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OCUVIS: A Web-Based Visualizer for Simulated Daylight Performance

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ABSTRACT

This paper introduces an interactive web-based visualizer for multi-metric daylight simulation results, named OCUVIS. It is able to display simulation-based results for a diverse range of ocular human-centric metrics such as non-visual health potential (nvR_D), daylight-related visual interest (mSC_5) and visual comfort (DGP with Ev), as well as horizontal illumination metrics such as spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE) and Daylight Factor (DF)). To provide a holistic representation of performance across a multi-directional field-of-view, OCUVIS creates an interactive visualization of results over time and across space, linking temporal and 3D graphics. This allows the user to explore the impacts of dynamic sky conditions, view position, view direction and program use on localized and building scale performance. OCUVIS bridges the gap between human and building-scale daylight potential to offer a more holistic and intuitive representation of daylight performance in buildings.

Author Keywords

Daylight simulation; ocular performance; web-based; user interaction; visualization.

1 INTRODUCTION

Daylight offers clear benefits to the energy efficient and healthy occupation of buildings, but due to its variable nature and impacts on both our visual and non-visual systems, a holistic evaluation of performance can be difficult to achieve. While the current state-of-the-art in daylight simulation has embraced annual methods for evaluating illuminance and to some extent glare risk, the development and integration of human-centric analysis methods for health and perception have been slow to take hold. There are several clear reasons for this. First, research focusing on the evaluation of daylight for its impacts on health and perception in buildings has only begun to make the jump from foundational knowledge to applied models in recent years. Second, the evaluation of models related to these human factors relies on time intensive simulations with an array of inputs: light exposure at eye-level, light composition across an occupant's field of view, variability over an annual time series, and variability under various sky conditions. Finally, to assess these responses *throughout* a building, the factors mentioned above have to be evaluated across an array of possible view positions and view directions where an occupant may reasonably be located and change locations over time. As both non-visual and visual performance models evaluate an occupant's ocular exposure to daylight, simulations are computationally expensive and produce a large volume of data that must then be synthesized into a comprehensive and intuitive evaluation [1]. This paper introduces OCUVIS, an interactive web-based visualizer for daylight which was developed to display the simulated ocular daylight performance of human vitality, emotion, and comfort in buildings alongside more traditional horizontal illumination metrics.

1.1 Barriers in visualizing BPS results

Comprehensive and intuitive visualization strategies are very important for the successful implementation of building performance simulation (BPS) methods in the design process. While there are many BPS tools developed for use by architects, a comparative study by Weytjens et al. [2] on the architect-friendliness of several BPS tools found that while no one tool in their study was entirely adequate for assisting the architect's decision-making process, the poor communication and visualization of results was found to be a major limitation. Along those lines, Attia et al. [3] found that the three most important factors in the usability and graphical visualization of building performance simulation were: the graphical representation of outputs, flexible use and user navigation, and the graphical representation of results in 3D.

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A study by Dondeti & Reinhart [4] found that an inability to comprehend simulation data motivated the need for an interactive visualization tool that could allow users to *interact* with simulation results through an intuitive graphical format. In 2005, Crawley et al. [5] compared 20 BPS tools and found that most of them produced results in raw file formats, placing the burden of translation on the user. While there have been advancements in usability for many of these tools over the past several years, the lack of a standard data format continues to create barriers for holistic performance evaluation. When multiple software or algorithms are required to simulate a range of metrics needed for a single multi-criteria assessment, the burden of synthesis often falls on the user. While some architectural designers are comfortable with this burden, many are not. The time-consuming nature of understanding and communicating results between BPS tools and performance metrics creates a costly barrier for users in the design process.

In daylight analysis, there are several rendering engines used for simulation, but Radiance [6] is arguably the most broadly accepted by experts in the field. While robust, this software is notoriously difficult for novice users based on the lack of a graphic user interface (GUI) [7]. To overcome this limitation, multiple tools and plug-ins have been developed to offer an intuitive and user-friendly interface for Radiance. Using Radiance as the back-end simulation engine, BPS plug-ins like Diva-for-Rhino [8] allow architects to set-up, launch, and manage simulations from within the 3D modelling environment of Rhinoceros, creating an easy workflow from digital model to performance metric. Diva-for-Rhino integrates performance metrics for point-in-time illumination, climate based-illumination, and visual comfort assessment (as well as thermal modelling capabilities), but the standard user interface (UI) launches and outputs results for one simulation at a time. DIVA's grasshopper plug-in allows for more dynamic simulation and visualization approaches, but requires a base level of expertise from the user to navigate results within the grasshopper environment.

