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# Balancing Thermal and Luminous Autonomy in the Assessment of Building Performance

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## Abstract

This paper proposes and evaluates a novel approach that simultaneously uses thermal and luminous autonomy for the assessment of human-centered passive design strategies, introducing a potential way to integrate these two metrics in the design process. In this study, we assessed the advantages and limitations of applying the two autonomy metrics with energy and lighting simulations in two climates. We developed a novel visualization to display the hourly thermal and luminous autonomy values for an entire year. The results showed that when we consider the two metrics together, designers may have contradicting design directions to mitigate the solar radiation; for example, the space is overly cool, but it is overlit at the same time, or the space is overly warm, but the daylight metrics predicts it is underlit. The visualization categorizes thermal and visual comfort in nine combinations allowing the designers to understand the trade-off relationships between thermal and visual conditions of the space.

## Introduction

High performing buildings can be achieved by both active and passive design strategies. Designers have focused on minimizing building energy use through optimized façade, lighting, HVAC systems and the application of climate-responsive design, but there is a need for a stronger focus on occupants' visual and thermal comfort as high levels of thermal discomfort are commonly found in buildings (Frontczak et al. 2012). In passive design, balancing solar gain scarcity and surplus from the heat transfer and energy point of views is well-established by researchers and practitioners (Andersen 2015). However, the effect on human thermal and visual comfort has not yet been fully assessed. Luminous autonomy is increasingly well understood, and refers to the percentage of occupied time over a year where daylight level meets the required range for a space with daylighting. Lighting standard LM-83, expands luminous autonomy with spatial requirements by introducing Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) as metrics for daylight sufficiency and visual comfort, respectively, in the built environment (IES 2012). In contrast, thermal autonomy is a relatively new concept, and can be defined as the percentage of occupied time over a year where a thermal zone meets a given set of thermal comfort criteria through passive means only (Levitt et al. 2013; Mackey 2015). It links occupant thermal comfort to climate through a proper building energy and performance modelling (loads, controls, etc.). Both thermal and luminous autonomy are related to the building envelope design, and these two metrics require time-intensive dynamic simulations based on hourly climate data of a certain geographical location and building program. However, how these metrics co-exist in a space has not yet been fully investigated. Therefore, the objective of this research is to propose and evaluate a novel approach that simultaneously uses thermal and luminous autonomy metrics.

## Simulation

### Models and assumptions

The building model is based on Commercial Reference Buildings provided by the Department of Energy (DOE 2016). In this paper, simulations were based on the Medium Office model on the DOE reference list, starting with a simplified box (4.6 m x 13.7 m x 2.7 m) with fully-passive conditioning, and a typical floor (single zone) with 0.48 window-to-wall ratio (1.22 m-height openings on the south and the north facades) in Figure 1.

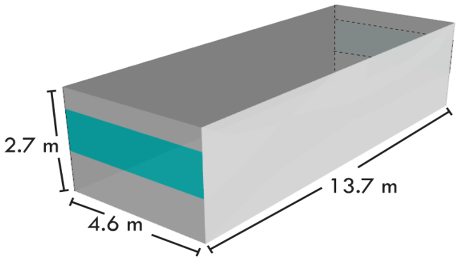

*Figure 1. A simplified model*

The boundary conditions of the ceiling, the floor, and the east and the west facades were kept "adiabatic" to better represent the model as a part of the larger floor plan. The testing locations were Phoenix, AZ, and Helena, MT, (ASHRAE Climate Zone 2B and 6B), which represent hot and cold climates in the US, respectively. The envelope characteristics are shown in Table 1. Visible transmittance values of window were modified based on the other glass properties (i.e., SHGC and U-Factor) due to the limited availability in DOE reference building inputs.

### Thermal autonomy calculations

Software: Grasshopper's Honeybee was used to simulate spatial thermal autonomy, using EnergyPlus (v8.4) as the simulation engine (Sadeghipour and Pak 2013; Mackey 2015; DOE 2016).

