The impact of daylight presence on cooling strategies: energy simulations of a test room in Austin, Texas, and Geneva, Switzerland

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Abstract. In order to understand how to reduce energy consumption in buildings, all factors affecting occupant comfort and behavior must be considered. Previous work from EPFL has elucidated the influence of daylight on thermal perception and its resulting potential to reduce cooling loads in a controlled test space in Geneva, Switzerland with three different illumination levels (130 lux, 600 lux, and 1400 lux) and under three different indoor air temperature levels (19°C, 23°C, 27°C). Occupants perceived the temperature as up to 2°C cooler when exposed to daylight, leading to reduced cooling loads. For climates with high cooling loads for much of the year, such as Austin, Texas, this reduction could yield significant benefits for low-energy building design. Simulations show the total amount of energy saved from adopting this strategy in Austin, Texas.

1. Introduction
Light is the essence of life and one of the most important environmental factors affecting the human body. In the last 20 years, a better understanding of the eye philosophy led to the discovery of light’s significant impacts on a variety of non-visual physiological, psychological, and behavioral responses in the human body, in addition to regulating the circadian rhythm [1], [2]. Many studies report that light can impact hormone levels, mood, cognitive performance, well-being, and alertness [3]–[5], in addition to affecting human body temperature and thermal responses [6], [7]. Hence, light is known to be an important asset to determine and provide comfort in an interior and advance occupant’s well-being.

To design energy-efficient buildings, we need to better understand the factors affecting human thermal comfort. There are two main models to determine the thermal comfort of an interior: the conventional heat balance model, which predicts human thermal sensation by creating the “predicted mean vote” (PMV) and the adaptive model, which depends on “actual sensation vote” (ASV) [8]–[10]. The adaptive model suggests that occupants can adapt to their thermal environment by different adaptive methods [11] and gives a wider acceptable range of temperature for buildings [12]–[14], and thus, the use of the adaptive method instead of PMV may improve energy efficiency. Besides, several studies demonstrated a gap between the calculated PMV values and the occupants’ actual sensation votes (ASV) mainly due to the participants’ behavioral thermal adaptations [14]. Jing et al. (2018) reported the highest percentage of consistency in occupant thermal adaptation at 27°C and stated that this temperature could be used as a comfort temperature for free-running buildings instead of 25.5°C which was obtained by the heat balance model [12].
Occupants experience the indoors as a whole [15], and thus, when focusing on human reaction to an indoor environmental factor, the other indoor factors should be taken into consideration as well [16]. Non-thermal factors such as light, odor, and sound may affect thermal responses (cross-model effect), and thermal comfort models need to include them as well [13]. Since the neural pathways activated by light and temperature have an intersection point inside the brain, light-induced thermal responses might occur, and thus, light can impact thermal perceptions and thermal comfort (TC) [6], [17].

Numerous studies have documented the effects of light intensity and lighting spectrum on thermophysiological responses and thermal perception [6], [17], [18]. But these studies focus mainly on the effects of artificial light, and the studies on daylight, its color temperature, and their effects on thermal responses are still very limited [19]–[22]. However, those limited studies argue that, in a daylight-lit interior, occupants can tolerate the warm environments more than in an artificially lit one due to the changes in their thermal perception [19], [22]. Chinazzo et al. (2019) reported that human thermal comfort and acceptability are affected by the presence of daylight and its intensity [19]. The experience took place in a controlled space with three different illumination levels (130 lux, 600 lux, and 1400 lux) and under three different indoor air temperature levels (19°C, 23°C, 27°C). At the warm thermal condition (27°C), they reported the thermal sensation of participants (ASV) being almost 2°C lower than the calculated PMV according to the measured indoor conditions. While the bigger gap being received under the lower illuminance, a gap between ASV and calculated PMV was observed in all light intensity conditions. Since participants had no possible ways to adapt to their thermal environment during the experiment, the study argued that PMV could not predict the psychological impacts of daylight and resulted in an overestimated PMV. Hence, we can assume that daylight-lit interiors may require different strategies, regulations, and conditioning than artificially lit ones to receive optimum energy values and reduce the carbon footprint.

