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THE SOLAR HELIODON: PHYSICAL SIMULATION OF DYNAMIC DAYLIGHTING CONDITIONS IN SCALE ARCHITECTURAL MODELS FOR SUBJECTIVE AND OBJECTIVE HUMAN-FACTORS EVALUATION

Kyle Konis, Ph.D[1]
[1]University of Southern California

ABSTRACT

This paper describes the design, operation, and demonstration of the Solar Heliodon, a novel mechanical instrument developed to enable automated simulation of interior daylighting conditions with physical architectural models using the sun as a light source. An experiment involving two physical models, one with angularly-selective complex fenestration and the other with a holographic window film, is performed to illustrate the applicability of the instrument for enabling subjective and objective human-factors evaluation of optically complex daylighting design concepts. Benefits and limitations relative to contemporary computational approaches to model generation, simulation, and evaluation are discussed.

INTRODUCTION

The thoughtful control of daylight in buildings is fundamental to the discipline of architecture. Light plays a central role in human perceptual understanding of space, via the rendering of surface color, material texture, and spatial qualities. The admission of daylight, in particular, can serve as means of spatial orientation and as an indication of time of day and outdoor weather conditions among other perceptual cues which serve to support human psychological needs in buildings. Architectural design objectives regarding the use of daylight are dependent on the program, climate, and physical context of the project, as well as the subjective intent of the designer. Quantitative performance metrics are becoming increasingly common for energy, Indoor Environmental Quality (IEQ), and occupant health/well-being objectives. However, daylighting design intent, from the perspective of an architect, remains fundamentally concerned with achieving a particular perceptual experience for building occupants. As a process which is dependent on design intuition, designers are often unable to specify the quantitative criteria that would differentiate the "performance" of various design options. Therefore, methods are needed which incorporate human perception and subjective evaluation to determine if a given design option meets design intent. Feedback relating design intent with perceptual outcomes can also help to train and refine design intuition. Perceptual methods are particularly important in early-stage design, where fundamental decisions impacting daylighting availability are made.

Modelling methods involving generative, analytical, and representational techniques are central to the daylighting design process. The study of physical architectural daylight models under real sun and sky conditions using direct physical observation of internal lighting conditions (often supplemented with physical measurements) has historically served to inform design decision-making. However, in both contemporary practice and in academia, daylighting analysis is becoming increasingly driven by computational processes. Advances in computing have enabled the capability to model complex glazing and fenestration systems (LBNL, 2019), the development of Climate Based Daylight Modelling techniques to quantify daily and seasonal availability of daylight (Mardaljevic, 2006), and multi-spectral simulation techniques to model the non-visual effects of light (Solemma LLC, 2019) among many others.

Computational modelling and simulation techniques enable both subjective (i.e. visual / perceptual) and quantitative modes of analysis. Subjective assessments typically involve the observation of rendered (i.e. static) images on a visual display terminal (e.g. LCD/LED screen). More recently, Virtual Reality (VR) techniques using VR headsets have been developed (Rockcastle, 2017). Quantitative methods rely on performance metrics which typically summarize global horizontal illuminances on a theoretical workplane or patterns of luminance observed from specified viewpoints. Performance metrics commonly used in analysis are derived from human-factors studies focused on visual task performance, uniformity, and visual comfort (i.e. avoidance of glare). More recently, perceptual metrics have been proposed (Rockcastle et al., 2016) which correlate lighting quantities with subjective assessments.

One of the central challenges of computational modelling is that the screen-based representations of light (e.g. LCD and LED screens) have less dynamic range compared with the real luminous scenes they are intended to represent. For example, the maximum screen luminance of an LCD or LED screen does not exceed 2000 cd/m^2. In comparison, the luminance of a surface under direct beam radiation can exceed 100,000 cd/m^2 and the luminance of the sun is about 1.6×10^9 cd/m^2 at noon. Additionally, screen-based methods lack spatial depth, and are often static. Challenges associated with measuring and characterizing the light-scattering properties of complex materials and systems further limits the fidelity of computational/screen-based analysis approaches. At a more basic level, a design approach driven by reliance on quantitative metrics and screen-based representations adds a layer of abstraction between the designer and the project that requires a set of assumptions to be made which may lead to misleading outcomes.

