Building envelope impact on human performance and well-being: experimental study on view clarity

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1. ABSTRACT

This project focused on investigating the links between daylight and human visual perception and performance in relation to the building envelope, first broadly, and then focused on view clarity. We conducted a brief literature review on current daylight metrics used in building industry. We found that debate remains on the practical applicability of these metrics, and gaps exist between daylight and other building envelope-related aspects such as view. We also provide an overview of research methods on human visual perception and performance measurements in relation to daylight and view, including subjective and objective measurements. In the later section of this report, we introduce and show results from a pilot study done at Lawrence Berkeley National Laboratory's Windows Testbeds. We tested High Dynamic Range (HDR) photography techniques to capture the different view clarity through the selected building envelope layers (shades and electrochromic glass) under various sky conditions. The experimental study reveals that light fabric shades restrict the view compared to dark fabric shades, and that view clarity through a blind can be significantly reduced when there is direct sun in the field of view (at certain sun angles). The direct sun caused white-spotted visual noise at the partial area of the fabric shade. Hence, the view was more obscured by the effect of the direct sun even though in this case there was a greater vertical illuminance than the others. The study also shows the potential of HDR photography techniques to be used for a standard view clarity rating method, while noting that further support is needed from human subject testing and advanced computational image analysis algorithms.

2. BACKGROUND

A view from a window enhances occupants' well-being by providing a connection to the outdoor environment. Many studies in environmental psychology have found that views have a positive impact on occupants' well-being and satisfaction by reducing stress level and relieving eye muscles. One study also showed that people who have a preferable view have lower glare sensation even though the Daylight Glare Index (DGI) was the same as a less preferable view (Tuaycharoen and Tregenza, 2007).

The quality of a view can be estimated by view content, angles, distances, and sky/sun conditions. It becomes important when occupants stay longer in one space (e.g. office). In most office spaces, designers use shading systems such as fabric shades, ceramic fritted glass or tinted glass to minimize glare. However, this might have a negative impact on how people can see the views through the shading system, and it sometimes shifts the color, clarity, and overall preference of the view, which could impact occupants' overall perception of other qualities of their built environment.

3. OBJECTIVE

The objective of this project was to assess the visual effect of selected aspects of the building envelope on human performance and perception. The initial literature review examined human factors that could be explicitly considered in building envelope design, operation and current daylight metrics. Following the literature review, we narrowed down our research question to experimentally investigate the visual performance of fabric shading systems and electrochromic windows under both diffuse and direct sunlight conditions, and develop a view clarity rating method.

4. LITERATURE REVIEW

We conducted a literature review about daylight metrics, view guidelines, and human visual perception and performance measurements, which are described below.

4.1 Review of Daylight Metrics. Two of the most common daylight metrics used for façade and daylight design are Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). But there are many more in the literature. This review looked into the different daylight metrics and their pros and cons, and organized them below by daylight sufficiency metrics, visual comfort/glare metrics, and combined metrics.

4.1.1 Daylight Sufficiency Metrics. There are three major daylight metrics that evaluate if the daylight level is sufficient for a given space: Single-point-in-time Illuminance, Daylight Factor, and Daylight Autonomy (of which there are various types, and we reviewed the differences).

Illuminance **(point-in-time, at a specific location and time)**

Definition. Illuminance is the amount of light falling on a surface per unit area, measured in lumens per square meter (lm/m^2) or lux. This method requires a work plane illuminance calculation for one time of the year. The time can be selected to represent an average daylight condition such as sunny equinox at noon, or an extreme scenario such as cloudy winter solstice.

Related building codes and standards. The Leadership in Energy and Environmental Design (LEED) v3 rating system gives a point that depends on the percent of area that achieves 25 fc (269 lux) at 9 a.m. and 3 p.m. at the equinox, calculated under the International Commission on Illumination (CIE) clear sky conditions, with the blinds closed if needed to block direct sun.

Pros and cons. The illuminance value only represents the amount of daylight falling onto a specific location and time. It is the value that designers can understand if their building design meets the required daylight performance by a lighting standard or guideline. However, it is hard to evaluate the annual daylight performance of a building based on a point-in-time illuminance. By using Climate-based metrics (discussed later in this section), we can compile and post-process the values from hourly illuminance calculations. Thus, determining these using annual simulation will take a lot more time than a single point-in-time illuminance calculation.

Daylight Factor

Definition. Daylight Factor (DF) is defined as the ratio of the internal illuminance at a point on a work plane in a building, to the unshaded and external horizontal illuminance under a CIE standard overcast sky (Moon and Spencer, 1942).

Related building codes and standards. Early versions of the LEED v2.2 rating system originally required a DF 2 for at least 75 % of the critical visual task zones to achieve indoor environment. The credit 8.1. of the British Standard Institution, BS 8206-2 (Mansfield, 2008) requires DF 2 or 5, depending on electric lighting requirements, to support human well-being. Recommendations on daylighting in buildings is also given in the newly revised Chartered Institution of Building Services Engineers (CIBSE) SLL Lighting Guide ("Lighting Guide 10: Daylighting - a Guide for Designers - LG10" 2017) and the BRE Report 'Site layout planning for daylight and sunlight: a guide to good practice' (Helliwell 2012).

Pros and cons. DF outputs are helpful in making quick comparisons of relative daylight penetration under overcast sky conditions. However, they do not take into account window orientation or sun position. DF is solely a function of building geometry and surface reflectances. Therefore, it tends to underestimate actual illuminance ratios in side lit rooms (Littlefair, 1993). DF can give a general sense of the average daylight conditions in a space, but cases of exceedingly high illuminance cannot be addressed. In addition, DF does not take into account the effect of complex façade systems such as light shelves and sun-redirecting films.

<u>Daylight Autonomy</u>

Definition. Daylight Autonomy (DA) is a measure of how often a specified illuminance level can be maintained by the use of daylight alone. It is expressed as the percentage of occupied time in a year. DA was the first generation of annual daylight metrics, now commonly referred to as 'Climate-based metrics' ("Energy Design Resources: Design Brief, Understanding Daylight Metrics" 2017). The minimum specified illuminance that DA typically uses is based on the Illuminating Engineering Society's (IES) recommendation for a given space type (*The Lighting Handbook, 10th Edition* 2011). The metric also has the ability to relate itself to electric lighting energy savings if the user defines a threshold based on electric lighting criteria (Reinhart, 2002). The user is free to set the threshold above which DA is calculated (Reinhart et al., 2006).

Variations. Four variations of the original DA have been developed and some, such as continuous DA, may predict daylight performance more accurately than others.

- **Daylight Autonomy.** The original and simplest of the four variations, DA is the percentage of the occupied times of the year when the minimum illuminance requirement is met by daylight alone (Reinhart and Walkenhorst, 2001).
- **Continuous Daylight Autonomy.** Continuous Daylight Autonomy (cDA) awards partial credit to time steps when the daylight illuminance lies below the minimum illuminance level (Reinhart et al., 2006). For example, if the target illuminance is 200 lux and the calculated value is 100 lux, DA would give zero credit, while cDA would give 0.5 credit (100/200 = 0.5). The benefit of cDA is that it takes into account acceptable illuminance. For example, office occupants usually prefer to work in daylight conditions below the office illuminance threshold defined by IES (*The Lighting Handbook, 10th Edition* 2011) since the lower levels avoid potential glare and excessive contrast (Jakubiec and Reinhart, 2012).
- **Zonal Daylight Autonomy.** Zonal Daylight Autonomy (zDA) represents the sum of the number of hours at each sensor that the measurements meet or exceed the IES' required thresholds for a specific space type (The Lighting Handbook, 10th Ed. 2011). zDA applies to one sensor at a time, while Spatial Daylight Autonomy (sDA) adds up sensors for an area.
- **Spatial Daylight Autonomy.** sDA is a metric describing the annual sufficiency of ambient daylight levels in interior environments. It is defined as the percent of an analysis area that meets a specified minimum daylight illuminance level for a specified fraction of the operating hours per year. The user can define the analysis area where he/she performs the calculations, but the area is typically across an entire working space. IES of North America has introduced

the concept of sDA, as well as Annual Sunlight Exposure – which will be described later ("Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)" 2017). It suggests default values of 300 lux for the minimum illuminance and 50% for the fraction of operating hours (default operating hours are taken to be 8am to 6pm local clock time). This would be written as $sDA_{300,50\,\%}$.