A handful of daylight analysis companies now offer web-based tools like Sefaira [9] and Light Stanza [10] that combine cloud computing with an interactive user interface to compare performance criteria. Sefaira offers real-time feedback from a 3D model interface, but is limited by its analysis metrics (namely illuminance and Daylight Factor (DF)). Light Stanza integrates more sophisticated illuminance metrics like Spatial Daylight Autonomy (sDA), but has yet to implement human-centric metrics beyond visual comfort (Daylight Glare Probability (DGP)).

Software like Sefaira and Light Stanza have improved user experience and decision-making through the use of an interactive graphic interface. That being said, the research field continues to offer new computational models for human-centric performance in novel-areas like non-visual health and perception [1]. These metrics are directional and dependent on an immersive field-of-view or ocular light exposure. Light Stanza has implemented comfort metrics like DGP, but has yet to integrate other human-centric metrics or offer a visualization strategy specifically designed for dynamic temporal results at eye-level. Immersive human-centric metrics require a multi-directional analysis to account for an occupant's field of view. To tackle the challenge of visualizing dynamic eye-level performance metrics through an interactive UI, this paper offers a web-based tool called OCUVIS to deliver interactive human-centric results directly to the designer or decision-maker.

1.2. Occupant-centric daylight performance

Daylight performance is generally assessed using two photometric inputs: Illuminance and Luminance. Illuminance, which is the total flux incident on a surface for a given unit of area, is by far the most common input for daylight standards and general illumination metrics. Illuminance on a surface, usually at task height like a table, might be evaluated instantaneously under one sky condition or annually, across many instances and sky conditions. Metrics that rely on Illuminance, such as daylight factor (DF) [11], spatial daylight autonomy (sDA) [12], and annual sunlight exposure (ASE) [12,13], generally assign a threshold and display their performance as a colored 2D surface of values that fall either below or above that threshold. This allows a designer to understand whether daylight levels are sufficient for recommended task activities on that surface.

Luminance, a measure of light intensity per surface area travelling in a given direction (cd/m2), is most commonly used as input for metrics like daylight glare probability (DGP) [14] and modified spatial contrast (mSC_5) [15]. As luminance describes the light experienced at eye-level, it is used to assess the composition of light levels within a field-of-view.

The holistic assessment of daylight from a human-centric perspective requires both illuminance and luminance-based inputs, but necessitates a break from traditional performance visualization strategies. While surface-based lighting performance metrics can be easily represented by a grid of coded values, ocular (or eye-level) daylight performance metrics require a representation strategy that can translate multi-directional information from a human perspective to a building model.

Perhaps the most significant barrier for offering a holistic evaluation of daylight from an occupant perspective is the lack of tools that have integrated human-centric performance models within their workflow. In order to compare the effects of daylight on ocular human responses (non-visual health, perception, and visual comfort), new models for predicting such factors must be integrated within a single workflow or output format to provide coordinated results.

A first approach can be found in Amundadottir et al. [16], where performance modules for non-visual health nvR_D [17], visual interest mSC_5, and gaze response GR_L were combined within an integrated simulation-based workflow. Ocular daylight from a single eye-level view position was rendered over an annual time series across an array of view directions and then used as an input to three prediction models (nvR_D, mSC_5, and GR_L). This method, while an important first step in the multi-criteria ocular evaluation of daylight performance, was limited in both the computationally intensive nature of the workflow and its reliance on a single view-position.

A further step in the evolution of this method, presented by Rockcastle et al. [1], built upon the single-view position approach mentioned above and expanded to offer a multi-view position workflow that allowed for a full-building-scale simulation of health (nvR_D) and visual interest (mSC_5). The gaze response model used in the previous study provided a novel method of predicting gaze behavior based on ocular light conditions, but did not provide a comprehensive indicator of comfort.

Using an optimized approach, multiple view positions could be simulated in batch at a much faster rate by building upon the same ambient lighting file in a given scene, substantially lowering simulation times for each additional view position for a given moment and sky. A new method of visualizing the results was also introduced, binning the performance of each view direction and assigning a color based on the specific threshold and performance metric. Results could be visualized both spatially (within a plan or axon diagram), temporally (over time), and synthetically (as a percentage of all simulated view directions). The added efficiency in simulation time did not, however, translate to an automated visualization method and still required the time-consuming process of manually formatting text-based data using vector-based graphic editing software. No 3D model or interactive capabilities were offered.