This paper investigates a) whether this daylight and thermal perception relation can help to reduce the total energy consumption of a test room during summer months (June, July, August) by rearranging the cooling set-point temperature according to the reported 2°C gap, and b) if this new setting would affect Austin differently due to its warmer climate and higher cooling demand than Geneva.

2. Material and method
To calculate the energy consumptions of a test room in summer months, based on daylight presence and rearranged cooling set-point temperatures, eight different energy simulations were performed.

2.1. Studied parameters
Several parameters, variables, and constants are identified and listed below for this study (Table 1). By these simulations, the increase in cooling loads due to solar heat gain and the changes in cooling loads due to rearranged set-points and the lighting loads due to daylight use have been observed separately.

| Parameters                        | Case 1     | Case 2     | Case 3     | Case 4     | Case 5     | Case 6     | Case 7     | Case 8     |
|-----------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Font                              |            |            |            |            |            |            |            |            |
| Location                          | Geneva     | Geneva     | Geneva     | Geneva     | Austin     | Austin     | Austin     | Austin     |
| Latitude                          | 46.25°N    | 46.25°N    | 46.25°N    | 46.25°N    | 30.29°N    | 30.29°N    | 30.29°N    | 30.29°N    |
| Date                              | June-July-August |            |            |            |            |            |            |            |
| Daylight                          | Yes        | No         | Yes        | No         | Yes        | No         | Yes        | No         |
| Cooling set-point                 | 25°C       | 25°C       | 27°C       | 27°C       | 25°C       | 25°C       | 27°C       | 27°C       |
| Independent variables             |            |            |            |            |            |            |            |            |
| Sky condition and outside temp.   | *VARIIES*  |            |            |            |            |            |            |            |
| Dependent variables               | Cooling and lighting loads | RESULTS |            |            |            |            |            |            |
| Constants                         | Window orientation | N & S     | N/A        | N & S     | N/A        | N & S     | N/A        | N & S     |
| Building model                    | 1          | 2          | 1          | 2          | 1          | 2          | 1          | 2          |
2.2. Selected case
The model data is a representation of the office-like test room used in Chiazzino et al.’s daylight experiments at EPFL [27]. Four energy simulations were performed (Case 1-4) to calculate the results of the different arrangements in Switzerland. Later, the same set of simulations were repeated for Austin (Case 5-8). To see the impacts of daylight use in a location with higher cooling demand, Austin has been picked due to its hot-humid climate and almost year-long cooling demands. Also, while Geneva is at 46°N latitude, Austin is at 30°N which is a preferable latitude to work on since it passes along a big portion of land and has an arid or semi-arid climate. These two locations are used to show the effects of latitude on energy consumption regarding daylight since the sun angle and intensity change by latitude.

2.3. Modeling process

Figure 1. Modeling process flowchart.

The modeling process consisted of five steps (Figure 1). The first step was to 3d model the EPFL test room on SketchUp. The test room geometry, the building type (office), the space type (closed office, 1-3 people), thermal zones (one thermal zone), two daylight control devices (fraction: 0.5, illuminance set-point: 500 lux), illuminance maps, and the exterior condition of the surfaces (ground, adiabatic, and exterior wall) have been modified by SketchUp and its OpenStudio plug-in. Two different models, with and without windows, (Figure 2) were created. As a difference from the original EPFL test room conditions, in this research, the east and west-facing walls, roof, and the ground have been considered as adiabatic surfaces to represent a cut portion of a regular office building.

Figure 2. The test room geometry, model 1 (left): with windows and model 2 (right): without windows.

