The effect of fenestration system on building daylighting and solar radiation – An experimental study in humid subtropical climate

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ABSTRACT

Modern buildings tend to have large glass facades for good outdoor view and daylight utilization. Compared to traditional masonry wall construction, the lower thermal resistance values can result in increased heat losses (and solar gains) and hence reduce the heating and cooling energy efficiency of modern transparent facades. The balance between daylighting benefits and energy requirements should be investigated in detail for optimizing the design of modern fenestration systems by local climate.

This experiment studies the effects of window orientation, size, and glazing properties (low-e) on Useful Daylight Illuminance (UDI) and Transmitted Solar Radiation (E_{SR}). Unlike other experimental studies, the window properties are varied without replacing the window installation – thus controlling construction-related sources of error. Window properties were instead varied by rotating the wheel-mounted test house to a different orientation and using opaque polystyrene foam to change the effective window size. Two test houses (1.8 x 1.8 x 2.4 m) were placed outdoors in a hot and humid climate of southeastern Texas. The test houses' windows had different low-emissivity glazings (visible transmittances of 74% and 64%). Seven combinations of window orientation (facing North, West, East, or South) and window size (16%, 25%, 36%, or 47% Window-To-Wall Ratio (WWR)) were tested for each test house. Solar radiation, light, and temperature were monitored inside and outside of the test houses every 5 minutes for several days per setting. Daily UDI at workplane height (0.8 m) and daily E_{SR} through the window were calculated and compared to determine optimal orientation-size settings. As expected for the sunny climate, glare (over 2000 lux) was the main source of non-useful daylight. Adding shade controls on east and west orientations will reduce E_{SR} and glare in the mornings and afternoons, respectively. South orientation should be protected by a shallow roof overhang at this latitude during summer months. These preliminary results suggest the best size-orientation combination tested was a 16% WWR window in the south orientation, which achieved a 99% average UDI for both window glazing types. These results were attributed to the sun angle and the proportion of direct and reflected sunlight. Global horizontal solar radiation, sol-air temperature, and clearness index (K_t) were calculated to control for weather variations and to improve comparisons for limited data.

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INTRODUCTION

Energy efficiency buildings are an area of great potential for emissions reductions in the US, where 41% of US energy consumption is used in buildings, including for air conditioning (EIA 2017). Recent improvements in computational capacity and efficiency have accelerated development of quicker and more precise simulation tools, which are used in both research and industry. However, experimental studies are necessary to validate simulation studies. Major limitations of past research include the need to extend results to different climates (Shen & Tzempelikos 2012), the uncertainty in weather conditions (Herrera et al. 2017), the complexity of full building systems (Cannon-Brookes 1997), and the sensitivity of simulations to chosen initial parameters (Reinhart & Davila, 2016; Shen & Tzempelikos 2013). Simulation studies use Typical Meteorological Year (TMY) to account for uncertainty, but according to Reinhart (2012), "many simulations find TMY not stringent enough to meaningfully test the performance of a building under extreme weather conditions such as heat waves." This full-scale experimental study uses Average Daily Useful Daylight Illuminance to evaluate daylighting performance and Average Daily Transmitted Solar Radiation to evaluate thermal performance.

METHODOLOGY

Two 1.8m x 1.8m x 2.4m test houses were constructed using a typical 2x4 stud wall construction with OSB instead of drywall on the interior of the houses. Each had a double-glazed insulated glass unit (IGU) window with a different low-emissivity glazing centered on a wall in a 4-inch-wide aluminum frame. These windows – denoted A and B – had UV transmittances of 40% and 6%; visible light transmittances (VT) of 74% and 64%; U-Factors of 0.33 and 0.28; and solar heat gain coefficients (SHGC) of 0.63 and 0.27, respectively, according to the manufacturers. The normalized transmittances are plotted in Figure 1 based on calculations from the Lawrence Berkeley National Lab's WINDOW software (Figure 1). Combinations of four window orientations and four window sizes – denoted by Window-To-Wall Ratio (WWR) – were tested for two test houses; these combinations of settings are summarized in Table 1.