*Table 1. Envelope properties*

| Climate | Location | Phoenix, AZ | Helena, MT |
|---|---|---|---|
| | **Climate Zone** | **2B – Hot and Dry** | **6B – Cold and Dry** |
| **Opaque Wall** | R-Value ($m^2 \cdot K/W$) | 0.42 | 0.31 |
| **Window** | U-Factor ($W/m^2 \cdot K$) | 5.84 | 3.24 |
| | Solar Heat Gain Coefficient | 0.25 | 0.39 |
| | Visible Transmittance | 0.6 | 0.6 |

Metrics: We used the adaptive thermal comfort model which are outlined in ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy (ASHRAE 2013; deDear and Brager 1998) because we evaluated passive design strategies. The adaptive comfort model is defined in the standard with specific limits on its applicability. In this study, we chose 80% acceptability limits. In the adaptive model, the indoor operative temperature is a function of prevailing mean outdoor temperature. The model can be applied in buildings that do not have a mechanical cooling system installed, no heating system is in operation, metabolic rates are between 1.0 to 1.3 met, occupants have the choice to adapt their clothing within a range at least as wide as 0.5 to 1.0 clo, and the prevailing mean outdoor temperature is greater than 10 °C and less than 33.5 °C. Using the online CBE Thermal Comfort Tool, which is compliant with ASHRAE 55-2010, we can calculate exactly how far the comfort range can be extended to at different air speeds. When the prevailing outdoor temperature is outside that range, Honeybee comfort analysis used a correlation from recent research (Humphreys et al. 2012).

The EnergyPlus simulations produced a single average indoor air temperature for the zone. The spatial distribution of thermal comfort was then based on differences in MRT calculated separately for each of the nodes in a spatial grid (120 nodes total, using the same spatial grid as for the luminous autonomy calculations). MRT for each node was based on view factors between that point and each of the visible surfaces. To compute the view vectors, one of the Honeybee components used a ray-tracing methodology that projected at least 290 evenly spaced view vectors from each test point to the surrounding surfaces, based on a Tregenza sky dome (Mackey 2015). The MRT calculation also implements the SolarCal method (Arens et al. 2015; ASHRAE 2013), which assesses the thermal comfort impacts of transmitted short-wave solar radiation that falls directly on an occupant. It assumes an occupant is always seated and the sun vectors that determine whether direct beam radiation is falling onto occupants are binned into sky patches. The sky patches match with the specified view resolutions. The single zone average air temperature was then coupled with radiant temperature to calculate the operative temperature for each node.

To meet the adaptive comfort range (80% acceptability limits), the minimum indoor temperature for natural ventilation was set at 18 ºC, and the maximum outdoor temperature was set at 28 ºC to close window if it gets too hot outside. Natural ventilation potential was calculated applied to the two windows on the south and north. Each window was sliding horizontally and it had two equally-sized openings. The fraction of the window area that is operable was set 0.5. The natural ventilation model accounted for the effect of wind, but not the stack effect. In addition, for the sake of simplicity in this proof-of-concept exercise, internal blinds were not deployed in the thermal autonomy calculation. (As seen later, this is a difference between the thermal and luminous autonomy models and is a complexity that will be address in a later phase of this research).

The climate conditions were based on typical meteorological year (TMY3) data, with an analysis period extending from 8 am to 6 pm local time (10 hours per day), excluding the period from Saturday at 5 p.m. to midnight on Sunday, in line with Honeybee EnergyPlus' mid-size office building template.

### Luminous autonomy calculations

Software: We used DIVA 4.0 and DAYSIM's annual climate-based calculation (using Radiance as the simulation engine) for the luminous autonomy simulation (Solemma, 2016).

Metrics: We used the commonly adopted metrics of sDA and ASE (IES 2012). Spatial daylight autonomy (sDA) is the percentage of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year. The sDA should be calculated with window shades down whenever more than 2% of the floor area of a control group has direct sunlight over 1000 lx present. Annual sunlight exposure (ASE), a proxy for evaluating the potential for glare, is the percentage of an analysis area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year.

LM-83 recommends $sDA_{300/50\%}$ and $ASE_{1000/250h}$. The $sDA_{300/50\%}$ metric analysis first addresses each node separately and assesses the number of hours per year that each node meets or exceeds an illuminance threshold of 300 lx on horizontal surfaces from daylight alone. After that, it counts which nodes met this threshold for at least 50% of the occupied hours, and reports this as the percentage of nodes across the analysis area. For sDA, the larger the number, the better. The $ASE_{1000/250h}$ metric analysis follows a similar 2-step process, calculating the percentage of sensor nodes in the analysis area that are exposed to more than 1000 lx of direct sunlight for more than 250 hours per year. Since ASE is a proxy for glare, the smaller the number, the better.

