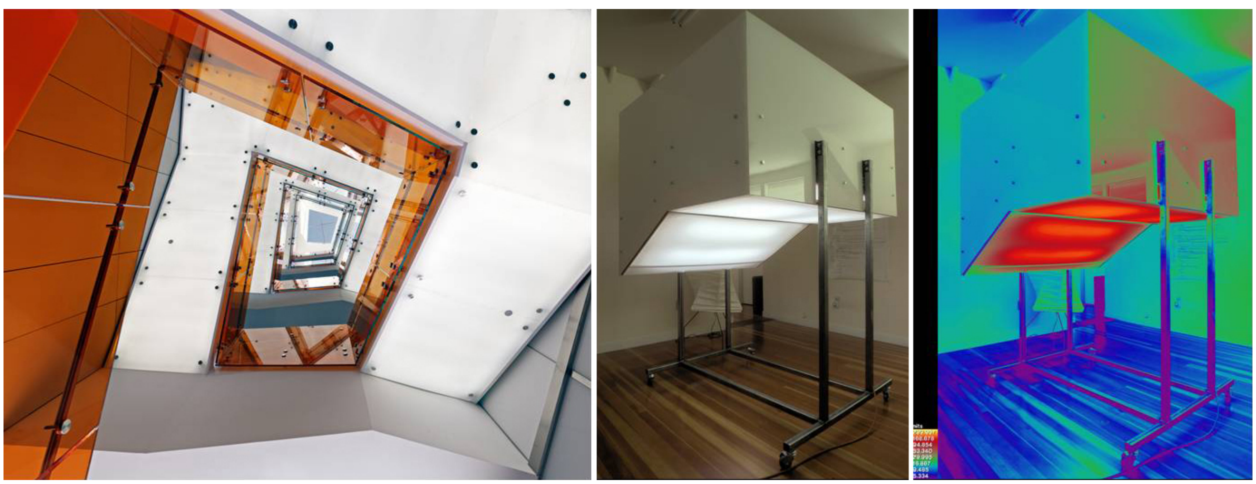

Figure 7b. Luminous Stair for Energy Biosciences Building, UC Berkeley, SmithGroup JJR Architects. Photograph of actual staircase and mockup to test LED installation with photograph and false color HDRI. View of underneath diffuser.

Luminance and visual comfort has also been an issue in luminaire design. In the design of a new LED fixture for classrooms, the design goal of the fixture was to provide lighting onto the ceiling deck into which the fixture is mounted in order to decrease the luminance ratios as someone looks directly at the fixture (Figure 8).

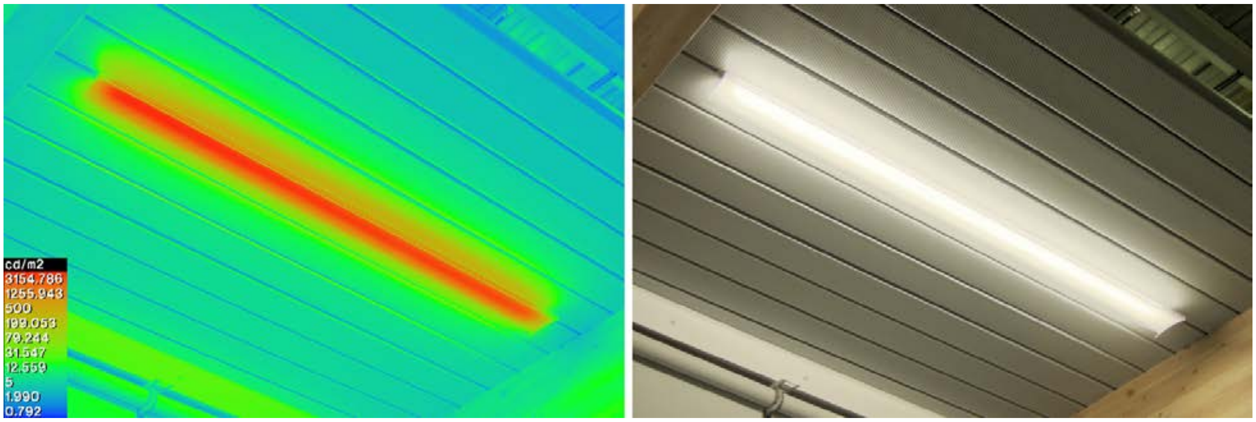

Figure 8. Lantana LED Fixture, Project Frog. Photograph and false color HDRI of mockup during design process.