Table 1. Window glazing, size, and orientation for each setting

Test House*	Window / UV transmittance / VT / U-factor / SHGC**	Eff. WWR / Size [m] / Lower-sill height [m] ***	Orientation	Amount of data [days]
A	A / 40% / 74% / 0.33 / 0.63	16% / 0.61 x 0.88 / 0.76	South	9
A	A / 40% / 74% / 0.33 / 0.63	25% / 0.76 x 1.1 / 0.65	South	2
A	A / 40% / 74% / 0.33 / 0.63	36% / 0.91 x 1.3 / 0.54	South	2
A	A / 40% / 74% / 0.33 / 0.63	47% / 1.1 x 1.5 / 0.44	South	4
A	A / 40% / 74% / 0.33 / 0.63	47% / 1.1 x 1.5 / 0.44	West	4
A	A / 40% / 74% / 0.33 / 0.63	47% / 1.1 x 1.5 / 0.44	North	4
A	A / 40% / 74% / 0.33 / 0.63	47% / 1.1 x 1.5 / 0.44	East	7
B	B / 6% / 64% / 0.28 / 0.27	16% / 0.61 x 0.88 / 0.76	South	7
B	B / 6% / 64% / 0.28 / 0.27	25% / 0.76 x 1.1 / 0.65	South	2
B	B / 6% / 64% / 0.28 / 0.27	36% / 0.91 x 1.3 / 0.54	South	4
B	B / 6% / 64% / 0.28 / 0.27	47% / 1.1 x 1.5 / 0.44	South	4
B	B / 6% / 64% / 0.28 / 0.27	47% / 1.1 x 1.5 / 0.44	West	4
B	B / 6% / 64% / 0.28 / 0.27	47% / 1.1 x 1.5 / 0.44	North	4
B	B / 6% / 64% / 0.28 / 0.27	47% / 1.1 x 1.5 / 0.44	East	7

*Test Houses A and B were constructed with the same design, but may have minor construction-related variability
** UV transmittances, VT, U-factor and SHGC for Windows A and B provided by manufacturer
*** Effective size measures the un-blocked part of the window, centered to the original window, frame, and wall.

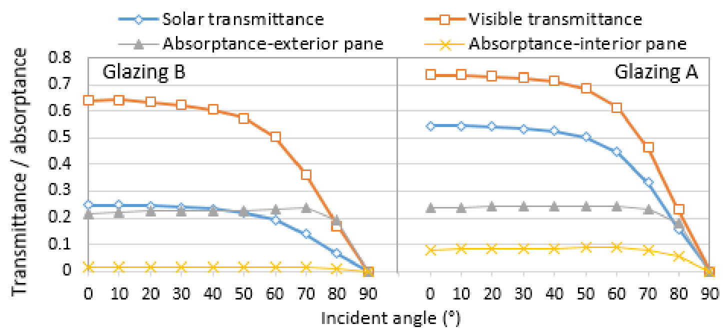

Figure 1 Glazing properties of Windows A and B by incident angle

This case study is the only known experimental study conducted in a hot and humid climate (US Climate Zone 2a) of Southern Texas (27°N latitude), and it is the only known experimental set-up in which the test cell is fully rotated to different compass orientations in order to vary the window orientation without changing any other test parameters. Sensors were installed on the house to monitor solar radiation on window surfaces, walls, and a typical work-plane location inside the test room. This includes pyranometers on the center of each exterior wall, thermocouples on the center of each interior wall, a photometer in the center of the room (0.8 m from the floor, 0.6 m from the window, centered between the walls at 0.5 m from each wall), and photometers, pyranometers, and thermocouples on the interior and exterior surfaces of the window. The test room could be thought to model a window-facing cubical with reflective wall treatment. Data was collected at a 5-minute time interval for a few days for each combination of settings from June to August.