Related building codes and standards.

- The IES document LM 83-12 gives two sets of recommendations for Spatial Daylight Autonomy, sDA. For preferred daylight sufficiency, it recommends that 75% of points analyzed exceed 300 lux for more than 50% of the above time period. For 'Nominally accepted' daylight sufficiency, it recommends that 55% of points analyzed exceed 300 lux for more than 50% of this time period ("Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)" 2017). The IES recommendations are based on a survey (Heschong Mahone Group, 2012) of 61 spaces (classrooms, open offices and libraries/lobbies) in the United States, which compared the opinions of occupants and visiting experts with daylight simulations of the spaces. LEED v4 adopted these requirements for their IEQ criteria.

- A recommendation based on daylight autonomy is also in the UK Education Funding Agency (EFA) Design Brief for New Schools, funded under the Priority Schools Building Program ("Contractors Framework - Part B- Generic Design Brief" 2013, "EFA Daylight Design Guide" 2014). This requires a daylight autonomy of 50% for the target illumination (typically 300 lux in teaching spaces), for the hours of operation from 8.30 a.m. to 4.00 p.m. (This is to be for 50% of the working plane). The working year covers weekends and school holidays as well as weekdays during term time.

- The European standard on daylighting recommends that, to be considered daylit, a workroom should have at least 300 lux at 50% of the grid points within the room for at least half of the daylight hours during the year ("Design Brief, Understanding Daylight Metrics" 2017), (Mardaljevic, 2013). If the daylight in the workroom is predominantly from roof lights, then 90% of the points should meet this criterion. There is similar guidance for classrooms and nurseries. In dwellings, the recommendation is the same, but there is an additional recommendation that none of the grid points in the room should receive less than 100 lux of daylight for more than half of the daylit hours in the year.

- The latest Building Research Establishment Environmental Assessment Method (BREEAM) criteria for daylight contain an alternative calculation method which is a type of daylight autonomy calculation ("BREEAM International NC 2016 Technical Manual 2.0.pdf" 2016). This is based on the number of hours per year for which a given average illuminance in the space (averaged over the whole working plane) is exceeded. Additional criteria require the minimum daylight illuminance to be above a set value for a certain number of hours of the year. The set illuminance values vary with the type of space. These recommendations are based on the existing average daylight factor based recommendations in BREEAM.

Pros and cons. The biggest contribution of DA to daylight metrics is that DA represents the annual daylight performance using sun and sky conditions based on meteorological weather datasets. It allows designers to understand the overall daylight conditions of their buildings over the course of a year. As it is a cumulative analysis (the prediction is based on the aggregate measurements of daylight), it is often difficult to investigate the temporal aspect of daylight conditions from only the DA metric. As DA reports the percentage of occupied hours over a year, it does not take into consideration the hourly variation of daylight, which is an important aspect when designing buildings.

4.1.2 Visual Comfort/Glare Metrics.

Currently, designers use both illuminance and luminance to analyze visual discomfort/glare in their building design. Illuminance was defined above. Luminance, more appropriate for glare calculations, describes the intensity of light emitting from a particular surface per a unit area in a given direction. It also indicates how much luminous power can be perceived by the human eye. Visual comfort is a complex phenomenon and depends heavily on occupants' perception, so it is hard to measure or predict, and the relative value of different visual discomfort/glare metrics is still debatable. We compared and analyzed multiple metrics, described below, that have different ways of analyzing visual comfort, but no single metric covers various conditions.

Illuminance-Based Glare Prediction Indices. A high level of Illuminance is one of the predictors of glare. The threshold and the aggregating methods (if applicable) are still under debate.

Variations. There are three variations of illuminance-based glare prediction indices:

- ***Annual Sun Exposure.*** 'Annual Sun Exposure' (ASE) is defined as the percentage of an analysis area that exceeds a specified direct sunlight illuminance level for a specified number of hours per year, both of which are indicated in the subscript for the metric ("Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)" 2017). IES recommends an analysis based on $ASE_{1000,250h}$ (i.e., the percent of the analysis area that is exposed to more than 1000 lux of direct sunlight for more than 250 hours per year), and that this should be the threshold before any shading device is deployed to block sunlight. One use use the same analysis period as sDA. LEED v4 ("LEED v4 for Building Design and Construction" 2014) adopted ASE as its glare metrics in the daylight credit. Some practitioners question whether the threshold, 1000 lux, is the reasonable value to determine direct sunlight or not.

- ***Maximum Daylight Autonomy.*** Maximum Daylight Autonomy (MaxDA) addresses the occurrence of direct sunlight in a daylit space and it is defined to be used in conjunction with DA (Architectural Energy Corporation, 2006). MaxDA indicates the percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions present. It uses a maximum illuminance threshold instead of a minimum illuminance, and the threshold is typically ten times the base design illuminance. This value is an indicator of potential glare and visual discomfort.

- ***Daylight Uniformity Ratio.*** The metric is calculated as minimum/maximum or minimum/average illuminance ratios that are common for electrical lighting. A few applications use more sophisticated mathematical concepts such as standard deviation or coefficient of variance to analyze daylight uniformity (Heschong Mahone Group 2012). One of the challenges of daylight uniformity is how building professionals define the effect of dynamic conditions. Furthermore, electric lighting is commonly judged by horizontal illuminance, since the fixtures are usually mounted in the ceiling. But daylighting, especially from windows, may contribute more importantly to the illuminance of vertical surfaces.

Luminance-Based Glare Prediction Indices. Compared to illuminance, luminance-based glare metrics are considered to be more accurate glare prediction indices as they are more comparable to what human eyes perceive in the built environment. Luminance is based on a scene associated with a view angle, which is one of the important variables when measuring glare. Luminance-based analysis methods have been historically difficult to conduct due to the variable nature of daylight scenes for a specific glare analysis. Handheld luminance meters are useful for getting an immediate readout for spot measurements, but present a challenge for recording temporal data in a comprehensive manner since daylight conditions are regularly changing. HDR photography techniques have made luminance data readily available from daylit spaces where, in the past, it was not feasible to generate a luminance map of a scene based on the measurements from handheld luminance meters. Advances in computational methods have been improving the speed of luminance analysis in HDR images and, in turn, this has facilitated the development of new luminance-based analysis glare metrics. There are four variations of luminance-based glare prediction indices:

- **CIE Glare Index (CGI).** Einhorn (1979) proposed CGI to correct the inconsistency and inaccuracy of the British Glare Index (BGI), one of the first glare metrics (Petherbridge and Hopkinson 1950). Later, the CIE adopted this metric and the equation is as shown below:

$$CGI = 8log_{10}\left[2\frac{1+(E_d/500)}{E_d + E_i}\sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}\right)\right],$$

  where the variables are the luminance of a glare source ($L_{s,i}$), the Guth position index (P_i), the size of the glare source measured in steradians ($\omega_{s,i}$), and the illuminance at the observer's eye (E_d and E_i).

- **Discomfort Glare Index (DGI).** DGI directly derives from CGI and extends its scope to predicting glare from large sources, such as windows. The final formula was refined by Nazzal (2005).

$$\mathrm{DGI} = 8log_{10}\left[0.25\ \frac{\sum_{i=1}^{n} L_{exterior,i}^2\ \cdot \Omega_{pN}}{L_{adaptationd} + 0.07\left[\sum_{i=1}^{n}\left(\omega_{N,i} \cdot L_{window,i}^2\right)\right]^{0.5}}\right],$$

  The size of each glare source (ω_N) is measured in steradians from the point of observation, and the variables are: the corrected solid angle subtended by the source (Ω_{pN}), the average luminance of the window surface (L_{window}), the average luminance of the surroundings ($L_{adaptation}$), and the average vertical outdoor luminance ($L_{exterior}$).