This paper describes the design, operation, and demonstration of the Solar Heliodon, a novel instrument developed to enable automated simulation of interior daylighting conditions with physical architectural models using the sun as a light source. Heliodon devices have been developed in a variety of forms to support prediction of solar conditions in architectural design, with the first example (to the author's knowledge) published in 1932 (Dufton and Beckett, 1932). Fundamentally, a heliodon consists of a plane and a light source, where the orientation of the light source with respect to the plane can be adjusted to simulate the position of the sun for a given latitude and time of year. Typically, an electrical light source is moved in a circular arc around a static model (e.g. Knowles, 2019; Pajek et al. 2018). Examples of instruments capable of using the sun as a light source include a desktop heliodon (Cuttle, 1974), the repurposing of a cement mixer apparatus as a tilt table used in conjunction with a digital video camera (Lam Partners, 2009), and a device made from repurposed precision machining components (Cheung et al., 1999). Prior to computational simulation methods, heliodons were commonly used to study the hourly and seasonal variation in sunlight penetration and to quantify the number of hours per year a given surface received sunlight. More recent applications have focused on visualization of dynamic changes in interior daylight distribution (e.g. Lam Partners, 2009).

The instrument presented in this paper is designed with the objective of enhancing the capability of designers to perform subjective perceptual evaluation and objective quantitative analysis of dynamic daylighting conditions during the design process using physical architectural models. The instrument can be programmed to automatically position a physical model at a precise angle relative to the sun, enabling the simulation of daily and seasonal variations in sun angle. A central advantage over computational approaches is the ability to directly perceive the luminance patters and spectral conditions produced by design options under real solar conditions (as well as how these factors change with sun angle) rather than rely on proxy screen-based representations or quantitative performance metrics to assess performance.

Physical models can also be monitored using an automated High Dynamic Range (HDR) enabled camera to record luminance maps and a spectrometer to measure the Spectral Power Distribution (SPD) of interior daylighting conditions to place quantitative performance metrics in context with the outcomes of the designer's own perceptual evaluation. The instrument is particularly applicable to evaluation of architectural daylighting concepts which utilize complex fenestration systems, such as angularly-selective fenestration, and designs which rely on optically-complex materials where the light-scattering and spectral properties are not described through physical measurements or a function definition and thus not possible (or overly burdensome) to simulate using a computational approach.

SOLAR HELIODON

The following sections of the paper documents the design, operation, and demonstration of the Solar Heliodon to enable automated simulation of interior daylighting conditions with physical architectural models using the sun as a light source.

The Solar Heliodon (**Fig. 1**) is a mechanical instrument which automates the physical simulation of architectural daylight models under real sky conditions. The Solar Heliodon was conceived to enhance the potential of human visual perception as a diagnostic tool in contemporary processes of daylighting design and analysis. Unlike conventional heliodon devices, which typically move an electrical light source in a circular arc around a static physical model, the Solar Heliodon animates a physical model in relation to direct beam radiation from the sun to reproduce the daily and seasonal movement of sunlight and shadow patterns. Lighting conditions can be directly observed for subjective evaluation (e.g. **Fig. 1**) as well as quantified using devices for objective lighting measurements such as High Dynamic Range (HDR) imaging.

Figure 1 The Solar Heliodon in use in a daylit space (indoors). Note that the instrument is primarily intended for outdoor applications, but can also be used indoors (as shown) when direct beam radiation is available. The change in spectral quality of the light transmitted through glass should be considered.

