Chapter 2
Research Context

Keywords Daylight performance metrics · Task-based illumination · Visual comfort for task performance · Contrast · Luminous diversity

Of the many established metrics that quantify daylight performance, a disproportionately small group of these address factors of perceptual appeal. An obvious reason for this is that most metrics were developed to improve energy efficiency by replacing electric lighting, or to avoid human *discomfort* due to sources of glare within the visual field. Although architects use sunlight to choreograph the perceptual quality of space, there is limited research available to help designers understand the complex variability of daylight across an occupant's visual field. While there is some agreement on the minimum amount of illumination that is required for the human eye to perform visual tasks within a given space, there is little consensus on how much contrast or brightness makes a space visually appealing. Those studies that do address the luminous field-of-view are limited in their analysis of contrast composition and do not address the temporal variation that occurs due to the daily and seasonal variations in solar orientation.

Through a comparison of existing interior spaces, this chapter will introduce a range of daylight design strategies found in global contemporary architecture. Each strategy varies in its approach to sunlight penetration and daylight distribution, yet reinforces a specific spatial experience that is central to the architectural goals of the project. It is through these architectural spaces that we will introduce the role of contrast and temporal diversity as an indicator of visual design performance and discuss the need for new perception-driven metrics to complement existing *task-driven* and *comfort-based* performance metrics. Within the field of architecture, it is essential that we couple daylight performance criteria with design intent and provide metrics that address visual, perceptual, and task-related criteria.

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2.1 Contrast as an Indicator of Qualitative Performance

In architecture, spatial definition depends on the balance between light and dark, the eye's ability to perceive those differences, and the brain's ability to use that information to understand the depth and complexity of our surroundings. To introduce the importance of contrast in architecture, we will look at four contemporary examples and examine the differences inherent in their expression of contrast and spatial differentiation.

The first example is Norman Foster's renovation of the Kogod Courtyard in Washington, DC (Fig. 2.1). The articulated glass roof structure of the courtyard allows for a dramatic penetration of direct sunlight, imposing strong patterns of contrast onto the walls and floor of the interior space. Designed for temporary occupation and public gathering, the space's programmatic use does not require a tightly controlled lighting strategy. On the contrary, it takes advantage of the dynamic nature of sunlight through transparency to create a diverse and visually engaging environment for its occupants.

The second example, Herzog and De Meuron's Dominus Winery located in Yountville, California (Fig. 2.2), differs in its attitude toward the surrounding environment, allowing light to filter in through an exterior gabion wall. The architects sought to create a unified relationship to the landscape, using local stones to provide a naturally cool thermal environment with visually engaging effects. The interior spaces maintain a variable relationship to incoming light, but the overall lighting levels are dim in comparison with the Smithsonian Courtyard. Occasional spots of direct sunlight on the floors and walls of the circulation corridor create an abruptly contrasted environment. This daylight strategy filters direct sunlight from the south-facing façade while drawing attention to the materiality of its exterior wall, highlighting the seemingly organic non-uniformity of its composition (Ursprung 2002). One could argue that this strategy produces a highly contrasted interior like that of the Smithsonian Courtyard, but with more controlled variations over the course of the day and a darker base composition, overall.

Fig. 2.1 Kogod Courtyard dctim1, 'Kogod Courtyard—northeast corner and floor—Smithsonian American Art Museum' January 04, 2013, via flickr, creative commons license

Fig. 2.2 Dominus winery © Dominus Estate, Yountville, CA, USA

Fig. 2.3 Church of St. Ignatius Joe Mabel, 'Chapel of St. Ignatius' November 30, 2007, via wikimedia, creative commons license

For the third example, we will consider Steven Holl's Church of St. Ignatius in Seattle, Washington (Fig. 2.3). This space is vastly different in character from the two previous examples, composing sunlight into a series of carved, indirect figures which accentuate its volumetric qualities (Holl 1999). The light within this church could be described as more selectively diffuse, with compositional lines and volumes being defined through distinct spatial geometries. This example represents less extreme contrast than that of the Smithsonian Courtyard or the Dominus Winery, but still maintains a dynamic relationship to the exterior as shifting light levels cause figural volumes of light to change over time.