- **Unified Glare Rating (UGR).** UGR was developed and validated to describe glare from luminaires. Because luminaires are typically smaller than windows, UGR is not directly applicable to the measurement of glare from windows (Howlett et al., 2013).

$$UGR = 8log_{10}\left[\frac{0.25}{L_b}\sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}\right)\right]$$

- **Daylight Glare Probability (DGP).** DGP is proposed and validated by Wienold and Christoffersen (2006). The formula is based on the vertical eye illuminance produced by the light sources at the observer's eye (E_v), the luminance of a glare source (L_{si}), the solid angle of the source seen by an observer (ω_{si}), and the position index (P_i), which expresses the change in experienced discomfort glare relative to the angular displacement of the source (azimuth and elevation) from the observer's line of sight.

$$DGP = 5.87 \cdot 10^{-5}E_V + 0.0918 \cdot log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_V^{1.87} \cdot P_i^2}\right)\right] + 0.16\,,$$

In an article by Jakubiec and Reinhart (2012), they compared experimental results in three spaces utilizing individual Radiance simulations for each sky condition and space. Results showed that, of five tested glare metrics, DGP is the most robust and least prone to producing misleading or inaccurate glare predictions under a wide variety of analyzed solar conditions. The DGP method allows a more comprehensive analysis of yearly comfort data for a specific space, requiring a much smaller computational effort than performing thousands of Radiance simulations for sky conditions across the entire year. However, to perform the simulation still takes a substantial amount of time and thus, should only be attempted once basic performance and reasonableness have been established using luminance images from discrete time simulations.

Related building codes and standards. LEED v4 requires the use of ASE in conjunction with sDA for designers to earn two to three points, for being achieved in 55-75% of regularly occupied floor area, respectively. In order to achieve the points, designers should demonstrate through annual computer simulations that annual sunlight exposure ($ASE_{1000,250}$) of no more than 10% is achieved. It is required to be based on the regularly occupied floor area that is daylit per the $sDA_{300/50\%}$ simulations. Daylight Uniformity ratio is common in electrical lighting

Pros and cons. Illuminance-based metrics are quick and easy to calculate/simulate but it may not represent visual discomfort/glare accurately. This is due to the inherent limitation of the use of illuminance, which is the amount of light falling onto a surface that does not represent the human perception of entire scene. Daylight Uniformity Ratio can distort the visual comfort prediction where side windows exist, which tend to produce non-uniform light distributions. Hence, it is more appropriate to use where the space is daylit by skylights.

4.1.3 Combined metrics (both daylight sufficiency and visual comfort in a single metric)

Ideally, daylight sufficiency thresholds and visual comfort/glare thresholds could be integrated into a single metric to predict both aspects of daylight conditions.

Useful Daylight Illuminance

Definition. Useful Daylight Illuminance (UDI) is a modification of Daylight Autonomy, and is conceived by Nabil and Mardaljevic (2005). It is based on the idea that providing too high a daylight illuminance may be as bad as providing too low a level, since very high daylight illuminances can lead to glare, and then occupants may use shading devices to shut out the light. Thus, the UDI represents the operating hours during which the daylight illuminance falls within a 'useful' range. Initially 100-2000 lux was proposed (Reinhart, Mardaljevic, and Rogers 2006, Nabil and Mardaljevic 2005). It provides a full credit only to values between 100 lux and 2,000 lux, suggesting that horizontal illumination values outside of this range are problematic. In a later paper, Mardaljevic et al. (2009) further subdivided the 100-2000 lux "useful" UDI bin into a "supplementary" (100-500 lux) and an "autonomous" (500-2000 lux) range. UDI-supplementary gives the occurrence of daylight illuminances in the range 100 to 500 lux (Mardaljevic et al. 2009).

Related building codes and standards. The UK Education Funding Agency's design brief for new schools gives a UDI-based guideline. ("Contractors Framework - Part B- Generic Design Brief" 2013, "EFA Daylight Design Guide" 2014). The guideline says that UDI (100 lux – 3000 lux) should be achieved for an average of 80% of the time over the working plane within a space. The EFA daylight design guide states that 'There is some debate about the best range to use for UDI as daylight can be useful up to as high as 5000 lux depending on the activities taking place. Where the lighting designer believes the upper limit should be higher and will not introduce discomfort or disability glare then this can be raised.'

Pros and cons. UDI encourages designs which have limited window areas but better uniformity, either by the use of high ceilings and window heads, or by using roof lights, or by using windows in more than one side of the room. There is significant debate regarding the selection of 2,000 lux as an 'upper threshold' above which daylight is not wanted due to potential glare or overheating, as there is actually little research to support the selection of this value as an absolute upper threshold. For interiors, where glare is less of an issue and where people can move around to avoid it, UDI is less relevant. In these situations, daylight autonomy would be a more relevant climate-based metric than UDI. Useful Daylight Illuminances require both upper and lower thresholds which first have to be established for different building zones, requiring further research (Reinhart, Mardaljevic, and Rogers 2006).

4.2 Review of View Guidelines

View to the outside and daylight are the two major qualities that the most windows provide to people in the indoor environment. However, the relationships between view, daylight and glare through shading/façade systems have been minimally researched to date, and view-related metrics or guidelines are fairly limited. LEED v4 has view-related credits, and CIBSE (2017) also has a guideline for how to design to allow a good view to the outside.

4.2.1 LEED v4 - Quality views

LEED v4 awards one point for providing quality views, determined by requiring a direct line of sight to the outdoor via vision glazing for 75 % of all regularly occupied floors. The intent of this credit is to promote a connection to the natural outdoor environment for building occupants. This credit also defines 'View glazing' as the opening area that does not have obstructions by specially-treated glass such as frits, patterned and tints. The credit also requires that 75 % of all regularly occupied floor area needs to meet at least two of the four criteria: the view angles, the view contents, the distance to height of the vision glazing, and a view factor of three or greater. The view factors are based on a report, Windows and Offices; A Study of Office Worker Performance and the Indoor Environment (Heschong Mahone Group, 2003). Views into interior atria may be used to meet up to 30 % of the required area.

4.2.2 CIBSE – View in and out

The CIBSE Guide 10 provides a method to assess the view from a given position in a room. View quality is defined by parameters including width of view window(s), distance of the view, layers (sky, landscape and foreground), and environmental information (contents). The view quality can be rated as "insufficient", "sufficient", "good", and "excellent" and the minimum-maximum thresholds for the distance of the view is 6-50 m. The quality of a view is subjective and depends on many factors, such as the amount of control an observer feels over their particular view in a room ("Lighting Guide 10: Daylighting - a Guide for Designers - LG10" 2017). A view that provides a sense of time and mobility also contributes to the visual perception of view quality by observers.

4.3 Review of Human Visual Perception and Performance Measurements. The field of human perception and performance is enormous, and this literature review focused on research that has been done specifically related to daylight, views, and glazing-related human perception and behavior and their measurements. Empirical research on daylighting and building occupants has focused on the performance benefits of daylighting with regard to improved productivity in schools and offices (Watson et al., 1988), higher sales (Heschong Mahone Group, 2003), shorter recovery time in hospitals (Beauchemin and Hays, 1996), and increased job satisfaction and wellbeing (Butler and Biner, 1987, Heerwagen and Orians, 1986, Leather et al., 1998).

4.3.1 Subjective Measurements. Subjective measurements used in these studies include self-assessment of the occupants' satisfaction, comfort, and preference for their built environments. The measurements include the occupants' perceptions of environmental quality, task-related performance, non-visual functions such as emotion and mood, stress level, and work engagement.