2 INTRODUCING A WEB-BASED VISUALIZER

To develop and improve past approaches, this paper offers a web-based application for the visualization of dynamic, multi-criteria daylight performance. Building upon the multi-view position simulation workflow introduce above [1] (and now referred to as OCUSIM), the authors of this paper propose OCUVIS. Figure 1 shows the conceptual link between OCUSIM and OCUVIS, with an intermediary step where data produced by OCUSIM is tagged using variables for sky, time, and group. As mentioned in the introduction to this paper, any holistic evaluation of daylight performance from an occupant perspective must account for the variable nature of daylight over time and across multiple sky conditions. It must also account for the multitude of possible view positions and view directions where an occupant may be located and offer a way to compare visual and non-visual responses. In addition to nvR_D and mSC_5 models implemented in previous work, we have introduced a visual comfort module, composed of DGP and vertical illuminance (now referred to as 'Ev') to assess discomfort risk and adequate minimal brightness.

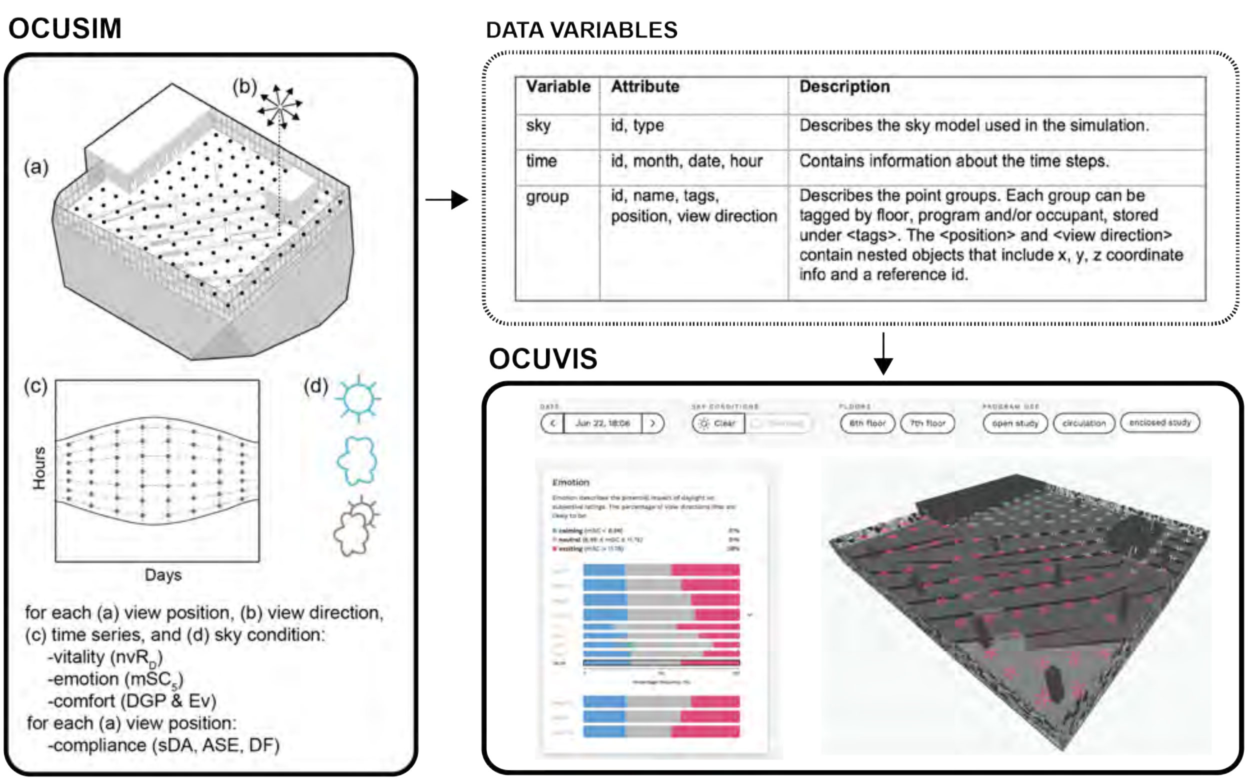

Figure 1. Conceptual diagram showing the relationship between OCUISM, data variables, and OCUVIS.