The final example, Renzo Piano's High Museum of Art in Atlanta, Georgia (Fig. 2.4), employs an indirect daylighting strategy similar to that of the Church of St. Ignatius. However, it differs in the stability of its internal illumination as the light tubes that compose the roof collect and distribute diffuse light from the north. The programmatic use of this space as a gallery necessitates an even distribution of internal lighting levels while preventing any direct sunlight that may cause damage to or distract from the artwork. As a result, the presence of strong contrast and temporal instability is minimized across the space.

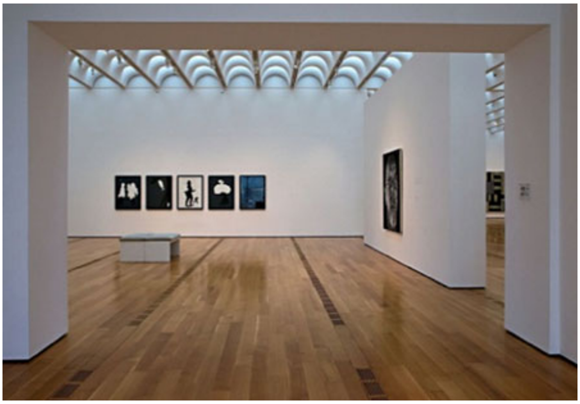

Fig. 2.4 High Museum Brookenovak, 'Wandering around the High' September 8, 2007, via wikimedia, creative commons license

These four contemporary examples represent varied site conditions, both urban and rural; varied latitudes, from Georgia to Seattle; and varied programmatic uses from art gallery to public atrium. They represent dramatically different compositions of contrast and temporal light stability, and yet they all produce visually stimulating environments that enhance the architectural expression of interior space. In considering this diverse range of architectural examples, our goal is to define the perceptual characteristics that distinguish them and determine what this can tell us about the role of contrast and luminous diversity in the visual performance of interior space. While the notion of perceptual 'quality' is, admittedly, a difficult element to quantify due to its subjective nature, we believe that there are metrics that could measure the compositional impacts of contrast and luminance diversity and help inform architects about their varied effects over time. Although we have no intention of prescribing universal threshold recommendations for contrast or luminance diversity, we feel that establishing a method for quantifying these compositional effects will provide architects a tool for comparing design options and contextualizing those options within a relative scale. Through measuring and comparing the impacts of spatial contrast and luminance diversity over time, architects will be able to communicate their objectives more comprehensively and choreograph the dynamic visual effects of a space to meet their intended design goals. In turn, this relative scale will serve as a foundation for new dynamic design metrics that measure spatial contrast and luminance diversity in daylight architectural space.

2.2 Spatial Considerations for Daylight Performance

Using these examples as context, we will now transition into a critical analysis of existing daylighting performance metrics to build a case for more visually dynamic methods as they relate to spatial contrast and daylight variability. Existing daylight performance metrics can be divided into three main categories: illumination for task-driven performance, visual comfort for task-driven performance, and occupant preference toward the field-of-view. The methods explored in this research do not seek to discount existing metrics, but rather to contribute to a more holistic definition of performance. To achieve high-performance architecture, we must consider existing task-driven and visual comfort metrics along with new methods for evaluating temporal visual performance, in order to reaffirm the importance of perceptual factors in daylighting design.

2.2.1 Illumination for Task Performance

Before we can discuss those metrics that define daylighting performance within a building, it is important that we define the units of measurement used to quantify light. Illuminance, which describes the total luminous flux that falls on a surface, per unit area (CIE 1926), is the most widely applied measurement of light and is the foundation upon which most other task-driven metrics such as daylight factor and daylight autonomy are based. Codes and standards most commonly reference illuminance measurements across a work plane to determine the amount of light recommended for various tasks (IESNA 2000). Most task-based illuminance metrics were developed to analyze minimum threshold levels in task-oriented spaces such as offices, libraries, and schools (Lam 1977), and while these thresholds can be seen as somewhat subjective, they were established to ensure that adequate illumination could be measured and achieved across a given task surface for a given activity (IESNA 2000).