The second step was to implement the weather data and assign the construction material, systems, and schedules of the building model with OpenStudio. The weather data was obtained from the Energy Plus website of the U.S. Department of Energy, and two sets of Typical Meteorological Year (TMY) file (Geneva 067000 (IWEK) for Geneva Cases and Austin-Mueller Muni AP 722540 (TMY3) for Austin Cases) have been used to receive meteorological data values. The data for materials, systems, and schedules comes from already existing OpenStudio construction and schedule sets for the office building type. The software has the average data of the construction materials, loads, and schedules of a regular office building. For exterior walls, in Austin cases, ASHRAE 189.1-2009 Exterior Wall Climate zone 2 material set, and in Switzerland cases ASHRAE 189.1-2009 Exterior Wall Climate zone 8 material sets have been used. As the HVAC system, Variable Refrigerant Flow (VRF) is used, which can be defined as a large-scale ductless HVAC system that can work at a high capacity and be used for heating and cooling simultaneously since it may operate as a heat pump or heat recovery system.

The third step was to define the parameters and create the energy simulations in OpenStudio. For each of the eight simulations, the location, the base models, the simulation run date for June, July, August, and the 25°C or 27°C cooling set-points have been applied by two new schedules.

The fourth step was to obtain daylight analysis for the daylight lit cases. To get accurate data, the windows were placed facing the same direction as the EPFL test room (north and south), for efficiency, daylight control devices and to provide data for illuminance levels, illuminance maps were used. The
material data of the windows (Table 2) have been modified to match with the visual transmittance values of the EPFL test room under the low illuminance condition [23].

Table 2. Glazing characteristics of exterior windows used in daylight-lit cases.

|                          | Case 1, Case 3, Case 5, Case 7 |
|--------------------------|---------------------------------|
| Name                     | Theoretical Glass [197]         |
| Source                   | ExtWindow C2, OpenStudio        |
| Thickness (mm)           | 3                               |
| Solar Transmittance at Normal Incidence | 0.2349                 |
| Front Side Solar Reflectance at Normal Incidence | 0.7151          |
| Back Side Solar Reflectance at Normal Incidence | 0          |
| Visible Transmittance at Normal Incidence * | 0.07                     |
| Front Side Visible Reflectance at Normal Incidence | 0.6988           |
| Back Side Visible Reflectance at Normal Incidence | 0          |
| Infrared Transmittance at Normal Incidence | 0          |
| Front Side Infrared Hemispherical Emissivity | 0.9            |
| Back Side Infrared Hemispherical Emissivity | 0.9            |
| Dirt Correction Factor for Solar and Visible Transmittance | 1          |
*Visible transmittance value is matched with the EPFL test room. (Prev. 0.2512, now 0.07)

The final step was to gather the results of these eight simulations. In the OpenStudio, the output variables regarding the total energy consumption, individual cooling and electrical lighting loads, and the data regarding the effects of daylight on heat gain and energy consumption have been collected for each simulation. Later, the most significant outcomes of each simulation are determined and evaluated to clarify how each factor has affected energy use in different scenarios.

3. Results

As briefly discussed before, four of these scenarios explored different daylight and cooling set-point temperature arrangements at the Switzerland location and calculated their energy consumption results for June, July, and August. The other four scenarios examined the same arrangements for the Austin location (Table 3). The energy simulation results are obtained in OpenStudio and Energy Plus formats, and the most significant outcomes of each case have been determined and evaluated.

Table 3. Characteristics of cases.

|                | Geneva                          | Austin                        |
|----------------|---------------------------------|-------------------------------|
| Cases          | Case 1, Case 2, Case 3, Case 4  | Case 5, Case 6, Case 7, Case 8 |
| Dates          | June, July, August              | June, July, August            |
| Latitude       | 46.20°N                         | 30.29°N                       |
| Longitude      | 6.14E                           | 97.7W                         |
| Elevation (m)  | 375                             | 213                           |
| Total building area (m²) | 20                          | 20                            |

3.1. Total energy use

In figure 3, the total site EUI (kWh/m²) results for each case are demonstrated. It is seen that Switzerland cases on average consumed 37.5% less energy than the Austin cases during the testing period. The highest energy demand in Switzerland was observed for the 25°C without daylight scenario (case 2: 30.6) and followed by case 4 (28.93), case 1 (27.1), and case 3 (25.3). On the other hand, in Austin, case 5 (47.95) had the highest energy consumption and followed by case 6 (45.87), case 7 (42.81), and the least was observed for case 8 (42.4). In both locations, 27°C with daylight conditions led to a decrease in total energy consumptions compared to their base conditions, which were the 25°C without daylight scenarios in their respective locations. However, there is a significant difference between these two locations when it comes to the daylight presence effects; in Switzerland, at both temperatures, daylight
use resulted in significant energy consumption reductions whereas, in Austin, daylight presence led to an increase in energy demand which was observed more at 25°C cases.