6.2 Comparison Spaces for Luminance Understanding

Our increased use of HDRI for mock-ups during the design process was in parallel with an increased use of the luminance maps generated in RADIANCE to discuss visual comfort in the design phase. We realized that many of the architects and owners we work did not have a framework for thinking about visual comfort or the luminance of the visual field and could not read the luminance maps as useful information. We began to take calibrated HDR photographs of spaces they already know in order provide a reference image for reading the false color luminance maps. We found that this was a powerful way to get everyone onto the same page talking about visual experience and lighting design intentions and performance; a set of tools to address the illusive "character" of lighting design that Kelly and Lam were advocating as design goal. It was then a small step to select existing spaces to photograph with HDRI that were comparable to luminous conditions predicted in the building under design.

We developed the illuminance rendering and luminance map for a complex new atrium design (Figure 9a) in order for the design team to understand the luminance conditions of a diffusing cat-walk and the potential impact on visual comfort and wayfinding. As we discussed the simulation results, it was clear we needed a way for everyone involved to understand the luminance map experientially and to read the false-color coding. We agreed that a similar analysis of an atrium space known by everyone on the team might work as a comparative basis for discussion and produced an HDR photograph and calibrated luminance map. We discovered that being able to walk into a space and connect that visual experience to a luminance map allowed people

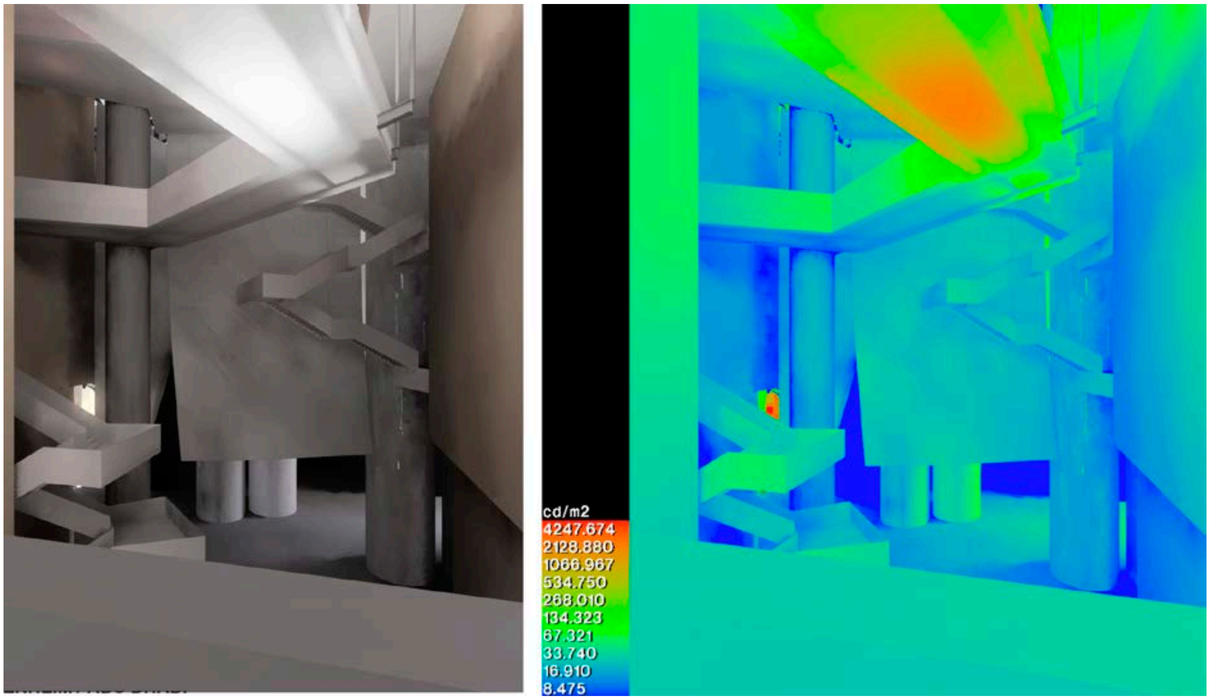

Figure 9a. Atrium design project with rendered illuminance (left) and false color luminance (right) during early design phase.