As far as practice and standards are concerned, daylight factor (DF), which measures the ratio between indoor and outdoor illuminance under overcast sky conditions (Moon and Spencer 1942), may be the most ubiquitous task-based illuminance metric in use (Fig. 2.5). This metric was originally created to estimate daylight access from a 'worst-case' perspective (Reinhart et al. 2006) while avoiding

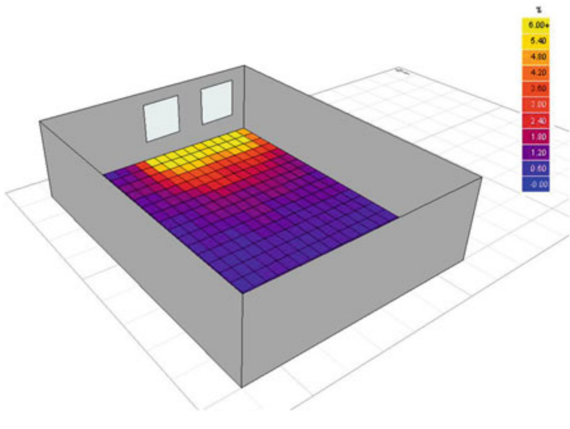

Fig. 2.5 Daylight factor simulation in ECOTECT, http://usa.autodesk.com/ecotect-analysis/

the difficulties associated with fluctuating sky conditions and the dynamic nature of sunlight (Waldram 1950). From an architectural standpoint, however, DF limits our understanding of daylight as a dynamic source of illumination, assuming a ‘more-is-better’ attitude, regardless of sky type (direct sun versus diffuse sky), climate, or programmatic use of the space under consideration (Reinhart et al. 2006).

If we were solely concerned with bringing light into a building, then we could maximize our lighting scheme using DF, but many of the problems we face in architectural design deal with controlling, animating, and understanding the impacts of direct sunlight under varied conditions (Steane and Steemers 2004). In the case of the High Museum by Renzo Piano, the use of DF would provide little value to the optimization of its daylighting strategy, which seeks to control the penetration of direct sunlight. Likewise, the DF is hardly an effective guide for the design of spaces like the Dominus Winery, by Herzog and deMeuron, where high-contrast, low-light conditions are preferred.

Over the past few decades, there have been significant improvements in our understanding of daylight as a dynamic source of interior illumination. We have transitioned from static metrics such as DF to annual climate-based metrics such as daylight autonomy (DA) (Reinhart et al. 2006) and useful daylight illuminance (UDI) (Nabil and Mardaljevic 2006), and goal-based metrics such as acceptable illuminance extent (AIE) (Kleindienst and Andersen 2012) to account for a more statistically accurate method of quantifying internal illuminance levels (Mardaljevic 2000).

Daylight autonomy (DA) was first defined as the percentage of a year when the minimum illuminance threshold was met by daylight alone and did not require supplemental electric lighting. In 2001, it was redefined as the percentage of *occupied time* throughout the year when the minimum illuminance requirements at a sensor are met by daylight alone (Reinhart and Walkenhorst 2001). As a metric, DA can evaluate annual illuminance thresholds, taking into account building orientation and climate-driven sky types. It is useful in determining whether a surface within a space achieves a minimum threshold of illuminance and what part of the year that threshold is maintained (Fig. 2.6).