- **Perceived Environmental quality.** There are a few studies in psychology that used questionnaires to assess perceived environmental quality such as: luminous perception of brightness (bright/dark) (Smolders and de Kort 2014), light appraisal (lighting quality scale and four items measured on Likert-type scales) (Veitch and Newsham 2000), self-assessments of the view through a window that is accessible from their normal work position, view interest factor (compared to glare, luminance range) (Tuaycharoen and Tregenza, 2007) and how occupants felt the room affected them.

- **Task-related measurements.** As a simple subjective method to measure task performance based on occupants' perceptions, many studies used self-assessed productivity ("The office environment survey," 1987), such as using questionnaires to ask how occupants feel the lighting environment affected them. The questions often collect responses using 5-point Likert-type scales. Attentional performance (concentration and distraction) is one of the fields that psychologists have developed as the part of task-related measurements. Based on computational advancements in data collection, recent studies used experience sampling methods (Csikszentmihalyi and Larson, 2014) in which human subjects wore an electronic pager for a certain period, and whenever the pager beeped in response to signals sent at random times each day, it recorded what they were doing and how they felt at the moment they were signaled. Other measurements include a general distraction questionnaire (Seddigh et al., 2014), the load theory of attention (Lavie et al., 2004), and the Attentional Function Index test (it measures perceived effectiveness in common cognitive activities that require directed attention) (Cimprich et al., 2011).

- **Non-visual functions and emotion.** There are a few affective dimensions that have been studied in the daylighting related literature: pleasure, arousal, and dominance (Mehrabian and Russell, 1974). The measurements of emotion could vary, and include: the scores of six semantic differential pairs on 9-point scales (Russell and Mehrabian, 1977), the Profile of Mood States (Curran et al., 1995), the Positive Affect Negative Affect Schedule (Watson 1988) and subjective surveys on alertness, mood, physical, well-being and relaxation.

- **Stress level.** Karasek's model of job strain is one of the earliest studies wherein strain is seen as resulting from the interaction of high job demands (time pressure & workload) and low decision latitude (control making & decision making at work) (Karasek, 1979). The National Aeronautics and Space Administration (NASA) has used Task Load Index (TLX) for evaluating work load, which was measured using a questionnaire presented on a PC (Hart and Wickens, 1990). The other study methods include increased psychological withdrawal measurements (Karasek and Theorell, 1992), the Copenhagen Psychosocial Questionnaire (Kristensen et al., 2005), and the Maslach Burnout Inventory - General Survey (MBI-GS), which assesses burnout (Schutte et al., 2000) such as emotional exhaustion, depersonalization, and personal efficacy.

4.3.2 Objective measurements. There are three main categories of objective measurements: performance tests, behavioral measurements, and physiological measurements. The behavioral measurements include work motivation, work structure, and facial expressions to assess emotion and autonomic physiology. Physiological measures include heart-rate variability, cortisol level and electroencephalographic measurements.

Performance Tests

- **Cognitive performance test.** Heschong Mahone Group (2003) conducted a series of occupants' performance test including Landolt-C, Letter search, Number search, Backward numbers (a standard psychological test for mental acuity), attention span, and short-term memory tests. In other studies, the researchers used N-back test (Münch et al., 2012), short-term/long-term recall test (Knez and Kers, 2000), and Stroop task (MacLeod, 1991) for elective attention.

- **Direct attention test.** Standardized clinical measures of attention are Digit Span Forward and Backward and Symbol Digit Modalities Test (*Neuropsychological Assessment*, 2012). Necker Cube Pattern Control Test is also designed to measure direct ability to inhibit competing stimuli, and it can also be used for direct attention test (Cimprich, 1993).

- **Task performance test.** There are a few tests to evaluate task performance of human subjects. The most simplistic way of doing the experiment is to give repetitive work such as filing, simple typing task (speed and accuracy), computational work (basic algebra), or creative work. In Stone and Irvine's study (1994), human subjects were asked to create 30 answers for 20 different items. The authors measured the task performance of the human subjects by the total number of questions that the human subjects completed. The human subjects' visual capabilities were also measured by using contrast sensitivity (correct responses per second), arithmetical questions, and GMAT-style questions.

- **Others.** Morrison et al. (2004) tested mental representations of relations between objects and events in working memory. The test included reading comprehension (as a way of testing short-term memory), analogical reasoning such as semantic memory, and People-Pieces (speed, accuracy, and overall efficiency) (Sternberg 1980).

Behavioral Measures

- **Work motivation**. These tests assess the speed in which the human subjects gave up trying, which is a measure of the willingness to persist at an impossible psychomotor task ("The Study of Persistence" 1962). The result shows the persistency in the given task, and it represents work motivation.

- **Work structure**. Work structure is a simple measure that observes how the human subject uses breaks between tasks. It assumes that changes in motivation are related to break durations between trials of the given tasks.

- **Facial expressions of emotion and autonomic physiology.** Different emotions (and different facial expressions) are linked to relatively distinct patterns of autonomic nervous system activity (Lewis et al., 2010). Using self-report instruments, several studies consistently found significant relationships between facial expression and emotional response. Within-subject designs and improved self-report measures yield more precise and robust associations between facial expression and the experience of emotion.

Physiological Measures

- **Job performance.** Electroencephalographic (EEG) based measurement offers a relatively noninvasive assessment of the brain activity that underlies all types of performance (including vigilance, judgement and sleep monitoring), whereas Actigraphy offers a field-practical way of monitoring the sleep of the occupants (Institute of Medicine, 2004). Heart-rate variability is a peripheral nervous system measure that also reflects the brain activity and eye-movements (i.e., PERCLOS: it has proven feasible for the detection of changes in alertness). Saccadic velocity and percentage-of-eye-closure measures have been shown to reflect the status of the central nervous system (Medicine et al., 2004).

- **Indicators of stress and immune responses.** Cortisol levels (measured from saliva, sweat, or urine) and heart-rate variability (HRV) are indicators of stress and immune responses. High-impedance electrocardiogram (ECG) electrodes measure HRV. Several studies have reported decreases in HRV with increasing cognitive workload. Specifically, it has been found that after performing a spectral analysis on the ECG signal, an examination of the mid frequency band (the 0.10 Hz component) offers information about the amount of mental effort that has to be invested to meet the task demands (Mulder, 1992), (Mulder and Mulder, 1980), (Opmeer and Krol, 1973).

5. VIEW CLARITY PILOT STUDY

5.1 Introduction

From the literature review on daylight metrics and human performance measurements in relation to daylight, we found that the current building envelope related performance metrics do not cover many of the view-related aspects, even though external view is one of the factors that strongly impacts occupants' satisfaction and preference in open offices (Aries et al. 2010). We narrowed down our research question to how we evaluate human visual performance through different building envelope layers and its relationship to daylight conditions, and conducted a pilot experimental study.

View Clarity Index (VCI), a new metric developed by Konstantzos et al. (2015), is the first known attempt to analyze the view clarity scoring system for complex shading/facade system. Their results showed that darker fabrics with higher openness or porosity generally achieve higher clarity scores. However, this research has some limitations. The major limitation of the study is that the index was developed in conditions that excluded the sun in the direct field of view, in order to avoid the potential influence of glare on the view clarity impression (which could happen in real environments). The other limitation of the study is that the clarity of view through the multiple fabrics was analyzed only through clear glass, and didn't consider visible light transmission (VLT) as a testing parameter that could affect clarity and color characteristics of the view through a window, such as if the window has a coating or is made of electrochromic (EC) glass. The last limitation of the study is that they developed the index by testing human subjects with only 14 different fabrics, rather than developing a method that can standardize the rating process for more fabric shading systems further (i.e., it would be difficult to replicate the study for new fabric systems). In our pilot study, we tested these missing pieces, assessing the impact of both direct sunlight and VLT of glass to the metric VCI of shading systems.