In this study, the daylight conditions were based on typical meteorological year (TMY3) data, with an analysis period extending from 8 a.m. to 6 p.m. local time. The analysis grid was based on a 0.6 m x 0.6 m area that was 0.9 m distant from the floor. The surface reflectance values were assumed as follows (LM-83 default interior reflectance values): 20% floor, 50% walls, 70% ceiling, 50% furniture, and 10% outside ground. With regards to sDA requirements for interior blinds, the simulation model used the conceptual DAYSIM methodology for the blind properties (0% of direct transmittance, 25% of diffuse transmittance). For the hourly data visualizations, the same thresholds were used: 300 lx (ambient bounces 6, ambient division 1000) for daylight autonomy (i.e., sDA) and 1000 lx (ambient bounces 0, ambient division 1000) for visual discomfort time (i.e., ASE).

### Data post-processing

Though the concepts of thermal and luminous autonomy metrics are similar, some aspects are different—for example, luminous autonomy uses 8 am to 6 pm for the entire year as the analysis period, but thermal autonomy calculations through Honeybee use 8 am to 6 pm excluding Sunday. In addition, the current daylighting metrics, sDA and ASE, added spatial requirements to the definitions of daylight autonomy. In order to compare thermal and luminous metrics in the same format, the simulated data must be post-processed. This includes adjusting the analysis period, creating an annual heat map for a specific point or area in the analysis grid, and generating data visualizations to show the different combinations of thermal and visual comfort aspects, including overly warm or overly cool periods and underlit (low illuminace) or overlit (potential glare) periods. The post-processing represents an important contribution of this work.

## Discussion and result analysis

Figure 2 shows the first step of the sDA, ASE and thermal autonomy comparisons between the buildings in Phoenix and Helena (i.e., the analysis of each node, showing the percent time it meets the respective threshold). $DA_{300}$ and $DA_{1000}$ calculations (which, unlike sDA and ASE, don't include any blind control) are in Figure 3, which are the relevance/basis of the spatial metrics, sDA and annual sunlight exposure, ASE in Figure 2. In Figures 2A and D for $DA_{300/\text{with blind}}$, the orange pixels represent 100% of occupied hours exceeding the threshold, 300 lx. In Figures 2B and E for $DA_{1000}$, the grey scale pixels indicate the goal of a maximum of 250 occupied hours being below the threshold, 1000 lx, and the pink pixel indicates the area where the nodes exceed the threshold and therefore represent potential for visual discomfort.

Thermal autonomy calculations are based on Adaptive Model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological parameters as explained in the previous section. The allowable indoor operative temperatures is determined using 80% acceptability limits followed by ASHRAE Standard 55(ASHRAE 2013). The thermal autonomy results reveal that, for the colder climate of Helena (Figure 2F), the south-facing perimeter area has more number of hours within the comfort zone compared to the core and north-facing perimeter, and this indicates the benefit of passive solar heating in the winter period. In the warmer climate of Phoenix (Figure 2C) the west side of the floor plate close to the south-facing window has better thermal autonomy than the east side of the plan due to the passive solar heating benefits in the morning (before noon time) when the building is already cooled over the night and needs some heat to warm up. The angle of the east morning sun coming through the window has a greater effect on the west corner.