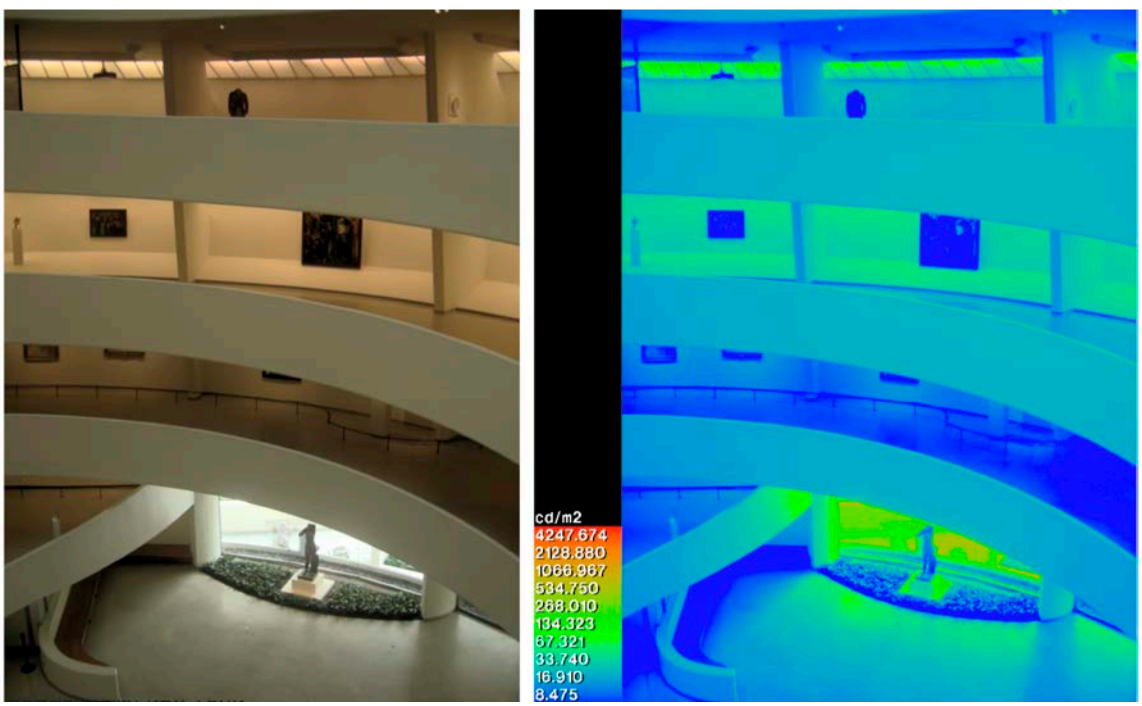

Figure 9b. HDR photograph and calibrated false color luminance map of known atrium space for comparison.

6.3 Discussion

The use of luminance maps to address issues of visual comfort and the impact of discomfort glare is still at an early phase of application in daylighting design. It is a rare project in which design phase luminance studies, comparative HDR analysis and post-occupancy validation of the predictions are all possible. In this project, daylighting quality and character were the essential issues in the design of the skylighted atrium space. Illumination levels were not an issue, either from the perspective of standards (circulation spaces should be illuminated to 100 lux, which was essentially a moot point for daylighting design, or as a method for characterizing performance. Rather, the client and architect were engaged in a search for a quality of space to operate socially and psychologically for the occupants, much like both Kelly and Lam would describe as the intent of lighting design.

Our predictive simulations during the design phase identified large areas of direct sun comig into the atrium (figure 10a) with high luminance ratios (on the order of 60:1) revealed in the luminance map. During discussions about the performance of the skylight design, the client suggested that the new atrium should "feel" like the atrium in their other building, which everyone loves (Figure 10b).