Data Analysis

Useful Daylight Illuminance (UDI) is the percentage of time during working hours (defined in this study as 8am-6pm) that a horizontal surface receives illumination within the range of 100-2000 lux. This study calculated the UDI for each day and averaged these daily UDI values for each setting. This study also considered the sub-bins of 100-500 lux ($UDI_{100-500}$), 500-1000 lux ($UDI_{500-1000}$), and 1000-2000 lux ($UDI_{1000-2000}$) to gauge computer screen glare. UDI is a more refined metric than daylight autonomy because UDI excludes glare, i.e. too much light, but accounts for the complementary use of low daylighting (as low as 100 lux) with artificial lighting. Daily UDI was calculated based on the light levels detected at 0.6 m behind the window at workplane height (0.8 m above the floor).

The daily transmitted solar radiation (E_{SR}) through the window was calculated by integrating the solar radiation data from sunrise to sunset over the effective area of the window. In this study, E_{SR} functions as an indirect measure of total solar heat gain and resulting indoor cooling loads, and it accounts only for the transmitted solar radiation through the window, which was the only variable in the test cell construction. The heat gains due to conduction through the building envelope were omitted also in part because the indoor temperature conditions for this experiment (30-60°C) were not easily relatable to the conductive heat gain patterns for typical indoor temperatures (20°C).

To check for correlation with and effect of weather variation, additional weather data was collected and analyzed. A pyranometer on the roof of a nearby building was used to determine the global horizontal solar radiation (S_R) profile, which is the tradition approach to identify weather variation. In addition, the clearness index (K_t), which is an approach for quantifying cloud cover, was calculated as the ratio of the measured direct solar radiation to the theoretical clear sky radiation. The theoretical clear sky radiation (also known as average extraterrestrial radiation incident on the top of the Earth's atmosphere) for a given day and location is calculated based on astronomical-geographical constants (Homer Pro 3.9 n.d.; NOAA ESRL GMD n.d.).

RESULTS

Daily Useful Daylight Illuminance (UDI)

Figure 2 shows the average daily UDI for each window type, size, and orientation setting, with UDI broken into different light bins of 100-500 lux, 500-1000 lux, and 1000-2000 lux. For each window setting, the daily $UDI_{100\text{-}500}$, $UDI_{500\text{-}1000}$, and $UDI_{1000\text{-}2000}$ were calculated and averaged separately; these binned UDI averages were then plotted with the averages for the other bins of that window setting. For both Windows A and B, average daily UDI generally decreased with size. This occurred because as the window size increased from 16% to 36%, the amount of glare also increased. However, the 47% setting had a higher average daily UDI than the corresponding 36% setting, including within the middle 500-100 lux bin (Figure 2).

For Window A, 6 of the 7 size-orientation settings had a majority of the useful daylight in the 1000-2000 lux bin, and 3 of the 4 orientation settings at 47% WWR had no light in the 100-500 lux bin. Window B had a more even distribution of useful daylight across the three bins: there will still 4 of the 7 size-orientation settings that had a majority of, but every size-orientation setting had some useful daylight in the 100-500 lux bin, and the East-facing setting had up to 32.8% +- 27.3% in this 100-500 lux bin.

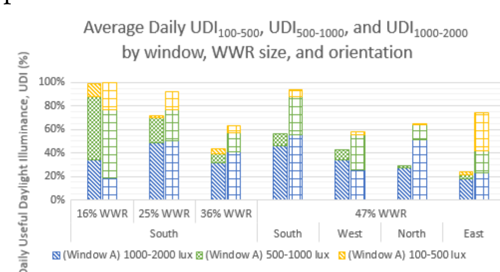

Figure 2 Average daily $UDI_{100\text{-}500}$, $UDI_{500\text{-}1000}$, and $UDI_{1000\text{-}2000}$ for Window A and B by size and orientation.