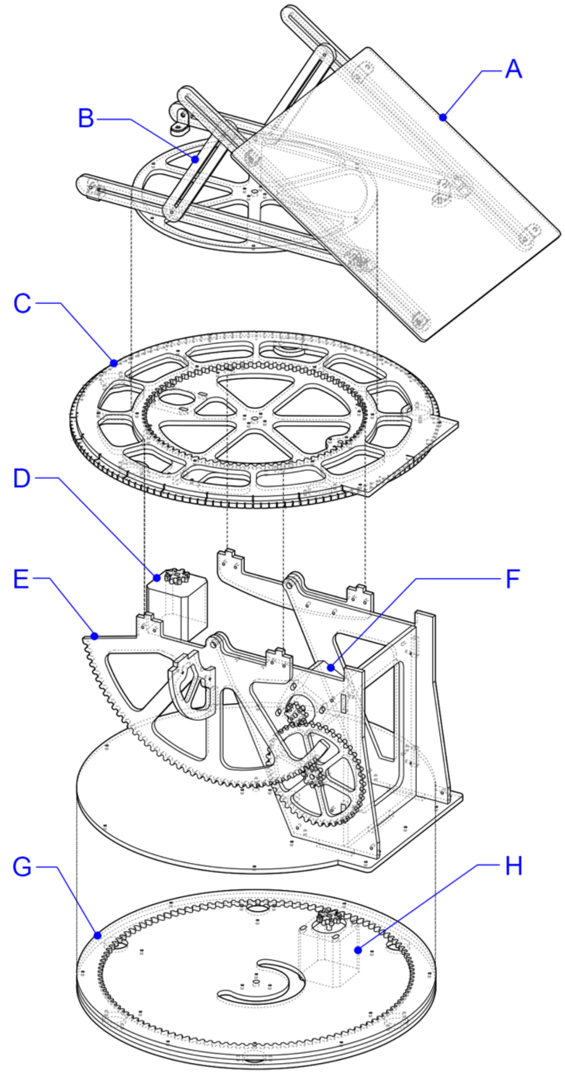

Figure 2 Exploded isometric view of the Solar Heliodon showing (A) model base plane, (B) latitude adjustment, (C) hourly adjustment, (D) stepper motor, (E) seasonal adjustment in solar altitude angle, (F) stepper motor, (G) sun-tracking adjustment, and (H) stepper motor.

The device (**Fig. 2**) is constructed from waterjet-cut aluminum components and consists of 4 sections: a motorized rotating base plate used to keep the device oriented towards the sun (G), a motorized rotating component (E) used to simulate seasonal adjustments in sun position, a motorized rotating component used to control the apparent solar azimuth angle of the model based plane (C), and the model base plane (A), which is manually-adjusted (relative to C) prior to operation to define the desired latitude.

The Solar Heliodon is controlled using a programmable microcontroller (Arduino Uno) which interfaces with two motor controllers (Adafruit Motor/Stepper/Servo Shield) and a clock (Adafruit DS1307 Real Time Clock) to control three high-torque hybrid stepping motors (NEMA 23, 1.8° step angle (200 steps/revolution), 14 kg-cm (190 oz-in) holding torque) (**Fig. 2**, D, F, H).

Once a physical model has been attached to the model plane (**Fig. 2, A**) and the desired latitude established (**Fig. 2, B**), The Solar Heliodon is operated by manually rotating the device's base so that the horizontal axis of the device is in alignment with the current solar azimuth position. The device then uses the onboard clock to automatically calculate the current (i.e. real) solar altitude angle following the process for solar position calculations using the Arduino Uno developed by Brooks (2015), which uses the equations from Meeus (1999). Once the solar altitude angle is known, any day of the year can be simulated by adjusting section E (**Fig. 2**) relative to the real solar altitude angle to simulate a given day (e.g. winter solstice) and then rotating section C (**Fig. 2**) to simulate the daily motion of the sun on that day. Incremental rotational adjustments are made at the base of the instrument (**Fig. 2, G**) to maintain alignment with the solar azimuth. Hourly and sub-hourly marks are indexed on section C (**Fig. 2**) to visually indicate the time of day for the current simulation. An example program may involve the simulation of each hour (e.g. 6:00 – 18:00) for each month between the winter and summer solstices.

The instrument is designed to accommodate a digital camera enabled for High Dynamic Range (HDR) imaging (Canon EOS M3) to automatically acquire images at regular intervals throughout the simulation process. The capability to acquire physical lighting measurements concurrent with human subjective evaluations is beneficial for enabling perceptual experiments which seek to correlated lighting quantities with subjective assessments.