There are growing interests (e.g. International Commission on Illumination (CIE) Research Strategy) in the view-related area: visual appearance of materials, the measurements (and metrics) of color quality of transmitted light, visual perception and preference. This VCI study has the potential to be expanded further to these other relevant research issues.

5.2 Pilot Study

In collaboration with the Lawrence Berkeley National Laboratory (LBNL), we conducted the following study:

Objective. Investigate visual performance of fabric shading systems and electrochromic (EC) windows under both diffuse and direct sunlight conditions (including the case where the sun is within the direct field of view), using HDR photography.

Hypothesis. The incident angle of direct sunlight and the different combinations among fabric shading system and EC glass can have a significant impact on visual performance of the building envelope.

Design of experiment. In order to document view and visual comfort conditions through the fabric shade and/or EC glass, we performed measurements in Windows Testbeds (71T) at LBNL (Figure 1) using HDR photography and vertical illuminance sensors. The HDR cameras inside the room were looking directly at the south-facing window, focusing on the exterior testing panel that is installed in front of 71T.

Figure 1. LBL Window Testbeds (71T): (left) exterior and (right) panel installation

Figure 2. The testing panel (left): Landolt-C vision testing chart and a reference color palette. A view (right) to the panel from the chamber

Figure 2 shows the testing panel images that has Landolt-C, a standardized symbol used for testing vision and reference color palette (see Appendix for more information).

Figure 3. HDR Camera positions at the chamber

We took the HDR images at a typical human eye level while sitting (1.22 m height) (États-Unis and Department of Energy 2001) with slightly different view angles, approximately 3 degrees, (Figure 3) under various combinations of fabric shades and EC glass states.

Table 1. Fabric specifications (Ts: solar transmittance, Rs: solar reflectance, As: solar absorptance and Tv: visible light transmittance)

Sample	Color	Fabric	Dual-Sided	Openess Factor	Composition	Ts	Rs	As	Tv
SP13-90-5, Lutron	Oyster/ Beige	Sheer	No	5	35% Fiberglass/ 65% vinyl on fiberglass	17	54	29	12
S3535-KB-3, Lutron	Charcoal/ Charcoal	Sheer	No	3	36% Fiberglass/ 64% vinyl on fiberglass	17	34	49	6

Table 1 summarizes the specifications of the shades that we tested in the study. There were two different colors of fabric shades (Figure 4 and 5) with the same solar transmittance (Ts) value.

Figure 4. Fabric shades: close-up views by LBL

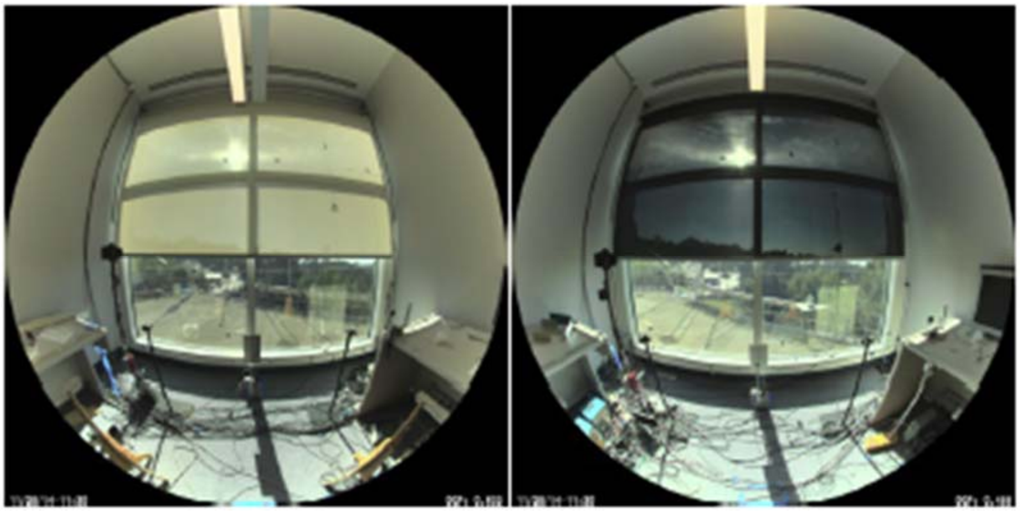


Figure 5. Fabric in the chamber by Windows and envelope materials group, LBL

We conducted a direct sun study by using SketchUp (Figure 6) to understand the shadow patterns and the sun angles over the course of a day in October.

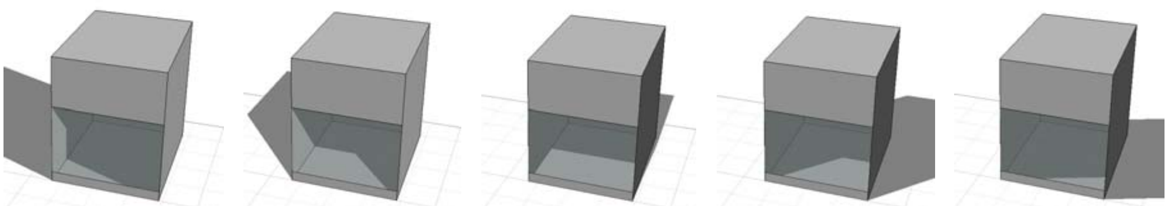


Figure 6. Shadow study at LBL Window Testbed (9 a.m. to 5 p.m. – 2 hours interval)

Timeline and facility. The testing period was nine days within a two-week period in October to early November 2016. We tried to capture both overcast and sunny sky conditions, with and without direct sun on the shades, and with and without the sun in the direct field of view. The chamber had three bands of EC glass and each band could be controlled to one of the four visual light transmittance (VLT) values (60 %, 18 %, 6 % and 1 %), based on the control system at 71T. There were no overhangs or vertical fins installed to provide a completely un-blocked view from the chamber to the testing panel and to the surrounding view overall. Table 2 summarizes the testing conditions (nine cases) that includes sky conditions, EC glass states (only at 12 pm) and fabric shade types for each testing day.

Table 2. Testing condition summary

Case	1	2	3	4	5	6	7	8	9
Sky condition	Overcast	Clear							
EC glass VLT state	60%	60%	60%	18%	6%	1%	1%	60%	6%
	60%	60%	60%	60%	18%	18%	18%	60%	18%
	60%	60%	60%	60%	60%	60%	60%	60%	60%
Fabric shade	No	No	Dark	Dark	Dark	Dark	No	Light	Light
Note		Baseline							

View and visual comfort measurements – HDR imaging. The HDR imaging technique involves taking several digital photographs of the same scene, each with a different exposure to record a difference level of brightness in the scene (Eismann et al. 2010). Two types of cameras were used for these measurements. For the typical rectilinear scene measurements, we used Canon A570IS point-and-shoot cameras. The original camera firmware was modified using publicly available software (“A570 IS” 2017) to automate image capture. For the primary measurements, we used Canon EOS 60D SLR cameras with Sigma EX 4.5 mm f/1.8 fish-eye lenses, controlled by a computer running Mac OS X custom software with light sensors for continuous calibration. In all cases, we operated cameras while they were mounted on lightweight tripods.

We combined HDR image data from the cameras to produce images mimicking human visual response. Based on the HDR images, each luminance map was then further condensed into a single number representing Daylight Glare Probability (DGP), a metric for visual comfort (Wienold and Christoffersen 2006). DGP values range from 0 to 1 and represent the percentage of people who would experience disturbing glare when viewing the scene captured in a luminance map. Table 3 shows the correspondence between DGP levels and qualitative perceptions of glare.