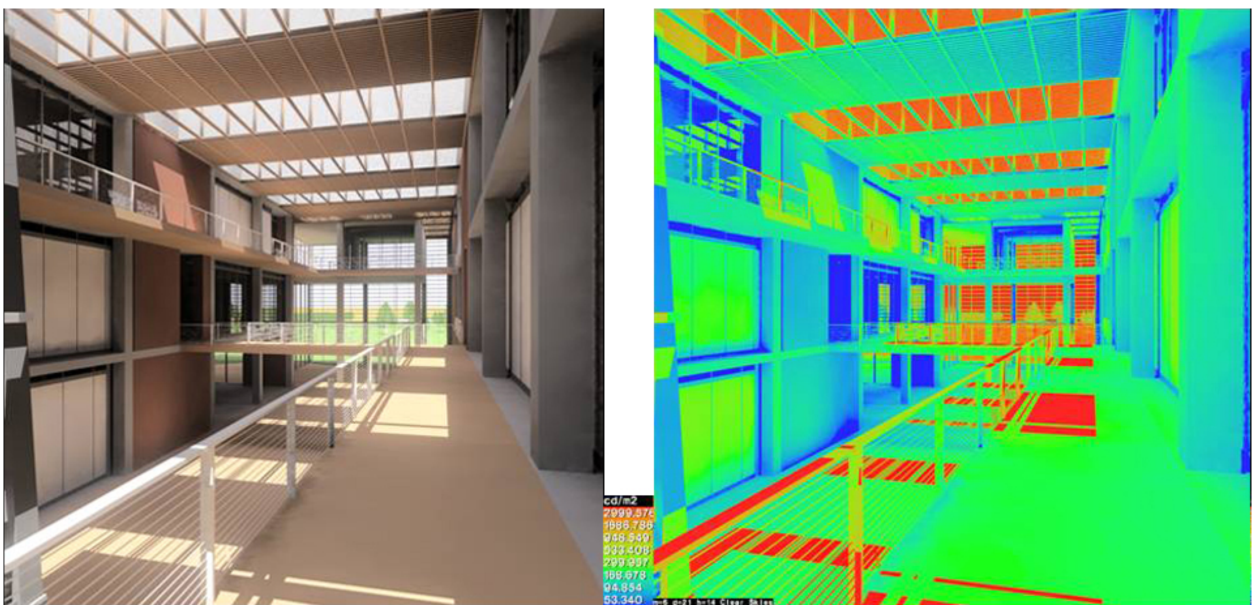

Figure 10a. Simulation of atrium in rendered illumination and false color luminance map, view to east under clear sky June 21 noon.

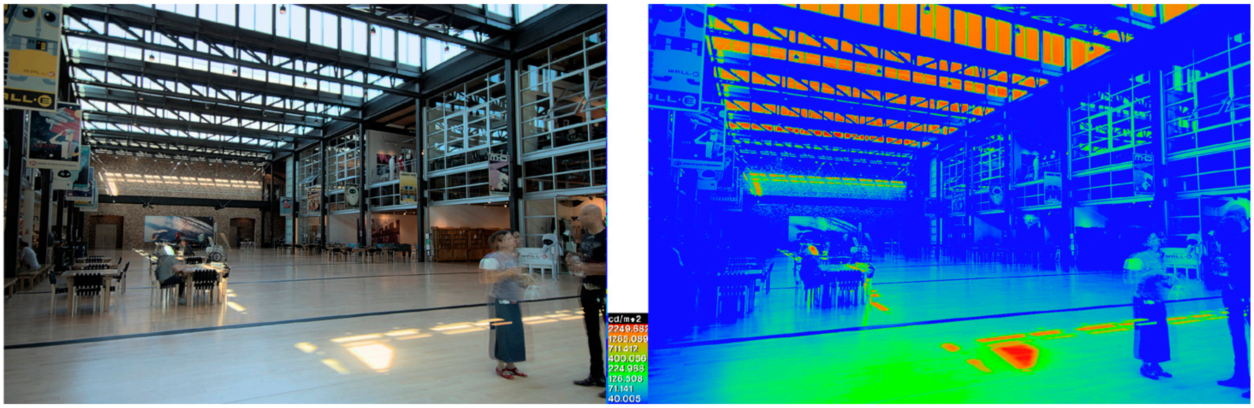

Figure 10b. HDR photograph and calibrated false color of known atrium space looking north for comparison.

The aspect ratio and the depth of the original atrium are different than the new design and the orientation of the new the atrium is turned 90 degrees. This known atrium glazing is a saw-tooth scheme facing north, rather than raised horizontal skylights. However, it was not the design details but the character of the space that the company was interesting in using as a model. HDR photographs and calibrated luminance map indicated that the luminance ratios, even when viewing the sky directly through the monitors, are limited and direct sun is admitted in small areas, adding more "sparkle" than "glare" to the experience of the space. Exterior shading louvers were added to the new atrium skylights and the dimensions and spacing of the louvers were tuned until the luminous experience of the new atrium was much closer to that of the original atrium (Figure 10c), without giving up some degree of luminous differences. The hearth at the end of the atrium was lighted from above with a variation on the louver spacing to emphasize the hearth area as a presence in the space.