### Figure 3. Total site EUI (kBtu/ft²) per all scenarios in June, July, and August.

Figure 4 provides a perspective on how each of the eight scenarios alters the total energy consumption and the cooling loads of the test room in the given period. The first row of graphs represents the Switzerland scenarios (Case 1-4) and the second row shows the results of the Austin cases (Case 5-8). Solid lines represent the total energy consumption, whereas the dashed lines indicate the cooling load in respective months. The light grey lines are used to refer to the results of the 25°C w/o daylight case in its respective city (Case 2 results for the Geneva cases and Case 6 results for the Austin cases), to use it as a base in comparisons. The significantly higher total energy and cooling demands can be observed in detail for Austin cases compared to Switzerland. These demands pick in July for Austin, whereas the highest levels are similar in July and August months for Switzerland. On average, the cooling load is responsible for around 30% of the total energy consumption of Switzerland cases, whereas this ratio is more than 55% for Austin. Again, it is seen that daylight presence at the same temperature reduces energy consumption for Switzerland, while in Austin, it increases the energy demand due to heat gain.

### Figure 4. Energy consumption per all scenarios in June, July, and August: total and cooling loads.

#### 4. Discussion and conclusions
This research aimed to find out whether daylight and thermal perception relation can help to reduce the energy consumption ratios of a test room in Austin and Geneva during June, July, and August, based on the results of previous work. It also explores if the higher cooling demand and warmer climate in Austin would create a different impact than the one on Geneva. To answer these questions, four different energy simulations have been performed per each location under two different temperature set points (25°C and 27°C) with and without daylight presence. According to the OpenStudio and Energy+ results, two main observations are made. Firstly, among the cases with the same temperature levels, the daylight presence in Switzerland led to a decrease in energy consumption while the opposite was observed in Austin, and cases with daylight received higher energy consumption results due to the additional heat gain. In
Switzerland, daylight presence reduced the total energy consumption so significantly that, even with a 2°C difference, the 25°C with daylight case (case 1) still had a lower energy consumption result than the 27°C without daylight scenario (case 4). Secondly, at both locations, the 27°C with daylight cases (case 3 and 7) had lower energy consumption results than the 25°C without daylight cases (case 2 and 6). In conclusion, if a location has lower cooling demand and mild solar conditions, like the Geneva cases, and a higher cooling set-point temperature is arranged, a bigger impact on energy use in summer due to daylight presence can be expected. Future research is needed to further explore how to adapt this strategy for hot or humid climates.