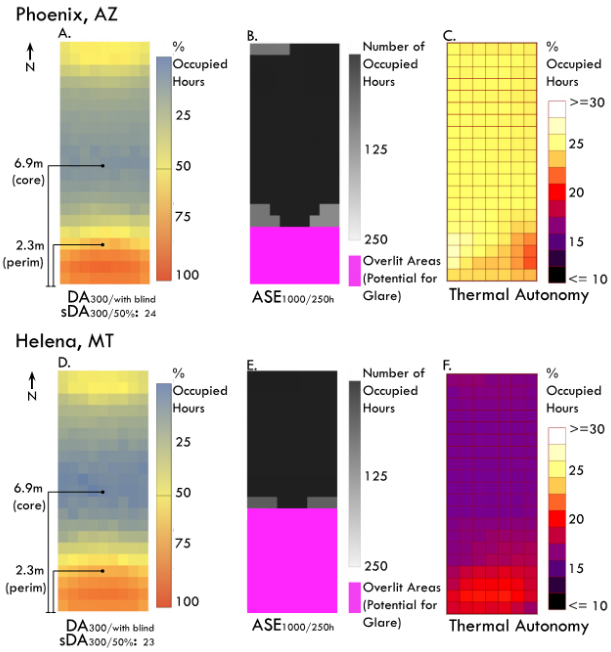

*Figure 2. Plan View Comparison: Luminous Autonomy (sDA, ASE) and Thermal Autonomy Simulations in Phoenix and Helena.*

*A and D)* $DA_{300/\text{with blind}}$*: the percentage of the occupied hours equal or above 300 lx with blind control.*

$sDA_{300/50\%}$*: the percentage of analysis points across the analysis area that meet or exceed this 300 lx for at least 50% of the occupied hours. Internal blind is modelled based on the metrics' threshold.*

*B and E)* $ASE_{1000/250h}$*: in the analysis area that are found to be exposed to more than 1000 lx of direct sunlight for more than 250 hours per year. ASE indicates the potential for visual discomfort.*

*C and F) Thermal Autonomy: the percentage of occupied time over a year where a sensor node meets the adaptive comfort criteria (80% acceptability limits) through passive means only. Internal blind is not modelled in Thermal Autonomy calculations.*

Looking at the daylight autonomy metrics, the building in Helena reveals more areas exceeding the ASE threshold of 1000lx (Figure 2E) compared to the building in Phoenix (Figure 2B). This is due to the higher latitude of Helena, and therefore a higher percentage of time with a low sun angle. However, $DA_{300/\text{with blind}}$ shows these two buildings have similar poor daylight autonomy performance in the core and north perimeter due to the blind operation (as required for sDA, the simulation deploys blinds whenever more than 2% of the floor area has direct sunlight over 1000 lx present in the buildings with more than 10% ASE per year). The need to have blinds for glare control had a negative impact by creating both overly cool and underlit areas – an example of the need to look at the simultaneous performance of these three metrics. This is especially true in the building in Helena, where buildings are overly cool for most of the year, and where passive solar heating would have been beneficial.

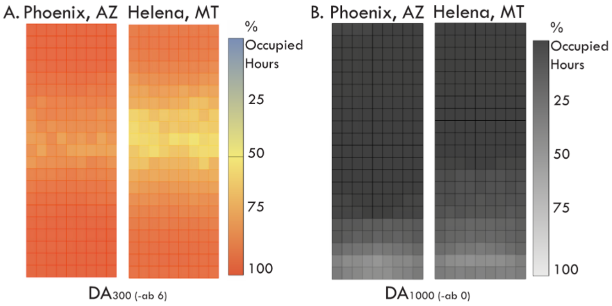

*Figure 3. Plan view of Daylight Autonomy calculations in Phoenix, AZ and Helena, MT: A) Daylight Autonomy 300 lx (daylight sufficiency; -ab 6). B) Daylight Autonomy 1000 lx (Potential glare; -ab 0). cf. Figure 5.*

Figure 3 compares $DA_{300}$ (with no blind effect) and $DA_{1000}$ (basis of ASE calculations) results. The $DA_{300}$ results in Figure 3A clearly shows the differences between daylight autonomy results in the two locations for conditions of no interior blinds; averaging across the nodes, the mean % of occupied hours that exceeds 300lx is 91% in Phoenix and 80% in Helena. In addition, the building in Helena shows a clear distinction between the core (mean of only 50% of occupied hours) and the perimeter (80-90%). As an indication of visual discomfort, $DA_{1000}$ results in Figure 3B indicate that, without blinds, the building in Phoenix has a slightly more focused area (near the south perimeter) that exceeds 1000 lx over a year compared to the building in Helena (the area is more spread-out in the space). When we compare Figure 2 and 3, luminous autonomy distribution is quite different in the two climates when one does and does not use interior blinds.