The following sections of the paper present an experiment conducted to demonstrate the applicability of the Solar Heliodon for evaluating real interior lighting conditions produced by physical scale architectural models incorporating optically-complex elements. Two test models, each 18cm x 28cm x 36cm in size, were constructed and simulated using the Solar Heliodon using a latitude setting representative of a site located in Los Angeles, California. The first model, (**Fig. 3**, left) represents a simple circular skylight aperture glazed with an optically-complex light redirecting film. The film used in the experiment (**Fig. 4**) is a polyethylene (PET) material (HOHOFILM Chamelon Color Window Film Rainbow Effect Iridescent Window Tint) made by superposition of hundreds of layers of polyester film, which cause the color and intensity of transmitted light to change based on the direction of incident light. The second model (**Fig. 3**, right) is an Angularly-Selective Complex Fenestration System (ASCFS) fabricated from PLA filament using a 3D printer, where the relative transmission of direct and diffuse radiation varies with daily and seasonal changes in sun angle (**Fig. 5**).

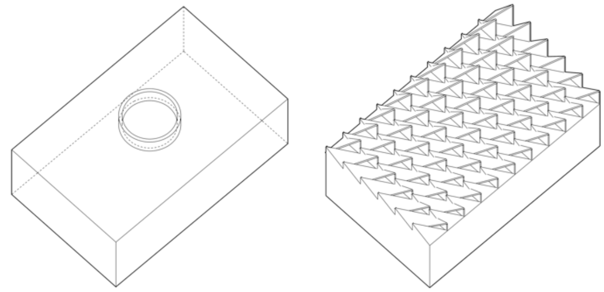

Figure 3 Isometric view of two test models used in simulation. Left: color-changing window film and Right: Angularly-Selective Complex Fenestration System (ASCFS).

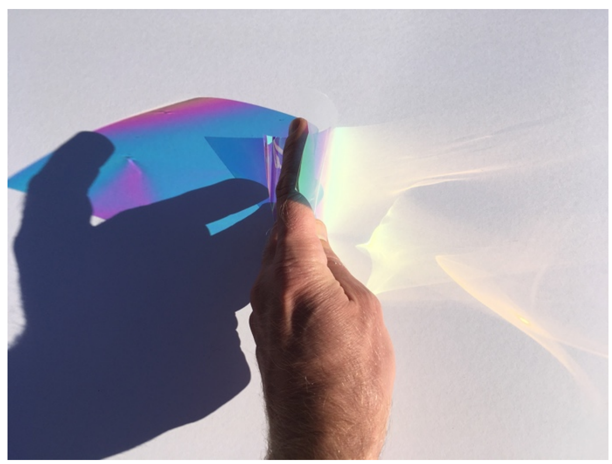

Figure 4 Optically-complex window film (HOHOFILM Chamelon Color Window Film Rainbow Effect Iridescent Window Tint).

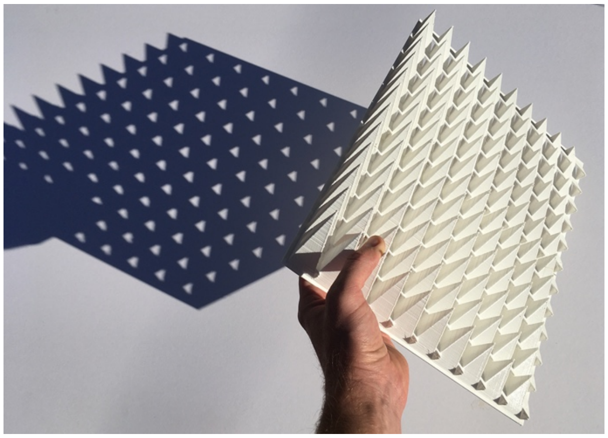

Figure 5 Angularly-Selective Complex Fenestration System (ASCFS).

Each model was simulated from 6:00 – 18:00 at monthly intervals from the winter to summer solstice. An HDR image was acquired at each hour, resulting in 91 observations for each model (e.g. **Fig. 8**). A spectrometer was used to measure the spectral power distribution concurrent with each HDR image. High dynamic range images were postprocessed using the software program Evalglare (source) to calculate a range of existing glare metrics. Spectrometer data were analyzed to calculate photopic illuminance (lux, referred to in this paper as "pLux"), Equivalent Melanopic Lux (EML), and the ratio of Melanopic to Photopic illuminance (M/P).