An indoor location and view that may be ideal for non-visual health responses due to sunlight exposure may be at risk for glare discomfort. Furthermore, the criteria for non-visual, emotional, and comfort responses often vary depending on the function of a space and it is critical to visualize the performance of view positions based on space type. To relate these human-centric performance models to more traditional illumination metrics OCUVIS has also integrated sDA, ASE, and DF. OCUVIS displays these climate-based illumination metrics across a grid of task-height points, with ocular daylight simulation results shown for separate points, simulated at eye-level.

2.1 Ocular Daylight Performance

In this paper, OCUVIS introduces a method to visualize the performance of a building in terms of three modules; vitality, emotion, and comfort experienced at eye level, which are simulated using the radiance and the OCUSIM tool. A fourth module, introduced in Section 2.2, integrates a collection of task plane illumination metrics.

Vitality

The OCUVIS application uses the term vitality to describe the non-visual direct effects of daylight driven by ocular exposure to across the day. The non-visual direct effects are predicted using the nvR_D model proposed in [17] and then translated into a dose measure (i.e. cumulative response). This module shows the vitality of each view direction in one of three daily thresholds: insufficient daily dose ($nvR_D < 4.2$), intermediate daily dose ($4.2 \leq nvR_D < 8.4$), and recommended daily dose ($nvR_D \leq 8.4$). These tentative thresholds correspond to the number of "vital" hours in a day, when adequate daylighting is desired as well. The threshold value of 4.2 was established in [16] as a reasonable criterion for achieving beneficial effects of light. The recommended daily dose, accumulated over the day, exceeds an nvR_D value of 8.4 or twice the intermediate dose.

As this dose is heavily influenced by the duration of daylight hours but still also considers variations in light intensity, wavelength, pattern, and history, it can be challenging to make sense of the cumulative daily values. This is especially relevant in locations where daylight hours are shorter than 8.4 hours, because in that case it is impossible to achieve the recommended dose with daylight only. To solve this problem the daily cumulative response is binned into periods of equal length for each simulated day and then normalized assuming an optimal day period of 12 hours. The values that exceed a recommended incremental dose are highlighted in dark green to indicate if that period lacks sufficient light exposure.

Emotion

In this paper, OCUVIS defines emotion using the Modified Spatial Contrast or mSC_5 algorithm. Modified spatial contrast was first proposed as an image-based method to predict the visual interest of a rendered scene [15]. The mSC_5 algorithm was applied to a series of images under varied sky conditions and then fit to a distribution of subjective rankings on a bi-polar scale from calming to exciting. The model proposed in this paper offered a method to predict the percentage of subjects that were likely to rate an image in the calming or exciting spectrum based on the composition of daylight in that image. To represent feelings of calm or excitement based on the daylight conditions perceived at eye-level in a building, OCUVIS uses the following thresholds [15,16]:

- calming ($mSC < 6.96$),
- neutral ($6.96 \leq mSC \leq 11.75$), and
- exciting ($mSC > 11.75$).

The values that fall within each of these threshold bins are then colored in blue (calming), grey (neutral), or pink (exciting).

Comfort

The visual comfort module used in this paper relies on both DGP [14] & vertical illuminance Ev. As the examples used in this paper were simulated without furniture or defined task surfaces, we use the vertical illuminance at eye level as a threshold for adequate brightness. View directions that exceed a specified DGP threshold are classified as 'at risk for glare' and those that are beneath a minimum Ev, are classified as 'too dim.' When view directions are above the Ev threshold and below the DGP threshold, they are classified as 'likely comfortable.' While DGP thresholds for predicted discomfort have been generally accepted in the literature (although subject to regular adjustments), there is still a lack of consensus about a universal threshold for adequate brightness, as recommended illuminance values for task acuity were developed for horizontal surfaces. As this paper focuses on a visualization tool and not on metric development, we have decided to use 150 lux as a lower hypothetical threshold for scenes that are comfortable (>150 lux). In this paper, that value is based on the acceptable illuminance level for stairs/circulation spaces (100-150 lux) [18]. These values can be adjusted to suit specific lighting goals. The thresholds for OCUVIS are indicated below:

- too dim (Ev < 150 lux & DGP<0.4)
- likely comfortable (Ev>150 & DGP<0.4)
- at risk for glare (DGP>0.40)

These values can be adjusted to accommodate new findings and customized for each project and /or program type independently.