Table 3. DGP classifications (Wienold and Christoffersen 2006)

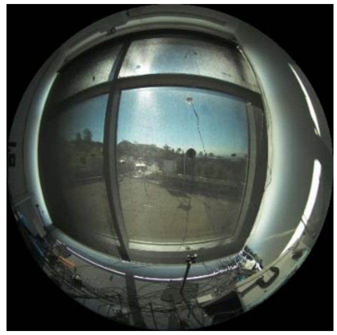
DGP	Qualitative interpretation
< 0.35	Imperceptible glare
0.35 to 0.40	Perceptible glare
0.40 to 0.45	Disturbing glare
> 0.45	Intolerable glare

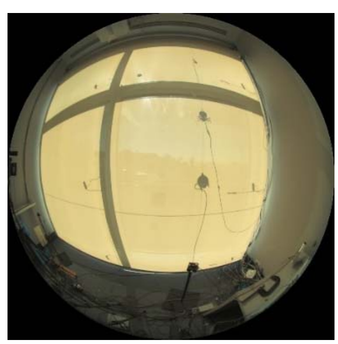
5.2 Pilot Study Results and Findings

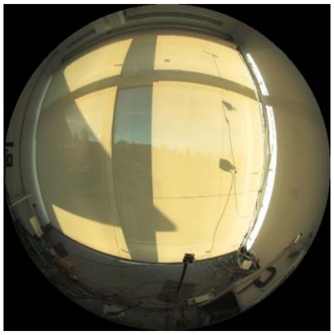
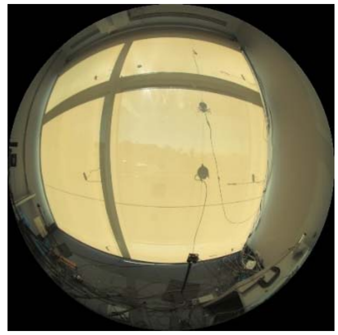
Fish-Eye Lens HDR Images. A fish-eye lens is a wide-angle lens that produces strong visual distortion intended to create a wide panoramic or hemispherical image (Eismann et al. 2010). The lens can take in nearly everything in front of the camera that is included in photographs such as the sky above, the ground below and the surrounding scene on the left and right. We collected HDR images with a fish-eye lens at 5-minute intervals, but the following section only shows the images taken at 9 a.m., 12 p.m., and 3 p.m. as the representative scenes on the testing days. Each image has the DGP value as well as the Vertical Illuminance (VI) value, indicating the sun and sky condition when the images were taken by the camera.

Table 4. Fish-Eye lens HDR Images

	9 a.m.	12 p.m.	3 p.m.
CASE 1. Baseline under overcast sky			
			
DGP	0.14	0.34	0.26
VI	140 lux	2170 lux	1020 lux
CASE 2. Baseline under clear sky			
			
DGP	0.36	0.53	0.53
VI	2070 lux	5840 lux	9120 lux
CASE 3. Dark Shade			
			

DGP	0.21	0.22	0.18
VI	140 lux	370 lux	290 lux
CASE 4. Dark Shade + Electrochromic Glass (VLT:18%, 60%, 60%), 12PM only			
			
DGP	0.23	0.17	0.18
VI	550 lux	250 lux	300 lux
CASE 5. Dark Shade + Electrochromic Glass (VLT:6%, 18%, 60%), 12PM only			
			
DGP	0.18	0.06	0.12
VI	130 lux	110 lux	140 lux

CASE 6. Electrochromic Glass (VLT:1%, 18%, 60%), 12PM only			
			
DGP	0.33	0.33	0.53
VI	370 lux	1820 lux	7840 lux
CASE 7. Dark Shade + Electrochromic Glass (VLT:1%, 18%, 60%), 12PM only			
			
DGP	0.18	0.09	0.14
VI	130 lux	130 lux	140 lux
CASE 8. Beige Shade			
			
DGP	0.23	0.53	0.21

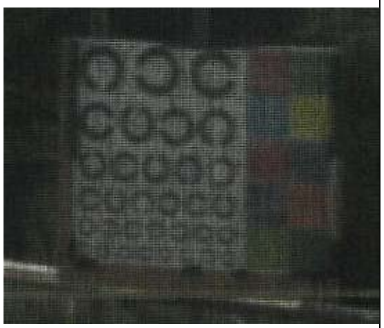
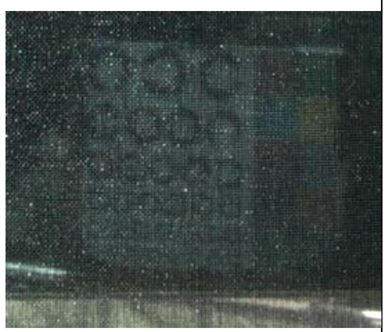
VI	2000 lux	3650 lux	2290 lux
CASE 9. Beige Shade + Electrochromic Glass (6%, 18%, 60%), 3PM only			
			
DGP	0.47	0.53	0.27
VI	2170 lux	5600 lux	1990 lux

One of the findings clearly evident from the fish-eye view images is the difference between the dark shades (Cases 3 to 7) and the light shades (Cases 8 and 9). Cases 8 and 9 clearly showed that the light fabric shades did not permit much of a view to the outside even though they had a better openness factor (5 %) compared to the dark fabric shades (3%). This is consistent what Konstantzos et al. (2015) found in their study. This is due to inter-reflections of the sunlight in the fabric and higher visual transmittance (even though the dark and light fabric shades had exactly the same solar transmittance).

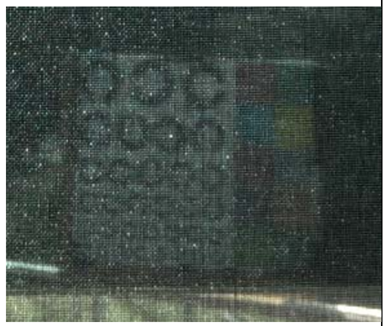
The difference between the two baselines Cases 1 and 2 was the sky condition. When the sky was clear (Case 2), DGP values were in the intolerable range (exceeding DGP 0.45). Under an overcast sky (Case 1), the DGP values were less than 0.35 all day, indicating an imperceptible glare. The only difference among the images at different times of day was the overall color of the scene: bluish in the morning compared to yellowish in the afternoon. In Case 3, the dark fabric shade significantly reduced both the DGP and VI as expected, but we were still able to see outside. Changing the VLT values of the EC glass (Case 4,5 and 7) lowered both the DGP and VI values, but it was not necessary as the DGP value was already below the imperceptible range in Case 3, and reducing the VLT then reduced the brightness and clarity of the view to outside.

Rectilinear scene HDR images. Camera lenses have what is called an 'angle of view', which is the limit within which the subject can be photographed in accordance with the focal length and the imaging format, similar to human vision (Eismann, Duggan, and Grey 2010). The angle of view of standard lenses, which is thought to be near that of the human eye, is approximately 50°, while that of a 15mm fish-eye lens is 180°. Therefore, we also used a standard lens to capture the target image more closely. Rectilinear scene study was only performed on Cases 4 to 9 due to the late introduction of the rectilinear scene HDR camera in this study. The cropped images in Table 5 show how the testing panel looked like under various building envelope layers and sky conditions at three different times on the testing days. The following HDR images represent the view to the target panel when the testbed deployed both dark fabric shade and EC glass (VLT 18%, 60%, 60%) (Case 4), EC glass (VLT 1%, 18%, 60%) only (Case 6), both dark fabric shade and EC glass (VLT 6%, 18%, 60%) (Case 5), and both dark fabric shade and EC glass (VLT 1%, 18%, 60%) (Case 7).