The previous graphs represented the spatial distribution of thermal and luminous conditions. The final step in calculating autonomy metrics is to count which nodes meet the respective threshold, and report them as the percentage of nodes across the analysis area. The percent time that is above or below these thresholds is also reported as overly warm/cool, or over/under lit. Table 2 summarizes these results, showing that in Phoenix, the building model is overly warm 45% of the time, whereas in Helena it is overly warm only 9% of the time. In contrast, overlit area (ASE > 1000lx for >250 h) shows the inverse for these climates: 24% of the time for the building in Phoenix and 41% for the building in Helena. As an example of putting the thermal and luminous results together - Helena is simultaneously overly cool (75% of the time) and overlit (41% of the time). This tells us that we cannot easily increase passive solar strategies (that are needed) without increasing the overlit issue, and so it would be important to figure out how to bring in more solar gain in way that better distributes and diffuses the light.

The percentages of the areas that meet sDA requirements are almost the same for the two locations (24% for Phoenix and 23% for Helena). Based on the values, a designer can conclude that the two locations have similar daylight performance, but this may not be true for thermal and visual discomfort. If a designer uses only one metric at a time to develop design strategies, it would not allow them to understand the trade-offs between daylight quantity, visual discomfort, and thermal comfort, and therefore come up with balanced design strategies. This shows the importance of simultaneous analysis of thermal and luminous autonomy for the passive design process.

*Table 2. Summary of the results*

| | **Location** | **Phoenix, AZ** | **Helena, MT** |
|---|---|---|---|
| | **Climate Zone** | **2B – Hot and Dry** | **6B – Cold and Dry** |
| **Adaptive Comfort** (mean, % of occupied hrs) | Thermal Autonomy | 25 | 16 |
| | Overly warm hrs | 45 | 9 |
| | Overly cool hrs | 30 | 75 |
| **LM-83** (% of analysis area) | sDA 300/50% | 24 | 23 |
| | ASE 1000/250h | 24 | 41 |
| **Daylight Autonomy** (mean, % of occupied hrs) | Overlit hrs $DA_{1000}$ (-ab 0) | 7 | 9 |
| | $DA_{300}$ (-ab 6) | 91 | 80 |
| | Underlit hrs: 100-$DA_{300}$ (-ab 6) | 9 | 20 |

### Luminous Autonomy - sDA threshold discussion

When we compare $DA_{300/\text{with blind}}$, sDA, $DA_{300}$ calculations and the results (Table 2, Figure 2 and Figure 3), analysing either the percentage of analysis area that meets 50% of daylight autonomy or the mean percentage of daylight autonomy may make us hard to understand the spatial variations of daylighting in different locations. In Figure 3, the Helena test site reveals very distinctive differences in $DA_{300}$ between the core and the perimeter. In contrast, in the Phoenix test site, the difference between the core and the perimeter is fairly minimal. sDA in the two sites is the same (Figure 2), therefore, we conclude that using 50% of occupied hours as a metric for spatial analysis (focusing on the area where we have sufficient daylight over the year only) and assuming internal blinds deployed all the time when the metrics required can be misleading. The sDA 50% metric shows that the daylight performances in Phoenix and Helena are almost the same, but it does not necessarily mean that the buildings in these two locations have the same daylight autonomy or daylight performance. It would be helpful to have a systemic way of integrating these uncovered aspects of daylight performance into the current daylight metrics such as implementing Continuous Daylight Autonomy (Reinhart, Mardaljevic, Rogers, 2006) which gives partial credits for the area with the daylight level less than the threshold, 300 lx.

### Luminous autonomy - ASE threshold discussion

The ASE indicates that Helena model has 17% more overlit area than Phoenix indicating that the building in Helena is getting too much direct sun. However, thermal autonomy results show that Helena building is overly cool for 45% more of their occupied hours than the Phoenix building, offering a contradictory suggestion that Helena building need for more passive solar heating. The current metrics require buildings to deploy blinds if the ASE is higher than 10%. Therefore, if we follow the blind requirements, we may increase overly cool hours even more than the simulated results we compared in this paper. Even if 1000 lx has the potential to have glare, the direct sun can be beneficial if it does not create glare or is falling onto occupants; in such locations, the direct sunlight can be admitted in a way where it is perhaps absorbed by darker surfaces, or distributed throughout the space, to reduce glare while still increasing passive solar heating.