The size setting with the greatest overall UDI was 16% WWR (99.8%±0.6% UDI for Window A; 99.2%±1.2% for Window B); the setting with the least overall UDI was 36% WWR (62.9%±7.7% UDI for Window A; 43.3%±7.5% UDI for Window B). The standard deviation of the average daily UDI was as high as 13% for several settings. However, the standard deviation for individual sub-bins was as high as 29%, including for settings that had a low standard deviation of the total UDI. For example, for Window A at 16% WWR size facing south, the UDI had a standard deviation of 1%, but $UDI_{500\text{-}1000}$ and $UDI_{100\text{-}500}$ had standard deviations of 28% and 29%, respectively. This suggests that the sub-bin UDI results are sensitive to the chosen thresholds, which must be considered when using UDI metrics in practice.

For both Windows A and B, the South orientation resulted in the maximum UDI and the minimum glare (Figure 2). This result is attributed to the sun angle at this latitude and time of year. Sun-path diagrams for summer dates shows the azimuth angle comes from the north during low-altitude angle, glare-prone time periods (i.e. dawn and dusk); thus, there is no direct path into a south-facing window.

The trend in UDI for different window orientations is inconclusive; the trend in UDI based on window orientation differed between Windows A and B. For Window A, the West orientation resulted in the second-highest UDI of the tests with 47% WWR size, but for Window B, the East orientation resulted in the second-highest UDI of the tests with 47% WWR size (Figure 2). More research is needed to understand how the placement of the test cells or other factors might have affected these results.

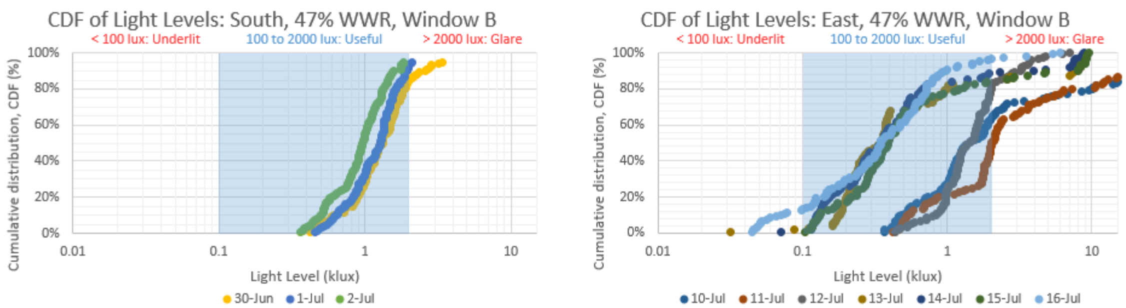

Figure 3 Cumulative distribution (CDF) of light levels for Window B in South- and East-facing orientations.

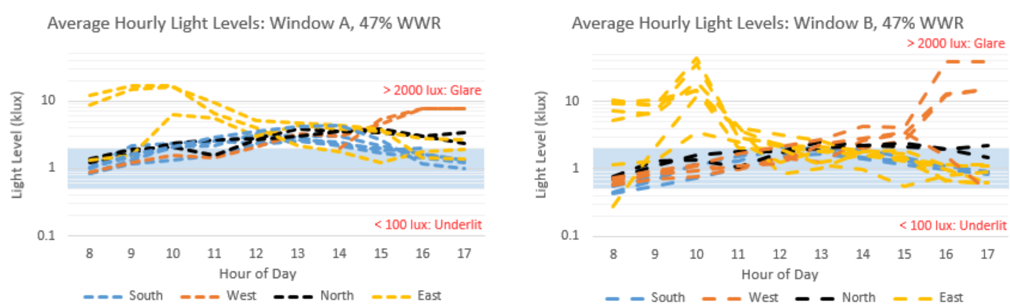

Figure 4 Average hourly light levels from 8am – 6pm for Windows A and B at 47% WWR by orientation. The blue band shows the range of useful daylight (100-2000 lux).