2.2 Illumination Performance

In addition to the three ocular-performance modules described above, OCUVIS integrates a fourth module for task-plane illumination, called compliance.

Compliance

The compliance module contains results for three illumination metrics: sDA, ASE, and DF. Selected based on their common use in both American and European daylight standards, these metrics are presented as a percentage % of points that exceed a given lux or numerical threshold.

- sDA > 55% or 75% of points (where DA > 300lux for 50% or more of the time between 8am and 6pm)
- ASE < 10% of points (where 1000 lux is exceeded for more than 250 hours between 8am and 6pm).
- DF > 2% or 5% of points

Thresholds for sDA and ASE were determined based on the IES LM-83-12 standard [12]. Thresholds for DF were taken from an earlier version of the LEED rating system by USGBC [13,19]. While now considered outdated, DF is still used by many designers and it was included for reference.

3 DATA STRUCTURE

While this paper does not present the simulation workflow behind the production of results (as it was adopted from [1]), it does require the translation of data from individual text-based outputs into a master web-based syntax used by the OCUVIS platform. The results produced using radiance and OCUSIM are therefore post-processed to transfer the results for each simulated position as data objects consisting of attribute-value pairs and array data types. The performance result data are organized by simulation variables: sky, time, and group. OCUVIS has been developed to visualize these results based on the variables called by a user. Figure 1 shows the variables in this data file.

To produce an interactive visualization, OCUVIS reads the formatted data file produced from OCUSIM and filters the performance results data based on user inputs. Each ocular daylight performance metric, in this case mSC_5, nvR_D, DGP and Ev, contain an array of values for each position and view direction. Those values are then normalized so they can be plotted within a 3D model and colored based on thresholds described in section 2.1. Values for the illumination metrics (sDA, ASE, and DF) only contain one value per position, without sky or time variables.

One of the biggest challenges in our understanding of daylight in buildings is the conflict that emerges between program type (i.e. office vs. atrium), performance consideration, location and dynamics (i.e. sky and time). For example, a view position that achieves good task illumination and adequate daylight exposure for vitality, may suffer from low comfort, and an inappropriate emotional response – perhaps the space is glary and exciting when it should be comfortable and calm. Perhaps the performance of that view position varies immensely based on the sky type and the time of day. OCUSIM allows us to tag positions based on floor, program use, and occupant type, which in turn, allows the user to navigate the 3D results in OCUVIS based on these tags. The user can also navigate the results by changing sky condition and/or time parameters.

4 INTERACTIVE DESIGN

The climate-based illumination metrics described above only contain a single value per point (representing annual or non-time dependent values), but the ocular metrics contain data that is temporally dynamic and variable by sky type. Both metric types, ocular and illumination, use group tags that allow points to be categorized and displayed independently or in aggregation by the end-user. To provide a holistic understanding of daylight performance from an occupant perspective, the temporal and spatial dimensions described above necessitate an interactive visualization strategy. The ability to compare the performance of various metrics over time allows for a more comprehensive understanding of how they relate or conflict and how a designer may alter their design to accommodate multiple criteria. Figure 2 shows the project information for an analysis of the Spencertown House by Thomas Phifer and Associates.

For each project, a top navigation panel allows the user to select which design variant they would like to view (in this case, the project was analyzed with and without exterior louvers), with a drop-down tab that shows more information about the project and latitude where the analysis was conducted. The design of OCUVIS allows the user to navigate between metrics (shown as tabs), sky types, time steps, and groups (shown as buttons) with temporal and spatial graphics connected globally. The main web interface contains two graphical elements: performance cards with collapsible bar graphs displaying a percentage of view directions in the associated thresholds for each metric and the spatial representation of that data in 3D. The user can jump between performance modules by either selecting the tab on the upper left or by scrolling down the screen to browse between cards

Figure 2 also shows results for Vitality, with daily data as a thick bar and hourly data as a thin bar, collapsible from the arrow on the right. For Vitality, the daily results are cumulative, with light green showing the percentage of view directions with an intermediate nvR_D dose of 4.2 and the dark green bar showing the percentage of view directions with a recommended nvR_D dose of 8.4The incremental drop-down values show the direct dose achieved across that period, normalized to the length of the period.