RESULTS AND DISCUSSION

Fig. 6 presents a selected set of HDR images (postprocessed into .tif files using the Radiance *ra_tiff* program and a fixed exposure setting) from the HOHOFILM model, simulating sun positions (left to right) for 12:00, 14:00, 16:00, and 18:00 (apparent solar time) on the summer solstice. Below each image is the corresponding plot of SPD (acquired from the spectrometer) showing the measured EML, pLux and M/P outcomes. The hourly change in color from greenish (12:00) to blueish (14:00), to purplish (16:00) to whiteish (18:00) is the effect of the optical film. Comparison of the SPD results for each observation shows significant variation in the M/P ratio, ranging from as high as 1.96 (blueish) to as low as 0.7 (whiteish). **Fig. 7** presents similar results for the ASCFS model, showing a selected set of HDR images (and corresponding SPD measurements) for the same hourly intervals, but for an equinox solar condition. In comparison to the HOHOFILM model, the ASCFS model produces no visible color variation and results in a more constant M/P ratio, ranging from 0.92 to 0.94. To illustrate the daily and seasonal color variation produced by the HOHOFILM model, **Fig. 8** presents all 91 HDR images acquired during simulation, ordered (left to right) by hour (6:00 – 18:00) and from winter to summer solstice (top to bottom). **Fig. 8** is significant because it demonstrates that both daily and seasonal "tuning" of color using optically-complex materials can be explored using the Solar Heliodon.

Fig. 9 and **Fig. 10** present a falsecolor mapping (yellow color indicates luminances > 20,000 cd/m^2) to visualize luminance intensities and distribution patterns of the observations shown in **Fig. 6** and **Fig. 7** respectively. For comparison, the maximum screen luminance of an LCD or LED screen does not exceed 2000 cd/m^2. Predicted glare outcomes (calculated using Evalglare, (Wienold, J., & Christofferson, 2006) with a glare source definition of glare as 4x the average task luminance) for five existing glare metrics (DGP, DGI, UGR, VCP, CGI) are provided in **Table 1** and **Table 2** respectively. Notably, both models resulted in high levels of predicted glare. However, when observing the interior lighting conditions of both models, the author did not perceive the lighting conditions of either model to be a source of glare discomfort, with the exception of the ASCFS model when direct view of the solar disc occurred.

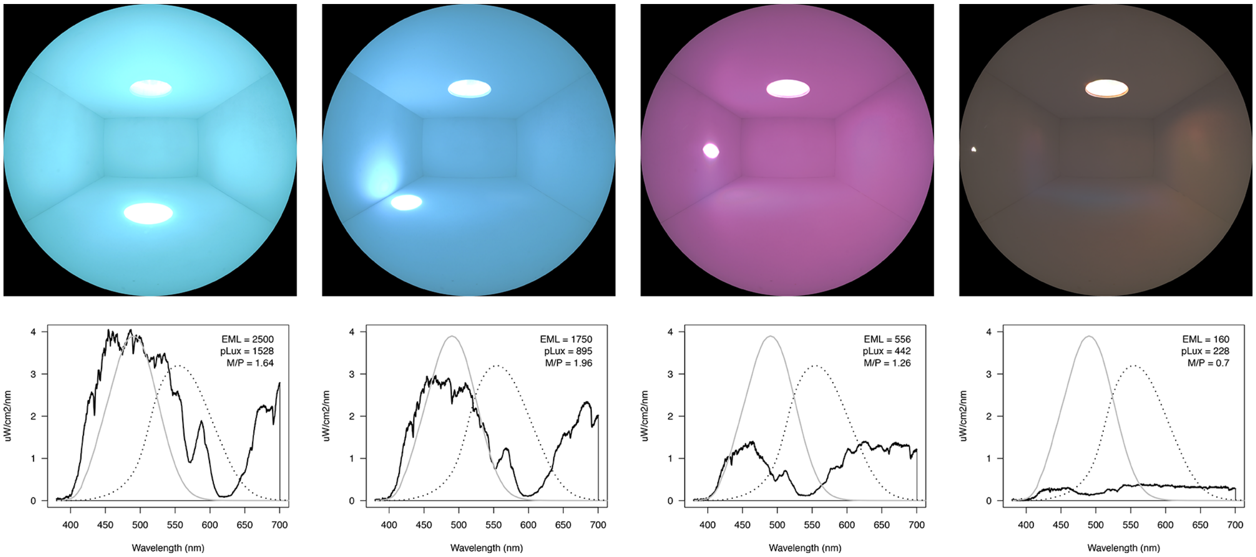

Figure 6 HOHOFILM model sun positions (left to right) for 12:00, 14:00, 16:00, and 18:00 (apparent solar time) on the summer solstice. The hourly change in color is the effect of the optical film.