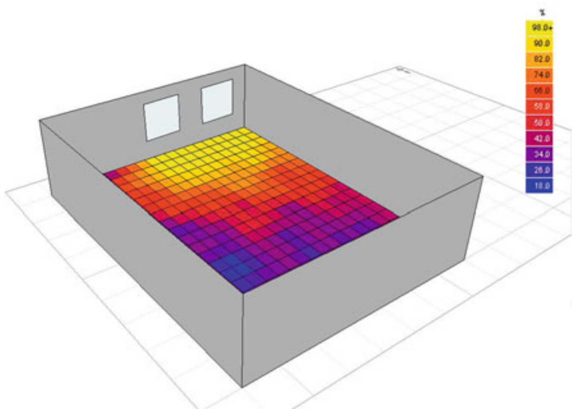

Fig. 2.6 Daylight autonomy ECOTECT, http://usa.autodesk.com/ecotect-analysis/

Continuous daylight autonomy (DAcon) is a similar method of evaluating annual performance through illuminance thresholds across a sensor plane. It awards partial credit for illuminance levels that fall below the minimum threshold on a weighted scale, supporting the notion that some daylight is still better than no daylight (Rogers 2006). This approach allows for a smoother gradient of threshold compliance, accommodating research which concluded that many people work comfortably at illuminance levels below standard minimum thresholds of 500 or even 300 lux (Reinhart and Voss 2003).

2.2.2 Visual Comfort for Task Performance

Unlike task-based illumination metrics that rely on illuminance, successful task-based visual comfort metrics (typically pertaining to glare) rely on luminance, defined as the amount of light emitted by a surface in a given direction (CIE 1926). Of the four photometric quantities (flux, intensity, illuminance, and luminance), luminance is closest to how the eye perceives light and, as such, appears to be the only quantity capable of expressing visual discomfort.

As luminance, brightness, and contrast are subjectively evaluated, glare discomfort is fragmented across no less than seven established metrics (Wienold and Christoffersen 2006; IESNA 2000; Osterhaus 2005). Daylight glare probability (DGP) (Wienold and Christoffersen 2006), considered the most reliable index for side-lit office spaces, is the only index that relies on daylighting conditions. While these indices do not always agree, partly due to the fact that some were developed for electric lighting sources and others for daylight, most are derived from the same four quantities: luminance, size of the glare source, position of the glare source, and the surrounding field of luminance that the eye must adapt to (Wienold 2009).

Daylight glare probability (DGP) is the percentage of people that are disturbed by daylight-based sources of glare in a side-lit office environment (Wienold and Christoffersen 2006). The resulting value, a percentage between 0 and 100, has only been validated for 20 % DGP or higher. Like other glare indices, DGP too was developed for task-oriented settings (Kleindienst and Andersen 2012). Comfort-based metrics such as DGP must be used carefully, as many architectural spaces do not require low-glare tolerance in their programmatic use and some even celebrate high contrast as an intentional visual effect. Figure 2.7 shows an example DGP analysis produced using the DIVA toolbar (http://www.diva-for-rhino.com, 2009), an analysis plug-in developed for Rhinoceros 4.0 (http://www.rhino3d.com, 2007) by the Harvard Graduate School of Design.

An annual DGP analysis (one rendering for every hour of available sunlight) using common RADIANCE rendering routines and *evalglare* requires substantial computing time. A simplified method, known as DGPs, was developed to minimize computational intensity while providing a reasonable assessment of side-lit office spaces where direct sun transmission does not impact the observer (Wienold 2009). To further explore the *dynamic* assessment of glare within a standard work

Fig. 2.7 Daylight glare probability, DIVA for rhinoceros, http://www.diva-for-rhino.com/

environment, the concept of an 'adaptive zone,' which accounts for occupant freedom to change position and view direction, was tested across five glare indices (Jakubiec and Reinhart 2012). DGP was found to be the most robust and accurate metric of those tested, while the enhanced simplified DGP method (Wienold 2009) was found to produce a comprehensive yearly analysis with a reasonable amount of computing power (Jakubiec and Reinhart 2012).