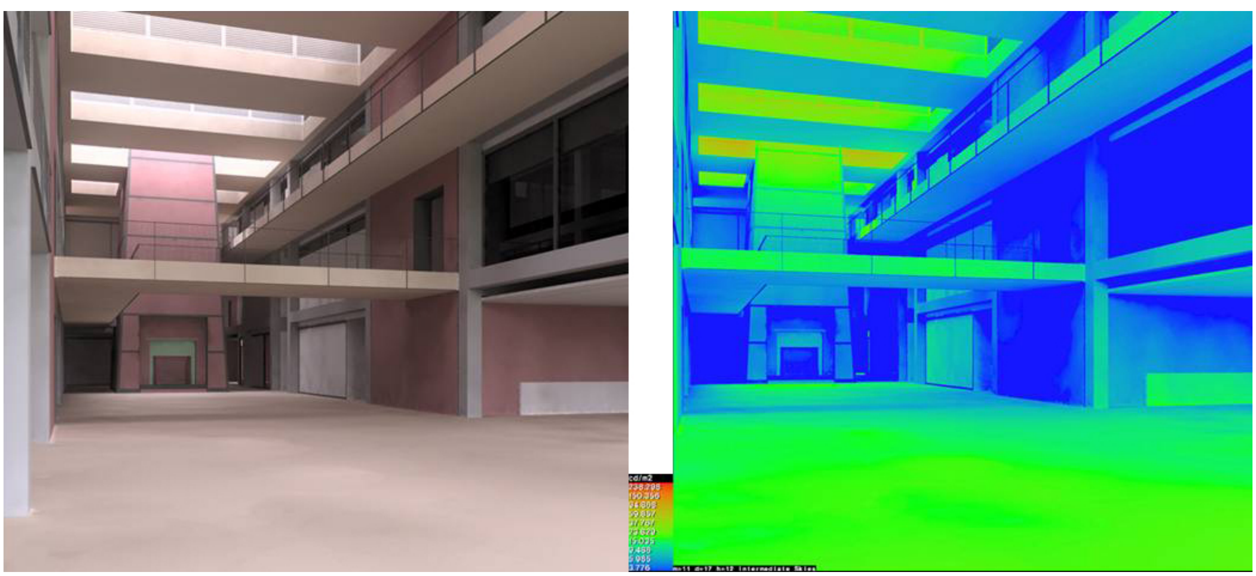

Figure 10c. Simulation of atrium after re-design with rendered illumination and false color luminance map, view to west.

Following construction and occupancy, HDR photographs were taken under the same sky conditions and at the same time as the simulations and a luminance map was produced (Figure 10d) for comparison to the predictive simulation. As with the law library reading room, the post-occupancy luminance mapping indicates that the predictive modeling is accurate. As stated earlier, this closes a loop between design and reality that is necessary in practice and generates confidence in the use of the luminance map as a predictive tool.