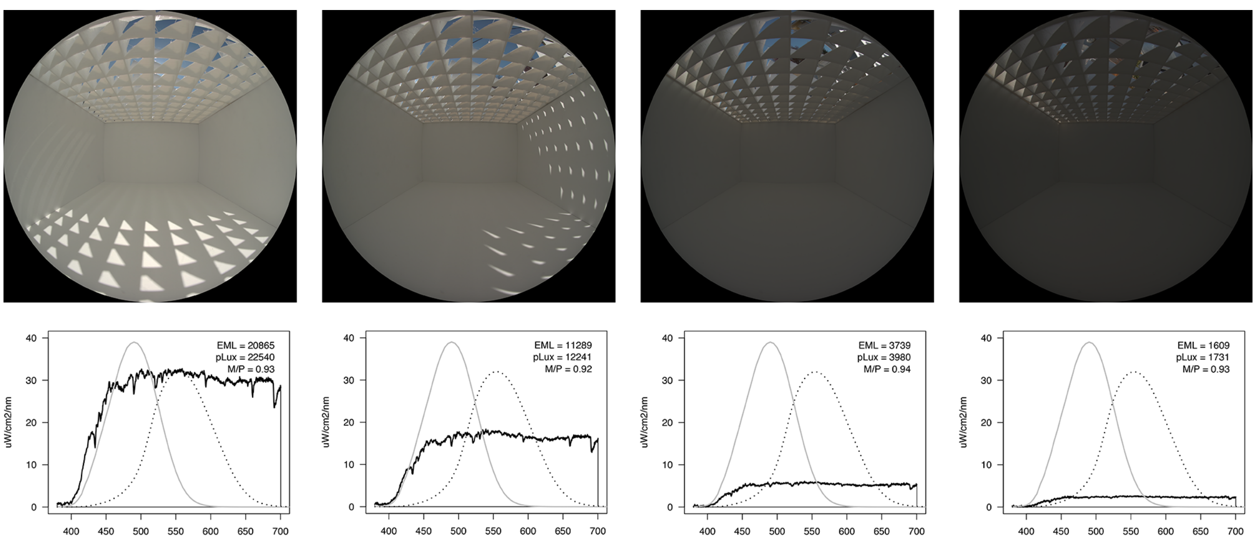

Figure 7 ASCFS model sun positions (left to right) for 12:00, 14:00, 16:00, and 18:00 (apparent solar time) on the equinox.