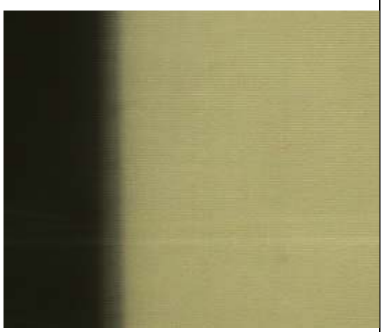
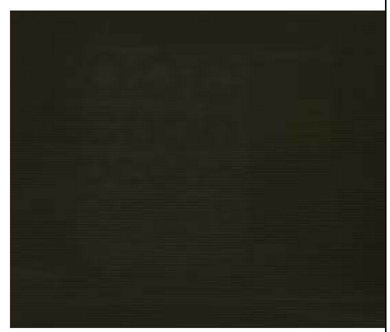
Table 4. Rectilinear scene HDR images

9 a.m.	12 p.m.	3 p.m.
CASE 4. Dark Shade + Electrochromic Glass (VLT:18%, 60%, 60%), 12PM only		
		
CASE 5. Dark Shade + Electrochromic Glass (VLT:6%, 18%, 60%), 12PM only		
		
CASE 6. Electrochromic Glass (VLT:1%, 18%, 60%), 12PM only		
		

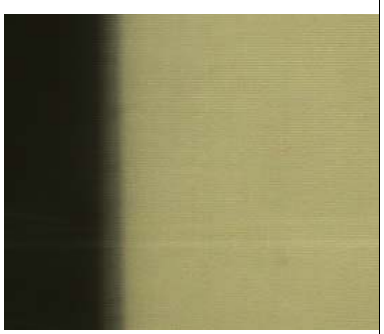
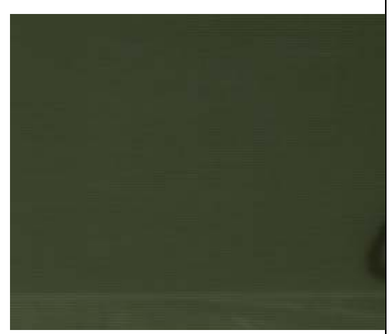
CASE 7. Dark Shade + Electrochromic Glass (VLT:1%, 18%, 60%), 12PM only

CASE 8. Beige Shade

CASE 9. Beige Shade + Electrochromic Glass (6%, 18%, 60%), 3PM only

In the close-up panel scenes, the 9 a.m. figure for Case 6 represents a baseline (no VLT shifts of EC glass and no fabric shades). When we compare Case 6 with different cases, a few interesting findings become clear. First, among the noon-time images, the direct sun caused noise effects from the fabric shades' inter-reflection (Cases 4, 5 and 7). In early November, direct sun hit the south-facing window at a solar altitude angle of approximately 45° and caused white-spotted noise at the partial area of the fabric shade (where we see the target panel through). This significantly impacted the clarity of the view of the target panel. It was clear that the noon-time images had a greater brightness (VI value) than the others, but the view to the target panel was more obscured by the effect of the direct sun. Hence, the Landolt-C figure and the color patches on the target were more difficult to read.

Second, comparing the VI values of the 9 a.m. and 3 p.m. images revealed that the overall panel illuminance was greater at 9 a.m. than 3 p.m. (which indicated a brighter sky condition), so the target panel was slightly clearer at 9 a.m.

Third, the images from Cases 5 and 7 did not show much difference in terms of view clarity to the target panel. The only difference was lower DGP and VI values due to the VLT states on the top band of the glazing system. Similarly, there was not much difference in view clarity between Case 4 and Case 5. Lowering the VLT from 60% to 18% reduced DGP values significantly, but this was not necessary as the DGP values were successfully dropped to imperceptible range in Case 4 (dark fabric shade only).

6. LIMITATIONS AND FURTHER WORK

This report proposes a method for analyzing the view through building envelope layers, while using the HDR imaging process as a proof-of-concept test. There are several limitations to this assessment method. The HDR images address the visibility of targets, but do not fully represent exactly what an occupant sees (as it is through a camera that has different visual image processing compared to the human vision system), how they perceive the external view (a subjective assessment), and its consequent effects on their psychological state. In order to ensure the applicability of this method, further human subject testing is required. This could allow us to establish a more rigorous statistical link between HDR image results and the occupants' visual perceptions with statistical quantifications.

Additional computational methods would be helpful to analyze how much the HDR images are obscured under given conditions (i.e., shades, sky condition, and VLT of glass) and how color patches are different under various façade layers. Analyzing HDR images should be standardized by using a computerized framework that can easily evaluate different building envelope layers for view clarity. The computerized algorithm could give us a potential opportunity to convey quantifiable information (i.e. edge detection rate, the percentage difference between the baseline and the testing image), which could then be correlated with the human subjects' responses. The following sections describe opportunities for further expansion of the scope of this study.

6.1 Human subject testing

The data from the HDR images and illuminance sensors should be correlated with occupants' perceptions so that it can ultimately be used as a standard evaluation method for fabric shades and different glass coatings that result in various VLT values. In order to establish the link between our proposed method and a human response, we would propose an additional lab study that simultaneously involves HDR image acquisition, illuminance measurements and human subject testing with a questionnaire (the possible questions are below). This would confirm the correlation between the method of this pilot study and the perception of occupants. In conducting the proposed study, it is critical to establish visual thresholds (what the maximum obscured rate that can be perceived as view is) such that occupants perceive the images as a 'view to outside' or 'connection to the outside'. Two main objective measures would be how many rows human subjects could observe in the Landolt-C chart in the testing panel and how accurately they could perceive the colors in the palette. Additional questions about subjective measures could be asked, for example about visual preference of view contents, satisfaction level of the view, or visual comfort.

Examples of questions for the future human subject testing and the computerized image analysis framework are shown below:

Objective questions

- Which outside objects can you distinguish from the following: cars, trees, the dome, buildings?
- Observe the target panel, and count how many C symbols you can clearly distinguish between each line?
- 1st line: 2nd line: 3rd line: 4th line: 5th line: 6th line: 7th line:
- Pick the colors in the survey palette that are most similar to the color patches that you see in the target panel.

Subjective questions

- How clear is the outside view through the window (and shade)?
- Can you tell the sky conditions outside by what you can see (sunny/cloudy/extends of clouds)?
- How would you rate the vividness of the view to outside?
- Are you satisfied with the view conditions (color and clarity)?

6.2 Computerized HDR image analysis framework

Edge detection (contrast sensitivity analysis). The Landolt-C chart consists of a ring with one open side (similar to the letter C). The opening can be at various positions (i.e., left, right, bottom, or top). The base case HDR image should have clear contrast when compared to the images with fabric shades and/or various VLT states. In order to compare how the images are obscured due to building envelope layers, we can use an image analysis technique called 'edge detection'. One technique, Canny edge detection (Canny 1986), is used to extract structural information from different visual objects. This technique has been widely applied to various computer vision systems (see the Appendix for more information). The Canny edge detector could be applied to detect a C figure. Human subjects could specify whether they see the shape as a C figure or not, based on the ground truth image (i.e. baseline edges) that the detector generated. With these results, we could analyse how the detection tool can be correlated to the way that human subjects detect the figures. Ultimately, we could determine whether the HDR image method, used in conjunction with the computerized edge detection tool, could work as a proxy for the view clarity measurements under various shading systems and environmental conditions. Something important to remember when using this tool is that that the inputs in the code should be set carefully. The Canny algorithm contains a number of adjustable parameters that can affect computation time and effectiveness. Thompson et al. (2017) used this algorithm to compare the ground truth edges in the base HDR image and the simulated HDR images with a low-vision filter. The computerized method they used clearly demonstrates which luminance boundaries are not shown in the testing images, compared with the ground truth images. Their approach to simulating loss of acuity and contrast sensitivity on visibility is an expansion of work by Peli (1990) and Menendez (1995), who described a method for transforming images to simulate the visibility associated with a particular contrast sensitivity function. Thompson's team (2017) parameterized Peli's method by using standard clinical measures of acuity and contrast sensitivity and by validating the parameterization by using a letter recognition task.