Too much light over 2000 lux (glare) was the primary source of not-useful daylight (Figure 3 and Figure 4). The shape of the daily cumulative distribution function (CDF) curves for light levels suggest that certain orientations may be more sensitive to the UDI thresholds. East and West yield greater ranges of light levels because of glare and direct sunlight in the mornings and afternoons, respectively. The shape of the CDF curves for the East orientation vary more than that of the South. This suggests that the East orientation is more sensitive to cloudiness, whereas the South orientation, which predominately receives indirect sunlight, may be more dependent on exterior reflectance of nearby buildings and surfaces. Additional data and analysis could quantify the sensitivity of UDI to light thresholds and to weather conditions.

Daily Transmitted Solar Radiation (E_{SR})

For both windows, the total average daily transmitted solar radiation (E_{SR}) increased with window size (Figure 5). Moreover, there was a linear trend between window-to-wall ratio and E_{SR}, which is expected because the incident solar radiation at the center of the window was expected to be independent of the window size and because the WWR is directly proportional to the window area by definition. Thus for both windows, the size setting with the minimal E_{SR} was the smallest size, 16% WWR; the size setting with the maximum E_{SR} was the largest size, 47% WWR. The South orientation had the minimum E_{SR}, and the West orientation had the highest E_{SR} (Figure 5).

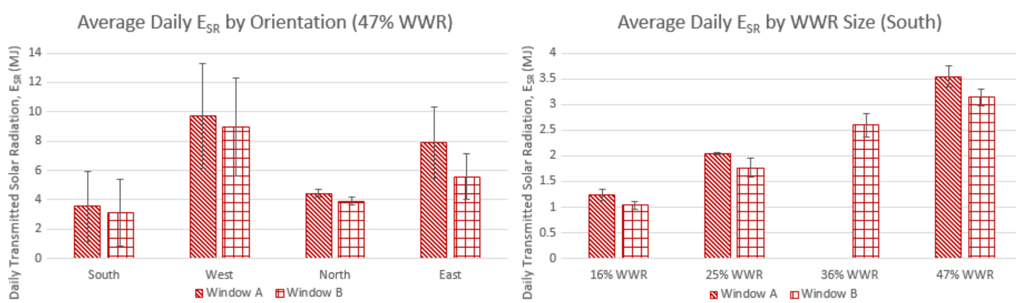

Figure 5 Average daily E_{SR} in megajoules (MJ) for Window A and B for different size and orientation settings. Data for 36% WWR for window A was corrupted.

For all size and orientation settings, Window B performed better than Window A for hot climates with a lower E_{SR}, as expected based on the manufacturer-reported solar transmittance properties (Table 2). On average, Window A had a 13% higher E_{SR} than Window B, which accounts for the difference in solar radiation transmittance between Windows A (62% expected solar radiation transmittance) and B (41% expected solar radiation transmittance). The setting with the greatest difference was the East orientation with 27% - 44% difference in solar radiation between the two windows. However, the setting with the least difference was the West orientation with 8% - 12% difference in solar radiation between the two windows (Table 2).

Table 2. Comparison of Transmitted Solar Radiation (E_{SR}) for Windows A and B by orientation

Orientation	Average Daily E_{SR} Window A [MJ]	Average Daily E_{SR} Window B [MJ]	Range of Daily E_{SR} Disparity [%]	Mean Daily E_{SR} Disparity [%]
South	3.55	3.14	10% - 16%	12%
West	9.72	11.01	8%- 12%	9%
North	3.66	4.16	12% - 13%	13%
East	7.86	5.58	27% - 44%	33%