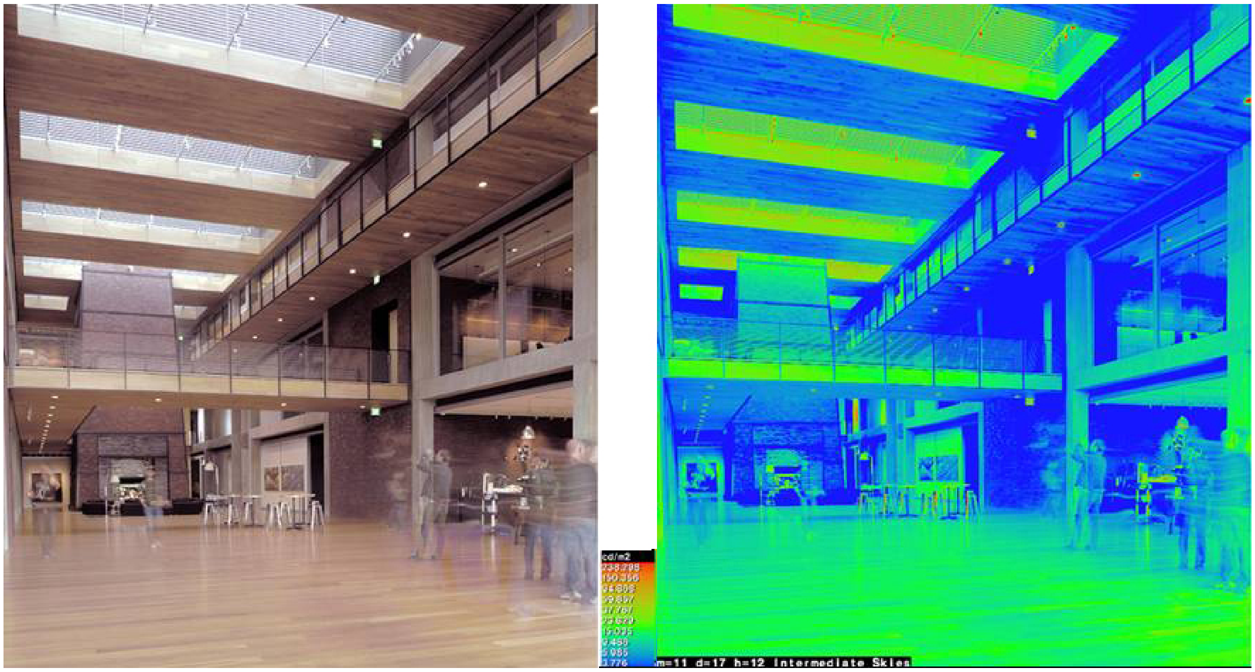

Figure 10d. HDR photograph and calibrated false color luminance map of atrium space as built looking west.

CONCLUSION

It is important that daylighted buildings delivery visual comfort as well as energy savings, or there will be no place for daylighting in building design. In practice we find that visual comfort is an increasingly critical part of the success of a daylighted building and therefore must be an integral part of the daylight design process. As research continues to better define glare and develop metrics for the phenomenon, we are nevertheless impressed with the facility and usefulness of the simulated luminance map in design and the corresponding HDR calibrated photographs of completed building. As our practice has continued to experiment with the application of both, we continue to discover correspondence, validation and new uses of both luminance simulation and HDRI, including mock-up evaluations, comparisons to known conditions, and building retrofit before/after comparisons. This new capability is a paradigm shift and may, more than anything else, bring visual comfort into use as a metric for daylighting performance.

The key to this, as we have come to understand it, is that daylight design is not simply a matter of avoiding glare. Hopkinson, who always seemed to understand daylighting before we were able to formulate the questions, noted (1971): "It can be seen that the control of glare is not only a matter of numerical manipulation of a complex empirical formula, but the use of architectural design sense which bears in mind the critical relationships between the main parameters. Research on glare has revealed the relevant psychophysical laws in their simplicity and complexity, and made the work of the lighting designer more numerate and less dependant on intuition, but it does not, and cannot, produce an instant single solution to a problem where amenity and preference are significant factors in a complex situation."

REFERENCES

Abbaszadeh,S. et al. Occupant satisfaction with indoor environmental quality in green buildings. Proceedings of Healthy Buildings 2006, Lisbon, Vol. III, 365-370

Athalye. R.A. et al, Analysis of daylighting requirements within ASHRAE standard 90.1. Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830. PNNL-22698. August 2013

Baker, N. et al, ed. Daylighting in architecture, a European reference book. London: Routledge, 1993.

Bellia, L. et al. HDR luminance mapping analysis system for visual comfort evaluation. I2MTC 2009 - International Instrumentation and Measurement Technology Conference, Singapore, 5-7 May 2009.

Borisuit, A. et al. Visual discomfort and glare rating assessment of integrated daylighting and electric lighting systems using HDR imaging techniques, Architectural Science Review, (2010) 53:4, 359-373

Cai, H., Chung, T.M. Improving the quality of high dynamic range images. Lighting Research and Technology 2011 43: 87

Cantin, F., Dubouis, M-C. Daylighting metrics based on illuminance, distribution, glare and directivity. Lighting Research and Technology. 2011; 43 291–307

Clear, R, "Discomfort Glare: What do we Actually Know?" Lighting Research and Technology, 19 April 2012

Cuttle, C. A new direction for general lighting practice. Lighting Research and Technology 2013 45-22
Daylight in buildings: A sourcebook on daylighting systems and components. Report of IEA SHC Task 21 / ECBCS Annex 29, July 2000.