### Temporal analysis between thermal autonomy and luminous autonomy

Below we show that it is useful to plot the hourly results of both thermal and luminous autonomy simultaneously to understand whether there is any relationship between them. This paper proposes integrating hourly data visualizations for both thermal and luminous autonomy at a specific point on a floor plan. These visualizations allow people to understand both when autonomy occurs throughout the year and when each of the different combination of these two metrics occurs. There are nine combinations, where “overlit” refers to potential glare and “underlit” refers to low illuminance:

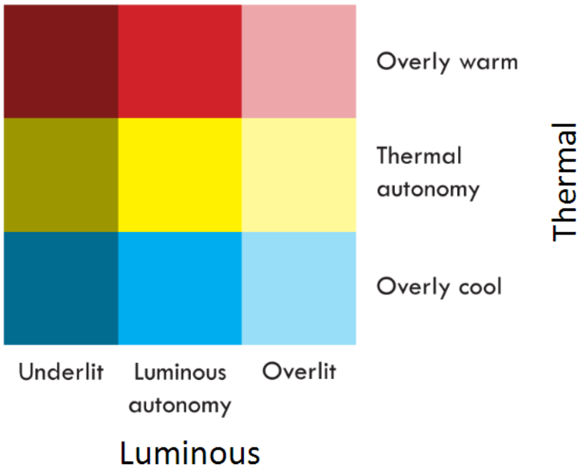

*Figure 4. Nine combinations of thermal and luminous characteristics: blue for overly cool hours, red for overly warm hours, yellow for thermal autonomy, shaded color for underlit hours, lighter color for overlit hours, and no change in color for luminous autonomy hours.*

Figure 5 show the autonomy comparison between the buildings in Phoenix and Helena with the nine combinations. The Figures on the left (A, C, E, G) show the representative hourly autonomy data as an annual heat map graph (Steinfeld et al., 2012). The x-axis represents Jan. 1st through Dec. 31st, and the y-axis represents the hours in a day. The white area indicates unoccupied hours, which are excluded in the analysis. The color legend represents each combination: blue for overly cool hours, red for overly warm hours, yellow for thermal autonomy, shaded color for underlit hours, lighter color for overlit hours, and no change in color for luminous autonomy hours.

The Figure in the right column (B, D, F, H) are the summary graphs for the number of autonomous hours at a specific point for each test climate. These are helpful for understanding the magnitude (i.e., the percentage of occupied hours) of each combination. The x-axis represents the percentages of underlit/overlit hours and the y-axis represents the percentages of overly cool/overly warm hours. Each circle size indicates the percentage of the number of hours for each combination. It is useful to categorize the thermal and visual characteristics into the nine combination as each combination might guide different design and analysis considerations.

For example, when a building is overly cool and overlit, designers should carefully analyze the potential benefits of passive solar heating (and how to achieve this without introducing glare) vs. the negative effects of reducing solar load simply to resolve the overlit issue. In contrast, when it is overly cool and underlit, the space simply needs more heating and lighting. This typically happens either deep within the floor plan or early in the morning (right before or after sunrise), when the building lacks sufficient thermal energy and daylight levels for the occupants. Overly warm and overlit most likely occur when it is warm and there is direct sun; this is when the building needs shades or blinds. Overly warm and underlit occur late in the afternoon, when there is less sunlight but too much thermal energy; during these times, the building needs supplemental lighting and cooling, ideally through passive means.

When we compare the perimeter and core zones, it is clear that, based on the ASE metrics, glare hours occur only in the perimeter zone. Luminance-based glare metrics (e.g., Daylight Glare Probability) may have difference results and this is briefly discussed in the future work section. The dark blue (overly cool and underlit) indicates the best opportunities for more passive solar heating, while the light blue (overly cool and overlit) also indicates a need for passive solar benefits but it will need to be done more carefully to avoid increasing the glare challenges. For example, in Helena, the light blue hours occur more than 11% of the time (October through March). In Phoenix, the light blue hours are limited, occurring during only 3.5% of the occupied hours. This indicates that the higher latitude locations are more likely to have light blue hours, during which the blinds can be pulled down to block the sunlight the whole time only solving the glare issue, but making the overly cool problem worse.