The solar radiation and visible light incident on the exterior and interior surface of the window was measured, and the average ratio between the interior and exterior values were compared to expected transmittance values (Table 3). The expected normal visible transmittance was provided by the manufacturer as per ASTM/NFRC 200. The expected solar radiation transmittance was estimated as 62% and 41% for Windows A and B, respectively, based on the approximate proportion of UV, visible, and infrared waves in sunlight and manufacturer transmittance specifications. The mean solar radiance and visible light transmittances (averaged from 11am - 5pm) for Windows A and B were less than the expected transmittance value (Table 3). Low transmittances before 11am and high transmittances after 5pm were attributed to low sun angle and the resulting increase in proportion of diffuse light, although a potential source of error may be long shadows from nearby objects. Further data analysis on the transmittance over time of day for specific window orientations could further explain the effect of sun angle and diffuse light on transmittance.

Table 3. Measured and expected radiation and visible light transmittances

Window	Average S_R ± stdev	Expected S_R	Average VT ± stdev	Expected VT
Window A	45% ± 10%	62%	58% ± 9%	74%
Window B	40% ± 11%	41%	49% ± 9%	64%

DISCUSSION

UDI results are expected to be significantly different during the winter, when the sun shines directly into South-facing windows at this latitude, but a shallow roof overhang may suffice to protect the South orientation. Moreover, up to 20 klux of glare were observed in the morning and afternoon for the East-facing and West-facing orientations, respectively. Shade controls on west and east orientations could reduce unwanted solar radiation transmission and glare in the mornings and afternoons, respectively, thus improving thermal and lighting performance.

The optimal size was the smallest size (16% WWR) for both UDI and E_{SR}. The linearly decreasing trend in E_{SR} with size suggests that the optimal size setting in practice is the smallest size. A practical lower bound for this trend may be 16% WWR, which was the smallest size tested in this study and which achieved almost perfect UDI (99.8%±0.6% for Window A; 99.2%±1.2% for Window B), but this is an unreasonable recommendation in practice because of aesthetic design considerations and an architectural trend towards large window facades with good views. However, new smart window technology including sensor-controlled shade systems (Shen 2012), switchable windows, electrochromic glazings, and thermotropic glazings may provide more flexibility and may allow for a high UDI and large views even in sunny climates.

High interior reflectance due to the glossy gray paint and small room dimensions may result in increased values at the sensor in the middle of the room. More research may be necessary to tailor the window performance and to determine accurate transmissivity values to the specific climate in question because the use of direct light for rating windows and assigning manufacturer specifications is an oversimplification that may lead to inaccurate or misleading specifications.

CONCLUSION

The combination of a 16% WWR size and South-facing orientation yielded the best UDI and lowest E_{SR} results in this preliminary study, with a 99% average UDI achieved in this setting for both windows glazing types. These results were attributed to the proportion of direct and reflected sunlight, which depend upon sun angle and reflective properties of the floor and ground.

In this experimental case study, custom full-scale test cells were set up in a hot and humid climate. The test cells were mounted on wheels so that they could be rotated in different orientations without changing any other aspect of the set-up. The effect of varying window size was produced by covering parts of the window with opaque foam insulation frames. From July to August, solar radiation, light level, and temperature data at 5-minute time intervals for a few days per setting were observed and used to calculate Useful Daylight Illuminance and Transmitted Solar Radiation as metrics for lighting and thermal performance.

Practical aesthetic design constraints, the lighting distribution needs, or the building occupancy patterns could impose additional constraints and yield different results. Further thermal analysis is necessary to link transmitted solar radiation to temperature increases in the cell. Follow-up studies using experiments, simulations, and statistics are planned to generalize results to other WWR values and settings, to cross-validate experimental results with simulation data, and to study how interior reflectance affects light distribution.

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NOMENCLATURE

S_R = solar radiation

E_{SR} = total energy of transmitted solar radiation through the window

UDI = Useful Daylight Illuminance

K_t = clearness index

CDF = cumulative distribution function

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