Color-space distance (chromatic sensitivity analysis). The differences among the colors in the HDR image's target panel is quantifiable. Color-space distance measures the distance between two colors. It allows for a quantified examination of pixels in different images. CIE XYZ color space (defined by the International Commission on Illumination (CIE)) is widely used in scientific work (Wyman, Sloan, and Shirley 2013). A derivative of this color space, the CIE XYZ color space, is used as a way to graphically present chromaticity. In our study, the color patches consist of ten different colors. By analyzing color space distance through a computer algorithm, we can assess how the colors in the base case differ from the colors in the testing cases. We can then transform the input images into the CIE XYZ color space; this can show color distances between colors in the base case and colors in the testing case.

6.3 General discussion

There are various aspects to consider when examining the view to the outside, and the potential for future research in this field is vast. As a start, it could be valuable to simply categorize and prioritize the factors that would increase our understanding of how occupants perceive view. Some fundamental questions we could ask include:

- How do occupants define view in terms of content? Does view refer only to the scenery outside? Or do occupants perceive "view" as including other architectural elements?
- How does color (hue, saturation etc.) impact the view sensation of occupants?
- How do mobility and dynamics of objects outside (such as cars and people) contribute to the occupants' perception of view?
- What architectural elements could make better view perception?
- What supplements could have a similar effect on the occupants?

7. CONCLUSION

This project attempted to find a link between daylight and human visual performance in relation to the building envelope, first broadly, and then focused on view clarity. In a literature review, we summarized information on current daylight metrics used in building industry, typical human performance measure used in daylight related research, and a gap between daylight rating systems and other building envelope-related aspects such as view. We also provided an overview of research methods on human performance measurements in relation to daylight and view, including subjective and objective measurements.

The experimental study done at LBNL's Windows Testbed showed that the light fabric shade restricted the view to the outside, even though it had a better openness factor compared to the dark fabric shades. This was due to more inter-reflections of the sunlight in the fabric, causing higher visual transmittance (even though they had exactly the same solar transmittance).

The study revealed that view clarity through a fabric shade could be significantly reduced when there was direct sun in the field of view. The direct sun caused white-spotted visual noise at the partial area of the fabric shade. Hence, the view was more obscured by the effect of the direct sun even though the case had a greater vertical illuminance than the others. The results from the pilot study shows the potential of HDR photography techniques to be used for a standard view clarity rating method, with support from further human subject testing and advanced computational image analysis algorithms.

8. APPENDICES

8.1 Summary of daylight metrics

(also available online: https://berkeley.app.box.com/file/221915252511)

Daylight Metrics				Definition	Inventor	Pros	Cons	Calculations	Related Building Codes and Standards
Daylight Sufficiency	Static	Sing Point-In-Time Illuminance (SPT)		a workplane illuminance calculation for one time of the year		Very specific	represent only an instant in time	measurements, computer simulations based on CIE skymodel	LEED v3
		Daylight Factor (DF)		the ratio of the internal illuminance at a workplane point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky.	Waldram, 1909	quick calculation under overcast sky, give a general report of the average daylight conditions	does not depend on window orientation or sun position, missing advanced daylighting system such as sun re-directing film and light shelves.	measurements, computer simulations based on CIE skymodel	LEED v2.2 BS 8206-2 CIBSE SLL Lighting Guide BRE Reports
	Dynamic	Daylight Autonomy	Daylight Autonomy (DA)	the percentage of year when a minimum illuminance requirement is met by daylight alone (redefined: within occupied hours)	Swiss norm (Association Suisse des Electriciens,), 1989 Reinhart and Walkenhorst, 2001(re-defined)	The first and simplist dynamic daylight metrics	seek for hard values such as 300lx, no partial credit for 299lx etc.	computer simulations using meteorological datasets that cover sun and sky conditions over the whole year	UK Education Funding Agency (EFA) BREEAM
			Continuous Daylight Autonomy (cDA)	basic modification of Daylight Autonomy. Continuous Daylight Autonomy awards partial credit to time steps when the daylight illuminance lies below the minimum illuminance level	Rogers, 2006	awards partial credit to time steps when the daylight illuminance lies below the minimum illuminance level	more complex		
			Zonal Daylight Autonomy (zDA)	all sensor hours in a space that meet or exceed the threshold.	HMG and IES Daylight Comm	simplified methods to compare the performance of three different options; blinds open, blinds operated, blinds closed	more complex		
			Spatial Daylight Autonomy (sDA)	the percentage area of a space which meets a minimum daylight illuminance for a specified fraction of operating hours.	HMG and IES Daylight Comm	includes spatial requirements	more complex		IES LM-83LEED v4British Standard Institute CE
Visual Comfort/Glare	Illuminance-based	Annual Sun Exposure (ASE)		the maximum number of hours per year each task-level sensor will see direct sunlight >1000 lux, given local weather conditions, exterior obstructions	HMG and IES Daylight Committee	Quick, easy to calculate based on annual illuminance calculation	taking account for blind effect is tricky glare prediction with illuminance is not as accurate as luminance-based calculations	computer simulations using meteorological datasets that cover sun and sky conditions over the whole year	IES LM-83LEED v4
		Maximum Daylight Autonomy (maxDA)		the percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions are present.	Rogers, 2006	proposed wtih cDA	more complex		
		Daylight Uniformity		metrics are common in the specification of electric lighting, but vary in format and criteria with different application types. Min/max and min/average illuminance ratios are common for indoor and outdoor lighting respectively	HMG and IES Daylight Committee	Shows the distribution of the light, One of the light quality measure (more for artificial lighting)	less applicable unless use luminance data which requires a specific time and position of the view.	computer measurement, simulations	
	Luminance-based	CIE Glare Index (CGI)		Refer to 2.3.4 'Luminance-Based Glare Prediction Indices'					
		Daylight Glare Index (DGI)							
		Unified Glare Rating (UGR)							
		Daylight Glare Probability (DGP)							
Combined Metrics	Dynamic and Illuminance-based	Useful Daylight Illuminance (UDI)		a modification of Daylight Autonomy providing too high and too low daylight levels.	Mardaljevic and Nabil, 2005	Shows too bright and too dark space at the same time	useful' range (100-2000 lux) could be vary where people can move around to avoid it, UDI is less relevant	computer simulations using meteorological	The UK Education Funding Agency design brief for new schools

8.2 Testing Panel

Landolt-C is the standard optotype for acuity measurement in most European countries. A Swiss-born ophthalmologist, Edmund Landolt, developed the method. The Landolt-C chart consists of a ring that has a gap, thus looking similar to the letter C. The gap can be at various positions (usually left, right, bottom, top and the 45° positions in between) and the task of the tested person is to decide on which side the gap is. The size of the C and its gap are reduced until the subject makes a specified rate of errors. The minimum perceivable angle of the gap is taken as a measure of the visual acuity and the stroke width is 1/5 of the diameter, and the gap width is the same (Danilova and Bondarko 2007).

8.3 Canny Edge Detection Algorithm

Canny edge detection (Canny 1986) is a technique to extract structural information from different vision objects. Among the edge detection methods developed so far, the Canny edge detection algorithm is one of the most strictly defined methods that provides good and reliable detection. Owing to its optimality to meet the three criteria for edge detection and the simplicity of the process for implementation, it became one of the most popular algorithms for edge detection (Rong et al. 2014).

Figure 10. Canny Edge Detection Examples (Martin et al, 2004)

8.4 Color distance measurements

Color-space is the basis of calculating the difference between two colors. Using the specific coordinates defined by a color model, one can extract the percentage of color differences between two pixels (or averaged color in a localized part of an image). For the color distance analysis, we can use CIE XYZ color space that is the mathematical limit of human vision (RGB color model is more common, but it does not cover what human eyes can perceive) (Kuehni 2003). We can calculate the distance between to reference colors and quantify how far they apart from each other. Computer algorithms can automate the large set of HDR images to compare the colors that appear in the targets. One of the major limitations of this method is the fact that the calculated numbers that represents the distance between two colors do not exactly match up with what human vision perceives (rather based on a theoretical, but imaginary distance). Therefore, human subject testing is required to establish the link between the color distances and the actual human perceptions.

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