2.2.3 Evaluating the Perceptual Field-of-View

While comfort-based luminance metrics such as DGP extend our quantitative methods of assessment beyond task-based illumination metrics such as DF and DA, the current state of lighting research is still generally dominated by what Cuttle would refer to as the rut of a nineteenth-century concept (Cuttle 2010). Lighting research has been historically dominated by task-performance and visual comfort criteria, which are only applicable to spaces where visual tasks are frequently encountered. For spaces where visual task performance is less indicative of lighting performance, we often seek to create acceptably bright and/or visually engaging environments (Cuttle 2010). To evaluate occupant *satisfaction* with the perceptual field-of-view and measure the *positive* impacts of luminosity within interior architecture, past research has relied on measurements such as average luminance, threshold luminance, and luminance diversity in line with occupant surveys to establish trends in preference.

Two dimensions that are widely accepted to impact the field-of-view are average luminance and luminance variation (Veitch and Newsham 2000). The former has been directly associated with perceived brightness and the latter with visual interest (Loe et al. 1994). As brightness is subjectively evaluated by the human brain, contrast and luminous composition are often regarded as qualitative indicators of daylight performance, prompting researchers to use empirical methods (i.e., surveys) to establish a relationship with occupant preference.

While renderings and digital photographs are used by architects to communicate design intent, high-dynamic range (HDR) images produced through RADIANCE can provide an expanded range of photometric information, allowing us to gain luminance values and evaluate characteristics such as brightness and contrast (Ward 1994).

In a study conducted by Cetegen et al. occupant surveys were used to establish a direct correlation between the average luminance across an HDR image and its perceived 'pleasantness' or relative 'excitement' (Cetegen et al. 2008). In this study, participants were shown digital HDR images of an office environment with varying partition configurations and view conditions. For each of the configurations, the participants ranked the images in terms of their satisfaction with the amount of view, light, and their own visual comfort. The results found a positive trend between increased average luminance levels and satisfaction for the view as well as increased luminance diversity and the participant's impression of excitement (Cetegen et al. 2008). It was determined that both *average luminance* and *luminance diversity* contributed to occupant preference.

In an experiment conducted by Tiller and Veitch, participants were asked to adjust the brightness between two offices (using a dimmer switch) until they reached a perceived equilibrium in brightness; one office had a uniform lighting distribution and while the other had a non-uniform lighting distribution. Both offices had the same average luminance across the observed field-of-view. Task-plane illuminances were taken in each space, and it was determined that the office with a non-uniform luminance distribution required 5–10 % less work-plane illuminance to achieve the same level of perceived brightness as the office with a uniform lighting distribution (Tiller and Veitch 1995). The researchers concluded that *luminance distribution* across an occupant's field-of-view does, indeed, impact the perception of brightness within a given space.

In a study on visual comfort, participants were asked to adjust a set of horizontal blinds within a side-lit office space until the light distribution reached a level that they felt was 'most preferable,' and then again into a position that they felt was 'just disturbing' (Wymelenberg and Inanici 2009). HDR photographs were taken after each adjustment and used to run a series of luminance metrics to analyze the participant's selection of scenes. While the results established an upper threshold value over which the average luminance of the office was considered disturbing by all participants, the study was unable to determine a lower threshold given the diversity of results. DGP was calculated for each selected scene, but there were no significant trends between the 'most preferable' and 'just disturbing' spaces. The best predictive metrics for occupant preference in this study were found to be predetermined luminance threshold values (Lee et al. 2007) and standard deviation of luminance values. The authors concluded that *adequate* variations in luminance created a stimulating visual environment, while *excessive* luminance variability tended to create uncomfortable spaces (Wymelenberg and Inanici 2009).