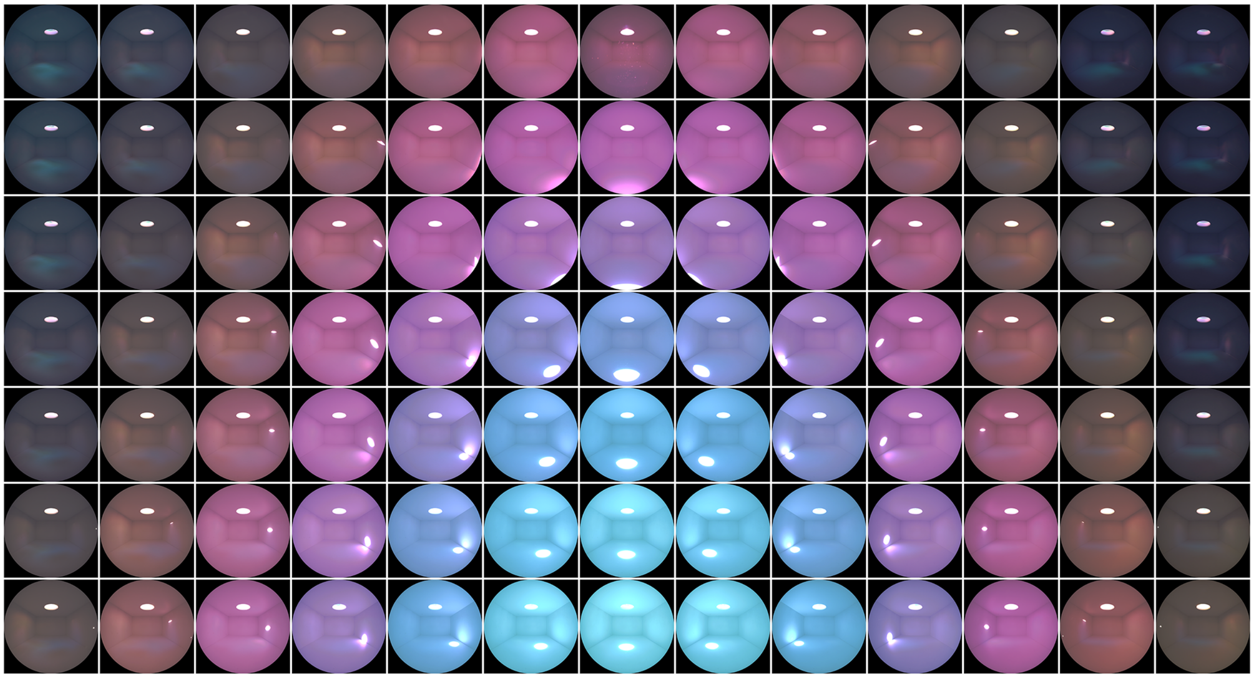

Figure 8 Composite image showing all 91 HDR images acquired for the HOHOFILM model illustrating full daily and seasonal variation in color, ordered (left to right) by hour (6:00 – 18:00) and from winter to summer solstice (top to bottom).

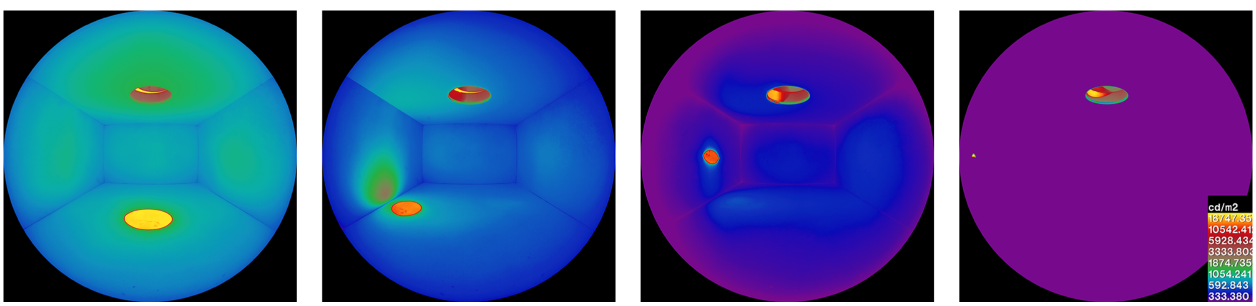

*Figure 9 HOHOFILM model observations from **Fig. 6** with falsecolor scale applied showing luminance distribution (yellow color indicates luminances > 20,000 cd/m^2).*

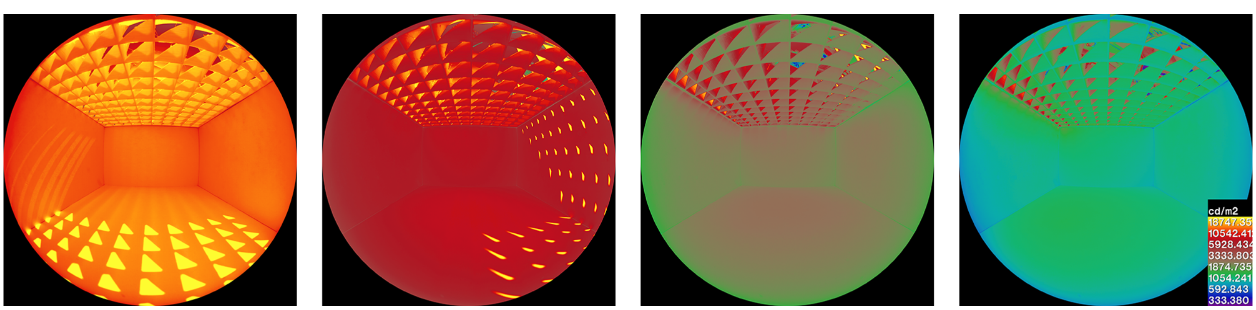

*Figure 10 ASCFS model observations from **Fig. 7** with falsecolor scale applied showing luminance distribution (yellow color indicates luminances > 20,000 cd/m^2).*