References

[1] M. S. Rea and M. G. Figueiro, “Light as a circadian stimulus for architectural lighting,” Light. Res. Technol., vol. 50, no. 4, pp. 497–510, 2016, doi: 10.1177/1477153516682368.
[2] G. C. Brainard et al., “Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor,” vol. 21, no. 16, pp. 6405–6412, 2001.
[3] S. W. Lockley, “Circadian Rhythms: Influence of Light in Humans,” in Encyclopedia of Neuroscience, L. R. Squire, Ed. Oxford: Academic Press, 2009, pp. 971–988.
[4] M. G. Figueiro, R. Nagare, and L. L. A. Price, “Non-visual effects of light: How to use light to promote circadian entrainment and elicit alertness,” Light. Res. Technol., vol. 50, no. 1, pp. 38–62, 2018, doi: 10.1177/1477153517721598.
[5] S. W. Lockley, “Spectral Sensitivity of Circadian, Neuroendocrine and Neurobehavioral Effects of Light,” vol. 11, no. 1, pp. 43–49, 2008.
[6] M. Kulve, L. Schellen, L. J. M. Schlangen, and W. D. V. M. Lichtenbelt, “The influence of light on thermal responses,” pp. 163–185, 2016, doi: 10.1111/apha.12552.
[7] M. Kulve, L. J. M. Schlangen, L. Schellen, A. J. H. Frijs, and W. D. V. M. Lichtenbelt, “The impact of morning light intensity and environmental temperature on body temperatures and alertness,” Physiol. Behav., vol. 175, no. March, pp. 72–81, 2017, doi: 10.1016/j.physbeh.2017.03.043.
[8] E. Halawa and J. Van Hoof, “The adaptive approach to thermal comfort: A critical overview,” Energy Build., vol. 51, pp. 101–110, 2012, doi: 10.1016/j.enbuild.2012.04.011.
[9] E. W. Shaw, “Thermal Comfort: analysis and applications in environmental engineering,” by P. O. Fanger. 244 pp. Danish Technical Press. Copenhagen, Denmark, 1970. Danish Kr. 76, 50, ”R. Soc. Health J., vol. 92, no. 3, p. 164, Jun. 1972, doi: 10.1177/146642407209200337.
[10] R. Yao, B. Li, and J. Liu, “A theoretical adaptive model of thermal comfort - Adaptive Predicted Mean Vote (aPMV),” Build. Environ., vol. 44, no. 10, pp. 2089–2096, 2009, doi: 10.1016/j.buildenv.2009.02.014.
[11] K. J. Mcclernan and J. F. Nicoll, “Developing an adaptive control algorithm for Europe,” vol. 34, pp. 623–635, 2002.
[12] S. Jing, B. Li, and R. Yao, “Exploring the ‘black box’ of thermal adaptation using information entropy,” Build. Environ., vol. 146, no. September, pp. 166–176, 2018, doi: 10.1016/j.buildenv.2018.09.038.
[13] R. de Dear and G. S. Brager, “Thermal Adaptation in the Built Environment: a Literature Review,” Forensic Eng. Damage Assessments Resid. Commer. Struct., vol. 7788, no. 97, pp. 421–436, 1998, doi: 10.1201/b14052.
[14] Y. Yang, B. Li, H. Liu, M. Tan, and R. Yao, “A study of adaptive thermal comfort in a well-controlled climate chamber,” Appl. Therm. Eng., vol. 76, pp. 283–291, 2015, doi: 10.1016/j.applthermaleng.2014.11.004.
[15] K. Parsons, Human thermal environments: The effects of hot, moderate, and cold environments on human health,comfort, and performance, third edition
[16] C. Laurentin, V. Bermotto, and M. Fontoynont, “Light Source Type on Visual Appraisal,” Ligh. Res. Technol., pp. 223–233, 2000.
[17] I. Golasi, F. Salata, E. de L. Vollaro, and A. Peña-García, “Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations,” Energy Build., vol. 185, pp. 112–122, 2019, doi: 10.1016/j.enbuild.2018.12.026.
[18] S. J. Park and H. Tokura, “Effects of different light intensities during the daytime on circadian rhythm of core temperature in humans,” Appl. Human Sci., vol. 17, no. 6, pp. 253–257, 1998, doi: 10.2114/pha.17.253.
[19] G. Chinazzo, J. Wienold, and M. Andersen, “Daylight affects human thermal perception,” Sci. Rep., no. August, pp. 1–15, 2019, doi: 10.1038/s41598-019-48963-y.
[20] G. Chinazzo, “A field study investigation on the influence of light level on subjective thermal perception in different seasons,” no. April, 2018.
[21] G. Chinazzo, J. Wienold, and M. Andersen, “The Effect of Coloured Glazing on Thermal, Visual and Overall Comfort Evaluation,” AIC Lisbon colour Hum. Conr., no. September, 2018.
[22] J. Veitch and A. Galasius, The Physiological and Psychological Effects of Windows, Daylight, and View at Home: Review and Research Agenda. 2012.
[23] I. T. Uckok, “Daylight and Thermal Comfort: Energy Performance Analysis of a Test Room Under Different Daylight and Cooling Strategy Scenarios in Austin, Texas, and Geneva, Switzerland,” 2020.