A study of particular relevance to this research established a new method for measuring luminance diversity, called the Luminance Differences (LD) index (Parpairi et al. 2002). While efforts to use standard deviation to predict occupant discomfort have had some success, predicting positive preferences toward luminance diversity has been less successful. This is because the previous studies were unable to quantify local variations and thus identify patterns that would trigger visual interest. LD is calculated by taking eye-level luminance measurements in a 360° polar array across a horizontal plane and then calculating the difference in luminance levels across a range of acceptance angles corresponding to eye and head movement (Parpairi et al. 2002). LD allows us to calculate the perceived *noise* or variation in luminance values across our field-of-view. In this study, participants were asked to answer a questionnaire on their impressions of three Cambridge libraries across a series of predetermined viewpoints. LDs were calculated for each view position and then compared against the surveyed data to draw conclusions about luminance diversity and occupant preference. The authors concluded that luminance variability was highly appreciated by the subjects in all three library spaces and that the more variable the luminance across the field-of-view, the more 'Pleasant', the spaces were perceived to be. Furthermore, high luminances were not required to achieve satisfaction—variability was found to contribute more to occupant satisfaction than power.

The studies discussed so far rely on occupant surveys as an empirical method for measuring human preferences toward luminosity within the perceptual field-of-view. Another category of research focuses on the analysis of architecture to measure the *relative* performance of light between existing spaces. An example of this research can be seen in Claude Demers' daylight classification system (Demers 2007). In her work on contrast and brightness analysis through the use of digital images, Demers used grayscale histograms to identify the dominance of bright, dark, and middle-range pixel values within interior architecture. Based on the mean brightness (average luminance) and standard deviation of those pixel values, she has developed a daylight classification system to compare daylight architectural spaces (Demers 2007). While this approach does not introduce empirical factors such as human preference, it does allow for the *relative comparison* of interior architectural spaces through methods such as average luminance and standard deviation. This research explored the *range* of daylight design strategies present within interior architecture and introduced a dialog about how we can contextualize and compare the visual effects of light (luminance). By extending the scope of research beyond tightly controlled side-lit office spaces, such as those studies presented in Sect. 2.2.3, we can begin to account for the complexity of visual effects that emerge from existing architecture.

2.3 Temporal Considerations for Daylight Performance

Section 2.2 introduced existing metrics for evaluating illumination and visual comfort for task-driven performance as well as research aimed at evaluating the perceptual field-of-view under daylight conditions. While the dynamics of daylight have influenced the development of annual climate-based illumination metrics such as daylight autonomy and visual comfort metrics such as annual daylight glare probability, there is a lack of consideration for temporal variability in those studies that evaluate the perceptual field-of-view.

Section 2.2.3 introduced existing methods for measuring luminance across our field-of-view, highlighting those methods that distinguish *spatial* diversity, such as the Luminance Differences index (Parpairi et al. 2002). However, we are still missing a method for measuring *temporal* diversity as it pertains to occupant satisfaction and human delight. Although HDR images can be used to quantify brightness and contrast in architectural space through luminance measurements, dynamic sky conditions necessitate a multitude of images, taken throughout the year, in order to account for the varied perceptual impacts of daylight through time.

One of the most challenging aspects of annual daylight analysis, whether it be luminance or illuminance based, is representing a large quantity of data simultaneously in both quantitative and visual terms. Spatio-Temporal Irradiation Maps (STIMAPS) were proposed as a way of representing annual data across a single graph, with days of the year on the horizontal axis and hours of the day on the vertical (Glaser and Hearst 1999) (Fig. 2.8). To help designers visualize the dynamic performance of daylight throughout the year, a simulation platform that combines ST maps with u-d goals and associated annual daylight renderings has been developed by Andersen and her research group, originally at MIT and now at EPFL (Andersen et al. 2013; Andersen, Gagne & Kleindienst, 2013; Kleindienst & Andersen, 2012, Gagne et al. 2011, Andersen et al. 2008).

This simulation method provides the designer with goal-based illuminance thresholds and allows them to navigate the resulting temporal maps alongside associated renderings. This provides a clear visualization of both the quality and quantity of light in a given space over time (Kleindienst et al. 2008; Lee et al. 2009) (Fig. 2.9). Although the ‘smoothness’ of any temporal map depends on the number of annual instances and the interpolation method between each data point, the method has been validated for illuminance across 56 annual periods representing 7 daily and 8 annual intervals (Kleindienst et al. 2008).