This allows the user to see the cumulative daily dose for each view direction as well as the relative incremental performance of each view direction over the day. If the space is only occupied during certain period in the day, this incremental potential becomes important. Unlike vitality, emotion and comfort contain hourly values that are instantaneous. For emotion, pink shows the percentage of mSC_5 values in the exciting spectrum, grey shows the neutral values, and blue shows the calming values. For comfort, values in the 'too dim' range are grey, in the 'likely comfortable' range are orange, and in the 'at risk for glare' are red. Daily values for both emotion and comfort are computed as an average for each view direction across all hourly time steps. The final performance tab, called compliance, displays results for sDA, ASE, and DF. As these metrics synthesize data across the year (in the case of sDA and ASE) or ignore time and sky altogether (like DF), sky and time variables are disabled under this tab.

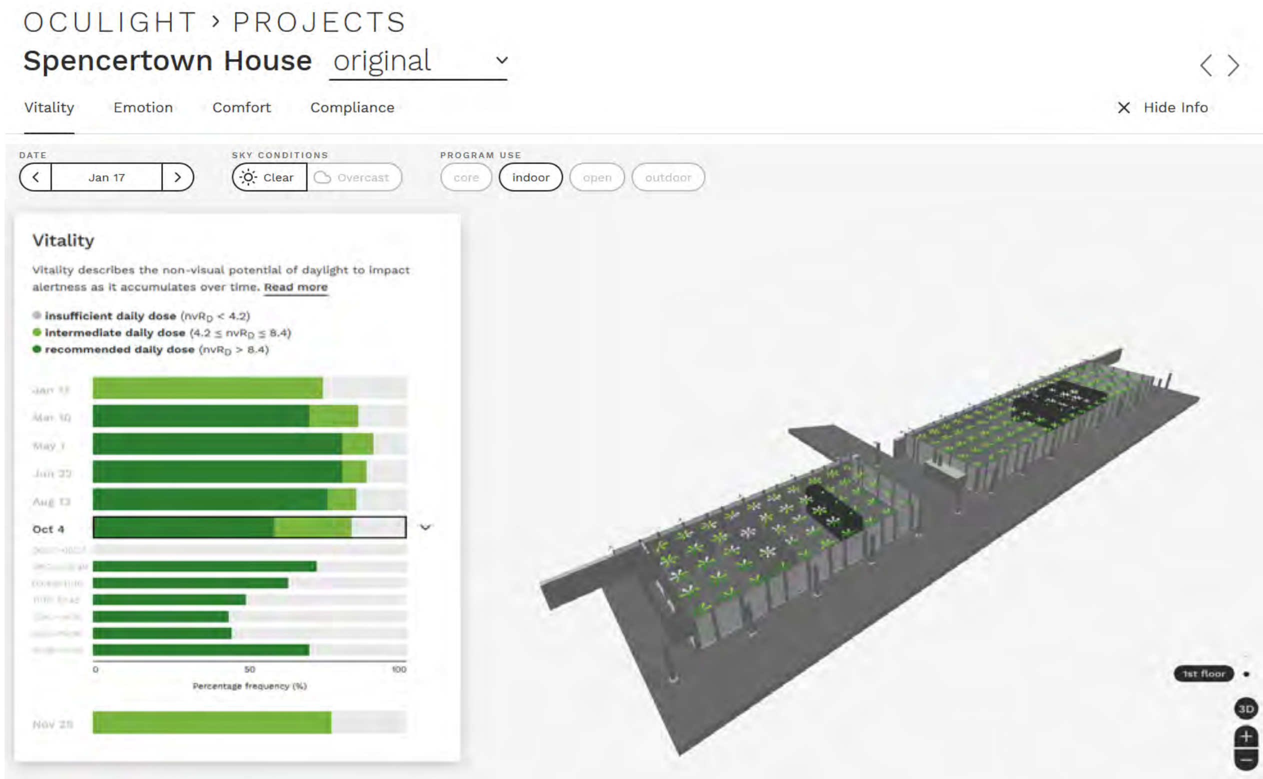

Figure 2. Shows the OCUVIS web interface for a one-floor house. The project info panel can be expanded or collapsed from above, with temporal and spatial data shown below for one of four performance tabs.

The number and spacing of points also differs from the ocular metrics, as they are determined based on standards (which vary based on geographic location) and must assess a standard task-height. Where task-driven performance metrics (DF, sDA, and ASE) require an analysis of the entire occupied floor plate, the performance of ocular daylight responses (vitality, emotion, and comfort) are more nuanced and require interpretation based on the space use and location of occupants. Figure 3 shows the web interface for a multi-level mixed use building. The interaction elements in the top navigation bar allow the user to explore the performance results between time steps (seasonal and hourly), sky condition, and space group. In this case, only some variables are engaged to show how the data is parsed: clear, 7th floor, open & enclosed study spaces.