The results for both Phoenix and Helena suggest that, for this building, it is easier to create luminous autonomy than thermal autonomy throughout the year, with the space in Helena generally too cool and the one in Phoenix warm. However, in Helena, the higher latitude results in a significant decrease in daylight levels in the core zone.

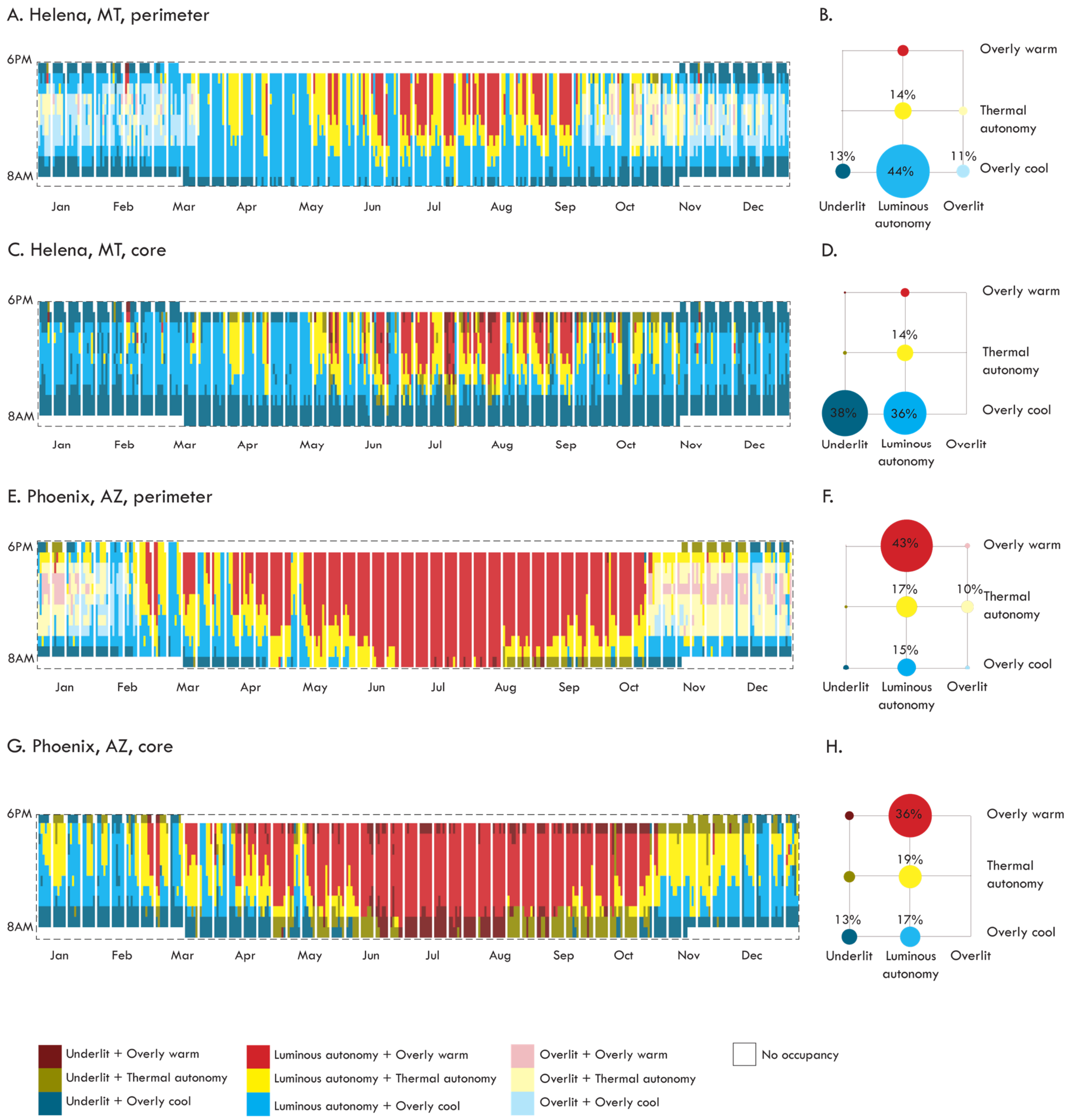

*Figure 5. Hourly autonomy map (based on Adaptive Comfort and* $DA_{300,\ 1000}$ *models) and the annual summary of the building in two climates*
*A. Hourly autonomy map – Helena, MT, south-facing, perimeter (2.3 m from the façade)*
*B. Number of autonomy hours, Helena, MT, south-facing, perimeter (2.3 m from the façade)*
*C. Hourly autonomy map – Helena, MT, south-facing, core (6.9 m from the façade)*
*D. Number of autonomy hours, Helena, MT, south-facing, core (6.9 m from the façade)*
*E. Hourly autonomy map – Phoenix, AZ, south-facing, perimeter (2.3 m from the façade)*
*F. Number of autonomy hours, Phoenix, AZ, south-facing, perimeter (2.3 m from the façade)*
*G. Hourly autonomy map – Phoenix, AZ, south-facing, core (6.9 m from the façade)*
*H. Number of autonomy hours, Phoenix, AZ, south-facing, core (6.9 m from the façade)*

This indicates that blind operations in this location need careful consideration, as they can negatively affect the daylight levels deep into the floor plan.

Figure 2C showed a very even distribution for thermal autonomy between core and perimeter for Phoenix. In Figure 5(E-H), on the other hand, there is a significant shift from overly warm (5E/F, perimeter) to overly cool (5G/H, core) hours. This highlights the potential of the visualization approach, which is missing in the current industry.

### Limitations and future work

This paper proposed a method and visualization to simultaneously analyse the thermal and luminous characteristics of a building, while using a very simple building model as a proof-of-concept exercise. There are several limitations of the assessment method. For visual comfort, this study uses the ASE metric, which analyses direct sunlight illuminance on a horizontal surface of each node. This metric is often criticized in that it doesn't include directional study and luminance-related aspects which is crucial in visual comfort predictions. This current study only looked at shading performance as required by the sDA and ASE metric calculations.