Table 1 Model 1 Glare Predictions

	DGP	DGI	UGR	VCP	CGI
A	0.45	21.54	27.45	4.60	33.92
B	0.33	17.89	22.71	26.67	27.63
C	0.27	16.76	20.93	27.61	25.10
D	0.22	12.91	17.47	54.65	20.54

Table 2 Model 2 Glare Predictions

	DGP	DGI	UGR	VCP	CGI
A	1.00	NA	NA	93.30	4.36
B	1.00	6.69	10.24	67.05	14.31
C	0.64	2.93	6.37	91.25	10.51
D	0.38	0.34	3.99	98.31	7.88

CONCLUSION

The Solar Heliodon can enhance the capability of designers to perform subjective perceptual evaluation paired with objective quantitative analysis of dynamic daylighting conditions during the design process using physical architectural models. An experiment was performed to demonstrate the applicability of the instrument to automatically position a physical model at a precise angle relative to the sun, enabling the simulation of daily and seasonal variations in sun angle (**Fig. 8**). A central advantage over computational approaches is the ability to directly perceive the luminance patters and spectral conditions produced by design options under real solar conditions (as well as how these factors change with sun angle) rather than rely on proxy screen-based representations or quantitative performance metrics to assess performance. Additional human-factors research is needed to explore how feedback from high-fidelity physical simulations using the Solar Heliodon may influence design decision-making relative to feedback from screen-based representations for a given set of design options.

The instrument is particularly applicable for the evaluation of architectural daylighting concepts which utilize complex fenestration systems, such as angularly-selective fenestration, and designs which rely on optically-complex materials where the light-scattering and spectral properties are not described through physical measurements or a function definition and thus not possible (or overly burdensome) to simulate using a computational approach. Physical models can also be monitored using an automated High Dynamic Range (HDR) enabled camera to record luminance maps and a spectrometer to measure the SPD of interior daylighting conditions to place quantitative performance metrics in context with the outcomes of the designer's own perceptual evaluation. The capability to pair physical and subjective (perceptual) data using the instrument has the potential to support future human-factors studies.

REFERENCES

Mitchell Brooks, D. (2015). Arduino Uno and Solar Position Calculations. Institute for Earth Science Research and Education.

Cuttle, C. (1974) A desk-top heliodon. Lighting Research & Technology. Vol 6 No 1 1974

Dufton, A. F., and Beckett, H. E., J. Sci. Instrum., 9, 251 (1932).

Knowles, R. (2019). Heliodon. https://en.wikipedia.org/wiki/Ralph_Lewis_Knowles

Lam Partners (2009). Heliodon 4.0.

Mardaljevic J. (2006). Examples of Climate-Based Daylight Modelling.

Meeus, J. (1991). Astronomical Algorithms, 1st English Edition. Willmann-Bell, Inc. Richmond, VA, 1991.

Pajek et al. (2018). Using Heliodon for Solar Building Design Education in the Age of Computer Simulations. International Solar Energy Society. EuroSun 2018 Conference Proceedings

Rockcastle S., Chamilothori K., Marilyne Andersen M. An Experiment in Virtual Reality to Measure Daylight-Driven Interest in Rendered Architectural Scenes. Proceedings of Building Simulation 2017.

Rockcastle, S., Amundadottir, M.L. and Andersen (2016). Contrast measures for predicting perceptual effects of daylight in architectural renderings. Light. Res. Technol.

Solemma, LLC. (2019). Adaptive Lighting for Alertness (ALFA) Software.

Ward G. 1994. The Radiance Lighting Simulation and Rendering System. Proceedings of SIGGRAPH 94, Computer Graphics Proceedings, Annual Conference Series, 459-572.

Wienold, J., & Christofferson, J. (2006). Evaluating Methods and Development of a New Glare Prediction Model for Daylight Environments with the Use of CCD Cameras. Energy and Buildings Vol 38, 743-757.