While we may be interested in the emotion of all spaces in this example, we may care more about comfort in the spaces where task work occurs (i.e. open study or circulation spaces). The same is true for vitality, where prolonged exposure to daylight is most likely in spaces of habitual occupation. By selecting groups of points on the upper right (for example '7th floor'), as shown in Figure 3, the user can aggregate the results based on floor and space use.

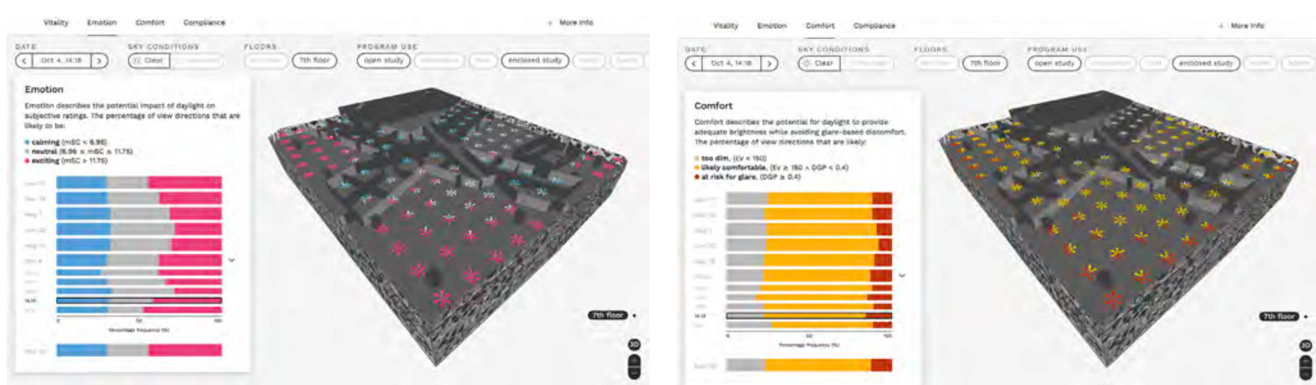

Figure 3. OCUVIS with temporal and spatial results for Emotion on the left and Comfort on the right.

A final feature, shown as a drop down in the project info panel in Figure 2, allows the user to navigate between design variants (i.e. 'original' and 'renovated' or 'option 1' and 'option 2'). Figure 4 shows results for the Spencertown house as originally conceived on the left and as modelled with exterior fixed micro louvers on the right.

This comparison feature allows architects and design stakeholders to explore the effects of their design options between performance criteria. The interactive exploration of performance between design options helps the architect to understand that the singular optimization of any one performance factor can result in diminished performance to another. In this case, the micro louvers on the right show a slight improvement to comfort, but degrade the daylight factor performance, used as an indicator of diffuse light penetration under overcast skies. The ability to compare human-centric and illumination metrics in a single interface is a novel contribution of the OCUVIS web viewer.

Advances in computational speed and workflow have made simulations in OCUSIM more efficient, but the sheer quantity and dynamic nature of the results pose significant challenges to a holistic assessment. As researchers, we often focus our energy on understanding and modelling measurable elements in the physical world, but the novelty of models implemented in this paper necessitate new methods of visualization that encourage learning through user interaction with the data itself. The OCUVIS web application can be accessed via: https://portfolio.oculightdynamics.com/.