Future studies should examine shading systems in more detail as they can have multiple impacts on building performance (i.e., they control solar heat gains, which affects dynamic thermal storage in building constructions; they control daylighting, which affects electrical lighting energy load, which in turn has an effect in the indoor). The current study was also done with free running buildings (no heating or cooling systems). Future studies should examine mixed-mode buildings, as well as the thermal benefits of turning the heating on at night in the cold climates.

There is great potential to establish modified autonomy metrics for passive design, including allowing for more ASE hours in higher latitude locations, and revising blind operations so they don't depend solely on the ASE metrics, but instead could vary based on the different thermal and visual comfort combinations: when areas are overly warm and overlit, when areas are overly warm and underlit, and when areas are overly cool and overlit. These strategies can be applied more specifically to each orientation.

In addition, the hourly data of the simultaneous analysis between thermal and luminous autonomy may be implemented in the building automation system. An increasing number of buildings have mixed-mode systems and automated shading systems to achieve high performance in energy and comfort. Often, these control systems lack an integration of both visual and thermal aspects, thereby making some occupants uncomfortable and distracted. The nature of the nine combinations can help to select proper shade types and operation systems responding to the diurnal and seasonal variations in both thermal and visual comfort of a building.

## Conclusion

In this paper, we simultaneously assessed thermal and luminous autonomy with a new way of visualizing the hourly comfort data. The visualizations categorize thermal and visual comfort in nine combinations, allowing the designers to understand these two autonomy metrics in an hourly format. Based on the comparison between the autonomy results in two climates, we learned that the current luminous autonomy metrics – when considered in isolation - inherently inhibit the use of passive solar heating in the higher latitude locations (i.e. the hours when it is overly cool yet overlit). The new way of simultaneously visualizing both thermal and visual comfort data may help designers to make more informed design decisions by better understanding the trade-off relationships between thermal and visual aspects. Building envelope design and operation strategies can vary based on the nine combinations that this paper proposed. In addition, the results show the current building autonomy metrics might need to be revised based on different climates.

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