Although they have not yet been integrated, perceptual field-of-view metrics that rely on HDR images are well suited for the Lightsolve platform, which generates 56 annual images as parts of its goal-based analysis. To conduct an annual analysis of both *spatial* and *temporal* diversity in light across our field-of-view, it is important that any new metrics be represented through dynamic quantitative and visual means.

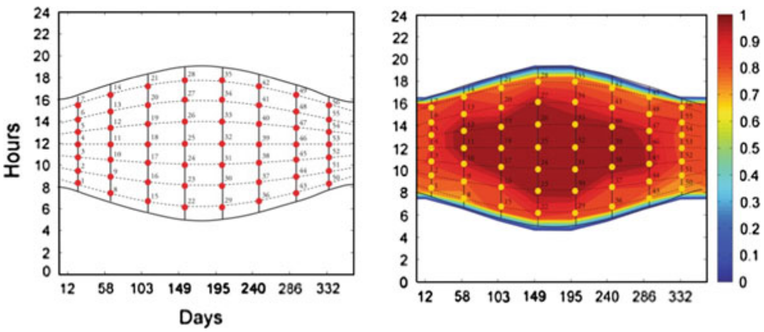

Fig. 2.8 Location of data points on a temporal map, 56 based on the temporal grid used in lightsolve

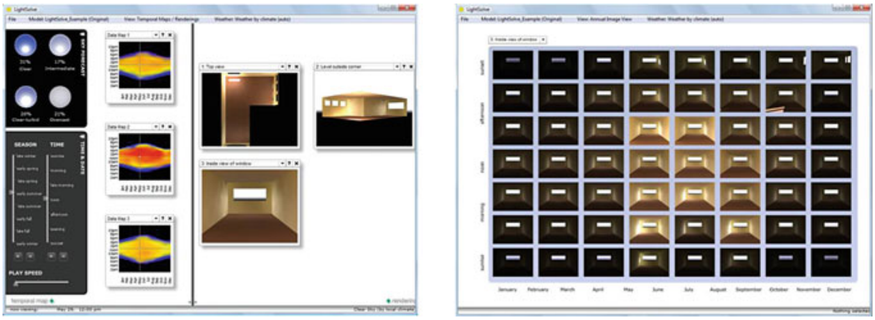

Fig. 2.9 Lightsolve interface, showing a default room with temporal illuminance maps on the top and annual renderings on the bottom (Kleindienst et al. 2008; Lee 2009)

2.4 Synthesis

Through a comparison of existing architectural spaces, this chapter introduced the importance of *spatial* and *temporal* diversity in our perception of daylight interior space. There are three categories that define existing daylight analysis metrics and methods: task-based illumination, visual comfort for task performance, and preferences toward the perceptual field-of-view. While task-based illumination metrics assess the amount of light required to perform visual task across a work plane, visual comfort metrics evaluate the potential for discomfort due to glare sources within an established view direction. Research directed toward the perceptual field-of-view has traditionally focused on brightness (mean luminance, threshold luminance, and luminance ranges) within a given view direction and occupant surveys to establish human preferences toward the luminous environment. Other studies of interest have coupled standard deviation (Wymelenberg and Inanici 2009) and/or visual *noise* (Parpairi et al. 2002) within an established view direction with occupant surveys to understand human preferences toward luminous diversity. While these studies begin to address the importance of *spatial diversity* in our perception of daylit space, they do not yet address the importance of *temporal diversity*, produced by the dynamics of sunlight throughout the year. The metrics proposed by this research will introduce a method for quantifying spatial contrast and luminous variability through the medium of digital images, so that these visual effects may be compared across a range of architectural spaces. It is the authors' perspective that existing task-based illumination and visual comfort metrics must be combined with dynamic perceptual metrics to create a more holistic understanding of daylight performance in architecture.

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