Spencertown ORIGINAL DESIGN Spencertown FIXED EXTERIOR BLINDS

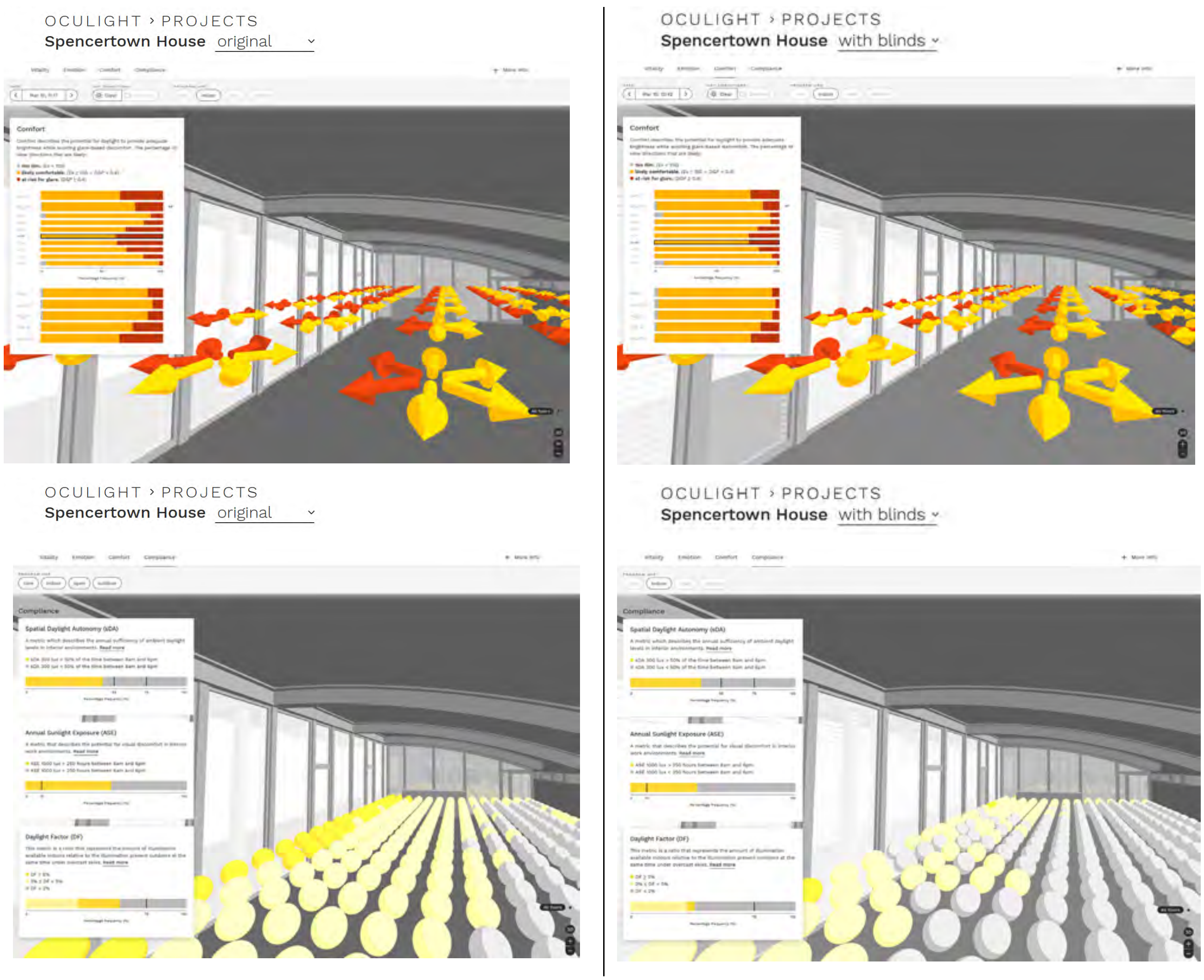

Figure 4 The results from two design options in a one-story house. Results for the original design are shown for comfort and DF compliance on the left. Results for a design variation with fixed exterior blinds are shown for comfort and DF compliance on the right.

5 CONCLUSION & NEXT STEPS

This paper has introduced OCUVIS, a web-based visualizer developed to display the results of immersive ocular daylight performance alongside conventional task-compliance metrics through an interactive graphic format. Using the results developed from a software called OCUSIM, the OCUVIS visualizer allows designers to interact and explore multi-criteria performance factors over time, between sky conditions, and across space. While it would be possible to connect the OCUSIM software with the OCUVIS web-based visualizer via cloud computing, there are advantages to keeping them separate for the time being. The management of computationally intensive simulations produced using OCUSIM requires some user expertise and a robust computing environment with correct software install, while the ability to explore the results interactively through OCUVIS requires little more than a web-browser and internet connection. The flexibility of sharing results via web-application facilitates the coordination between stakeholders in the design process. As such, splitting the back-end and front-end packages allows for easier development on both ends. Further steps to integrate occupant-centric factors beyond daylight as well as occupant-specific performance based on user-profiles are being explored. At the moment, OCUSIM relies on the Radiance simulation engine, but could integrate other simulation workflows as long as the data structure of the results file is maintained, with directional data stored using sky, time, and group tags.

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