DiLaura, et al. The lighting handbook: reference and application Illuminating Engineering; 10 edition (2011)

Frontczak, M. et al. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. Indoor Air Journal, Volume 22, Issue 2, 119-131

Green, D. Scott, M. Burkett, R. Managing occupant comfort with highly transparent all-glass facades. AEI 2011, 1291-38

High-performance envelopes: meeting new energy codes with manufactured systems ED+C June 1, 2013. http://www.edcmag.com/articles/print/95063

Hirning, M.B., Isoardi, G.L., Cowling, I. Discomfort glare in open plan green buildings. Preprint submitted to Energy and Buildings September 24, 2013

Hirning, M.B. et al. Post occupancy evaluations relating to discomfort glare: a study of green buildings in Brisbane. Building and Environment 59 (2013) 349-57

Hopkinson, R.G., Petherbridge, P., Longmore, J. Daylighting. London: Heinemann, 1966.

Hopkinson, R.G. Glare from dayight in buildings. Applied Ergonomics 1972, 3.4, 206-215

Inanici M.N., Galvin J. Evaluation of high dynamic range photography as a luminance mapping technique. Lawrence Berkeley National Laboratory, Lighting Research Group, LBNL-Report # 57545, Berkeley, CA, December 2004.

Inanici, M.N. Evaluation of high dynamic range photography as a luminance data acquisition system. Lighting Research and Technology 2006 38: 123

Jakubiec, J.A., Reinhart, C.The "adaptive zone" - a concept for assessing glare throughout daylit spaces. Proceedings of Building Simulation 2011. 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November. 2178-2185

Kämpf, J.J., Scartezzini, J-L. Ray-tracing simulation of complex fenestration systems based on digitally processed BTDF data. Proceedings CISBAT 2011, Lausanne, Switzerland. 349-354

Lam, W.M.C. Perception and lighting as formgivers for architecture. New York: Van Nostrand Reinhold. 1992 reprint of 1977 edition.

Lartigue, B., Lasternas, B., Loftness, V. Multi-objective optimization of building envelope for energy consumption and daylight. Indoor and Built Environment published online 26 April 2013

LEED 2009 for new contruction and major renovations. Washington D.C. US Green Building Council, September 2008

Lim, H.S. et al. Comparative verification of high dynamic range image tools for luminous analysis of visual environment. Indoor and Built Environment published online 28 January 2014

Mardaljevic, J. Daylighting metrics: is there a relationship between useful daylight illuminance and gaylight glare probability? First Building Simulation and Optimization Conference, Loughborough, UK, 10-11 September 2012, 189-196

Mendler, S. Thinking inside the box: the case for post-occupancy evaluation. February 2007. http://www.bdcnetwork.com/print/18580

Neumann, D. The structure of light: Richard Kelly and the illumination of modern architecture. New Haven: Yale University Press.

Osterhaus, W.E.K. Office lighting: a review of 80 years of standards and recommendations. Proceedings of the 1993 IEEE Industry Applications Society Annual Meeting, 1993. LBL-35036

Osterhaus, W.E.K. Discomfort glare assessment and prevention for daylight applications in office environments. Solar Energy 79 (2005) 140–158

Reinhart, C., Andersen, M. Development and validation of a Radiance model for a translucent panel. Energy and Buildings 38 (2006) 890–904

Selkowitz,S. Aschehoug, Ø., Lee, E. Advanced interactive facades - critical elements for future green buildings? Presented at GreenBuild, the annual USGBC International Conference and Expo, November 2003. LBNL-53876.

Straube, J. Can highly glazed buildings be green? www.buildingscience.com September 2008

Sutter, Y. Cumortier, D. Fontoynont, M. The use of shading systems in VDU task offices: A pilot study. Energy and Buildings 38 (2006) 780–789

Thompson, K. Let there be light - daylight, glare and thermal performance of facades. 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November, 1615-1622

Tuaycharoen, N. Tregenza, P.R. View and discomfort glare from windows. Lighting Research and Technology 39,2 (2007) pp. 185–200

Wienold, J., Reinhart, C. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings 38 (2006) 743–757

Ubbelohde, M.S., Humann, C. “Comparative evaluation of four daylighting software programs,” Proceedings of the 1998 Summer Study on Energy Efficiency in Buildings, ACEEE 1998, 3.325-340.

Ubbelohde, M.S., Carrier, K. "The role of daylighting in LEED certification: a comparative evaluation of documentation methods”, Proceedings of the 2005 Solar World Conference, Orlando, FL, August 2005.