

# Daylight Performance of Subdivided Windows with Automatic and Manual Shading Devices

Leyla Sanati, Ph.D.

Integrated Design Lab, University of Idaho, Boise, Idaho, USA

## Abstract

The admission of daylight into the buildings has numerous benefits concerning building energy use and occupant mood, well-being, and productivity. These benefits are rarely achieved in buildings where fenestration design is reduced to an opening with a manual blind due to occupants' infrequent shade operation. On the other hand, fully automated shading systems are often disliked and overridden by the occupants. This paper examines the daylight performance of two subdivided window systems with automatic louvers on the upper half and manual blinds on the lower half of the window. The results show that a subdivided window mixing manual and automatic shading devices has the potential to produce significant energy saving while keeping the occupants in the control loop.

## Introduction

Field studies of occupant shade control behavior often suggest that occupants do not control the shades actively in response to environmental conditions. Rather, their shade control behavior is affected by their long term perception of "worst case" solar condition. Therefore manual shading devices are assumed to interfere with daylight harvesting in buildings. Most of these studies however have been conducted in buildings with unsubdivided windows. The very few studied that observed occupant shade control behavior on subdivided windows demonstrate that occupants control the lower shades more actively than the upper shades and conclude that psychological factors might be involved in occupant shade control behavior (Konis 2012).

A field study of subdivided windows with fixed upper louvers and manual lower venetian blinds showed that perimeter occupants controlled the venetian blinds more actively on such windows compared to unsubdivided windows (Sanati & Utzinger, 2013). The electric light usage data and occupant satisfaction survey suggested that a subdivided window in which occupants controlled the lower shades only could provide an energy efficient and occupant-friendly daylighting solution for open-plan workspaces. However, to provide maximum daylight and equal level of satisfaction for the core and perimeter area occupants, the authors recommended a dynamic upper shading device.

This paper examines two design options for the subdivided window discussed above. The first option is a subdivided window with an interior motorized louver system on the upper half and a manually controlled venetian blind on the lower half of the window (Fig. 1,

middle). In this option, the upper louver slats are automatically retracted toward the center of the window when direct sun is not present. The slats are angled at 45° to control the low sun angles at west facade. The second option includes an exterior motorized louver system on the upper half, an exterior fixed lightshelf in the middle, and an interior venetian blind on the lower half of the window. In this design, the automatic louver is retracted toward the top of the window in the absence of direct sunlight (Fig. 1, right). The daylight performance of the two design options are compared to that of a conventional unsubdivided window with manual venetian blinds (Fig. 1, left).

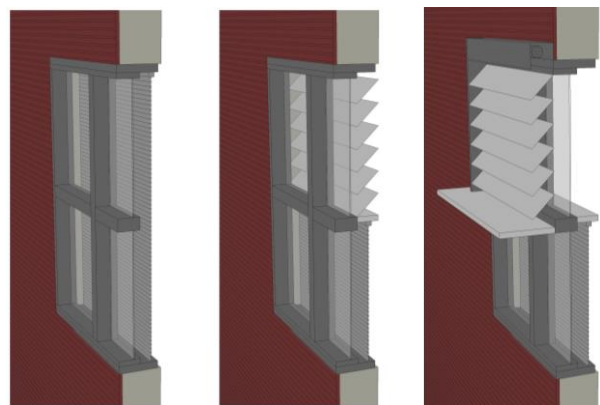


Figure 1: From left, the conventional window, design option 1 and design option 2.

## Method

An existing architecture school studio located in Milwaukee, WI was selected to be simulated with the subdivided window design options. The daylight performance of the shading devices was evaluated using the 5-phase method for simulating complex fenestration with Radiance (Ward et al., 2011). The visual comfort metrics were computed with Evalglare.

## Modeling Parameters

A detailed model of the room and the neighboring buildings was created in Ecotect (Fig. 2) and exported to Radiance. The rest of the simulation was carried out in Radiance. For accurate results, material reflectances were measured using a Gossion luminance meter and an 18%-reflectance grey card in the room. Table 1 shows the resultant material properties. For illuminance evaluations, 40 sensor points were defined in the room each representing the middle point of a desk (Fig. 3). The studied room has windows in three different orientations (Fig. 4). The two proposed window designs were modeled

on the west and south facades, while the north windows were modeled in their original design. The room's existing condition was also modeled as the base case.

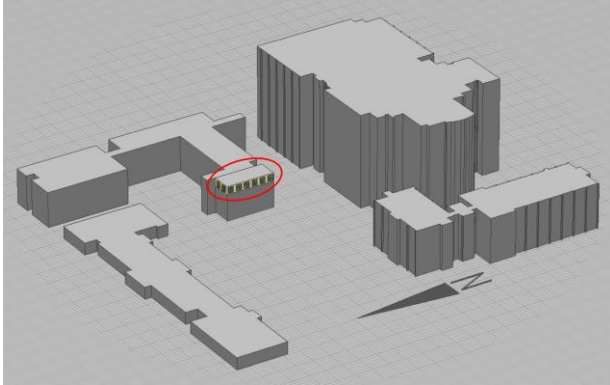


Figure 2: The Ecotect model of the room and its surround.

Table 1: The reflectance and visible transmittance of materials in the studied room

Material	R or VT	Material	R
Interior Walls	68%	Louvers	75%
Window Glass	VT: 73%	Exterior Walls	30%
Aluminium Window Frame	51%	Desks	67%
Ceiling	68%	Concrete Columns	39%
Floor	27%	Light Fixtures	80%
Venetian Blind Slats	50%	Divider Walls	60%
HVAC Ducts	40%	Ground	30%
Exterior Lightshelf	75%	Roofs	40%

### Validating the Radiance model with HDR imaging

To verify the accuracy of the Radiance model, an HDR image was captured inside the room and was compared to the Radiance rendering of the same view. The HDR image was computed from exposure bracketed images taken

with a Canon EOS 5D Mark II camera at night under electric lighting (Fig. 5). The electric lights were modeled in Radiance using the photometric data (IES file) of the existing luminaires. The luminance maps in Figure 5 show that the luminance values in the Radiance-rendered image and the camera-generated HDR image are very close.



Figure 4: The interior of the room

### The 5-phase method of simulation with Radiance

After validating the Radiance model, annual hourly daylight calculations for the shading systems were carried out using the 5-phase method of simulating complex fenestration with Radiance. The annual daylight analysis with Radiance is basically performed by two concepts of daylight coefficient (Tregenza 1983) and Perez sky model (Perez, Seals, & Michalsky, 1993). Although the daylight coefficient method can produce reliable results with non-complex windows, it is not adequate for simulating complex fenestrations or specularly reflecting daylighting systems (McNeil & Lee, 2013). For annual simulation of complex fenestrations, new tools have recently been added to Radiance that facilitate the use of BSDF data in annual daylight simulations (Ward, Mistrick, Lee, McNeil, & Jonsson, 2011).

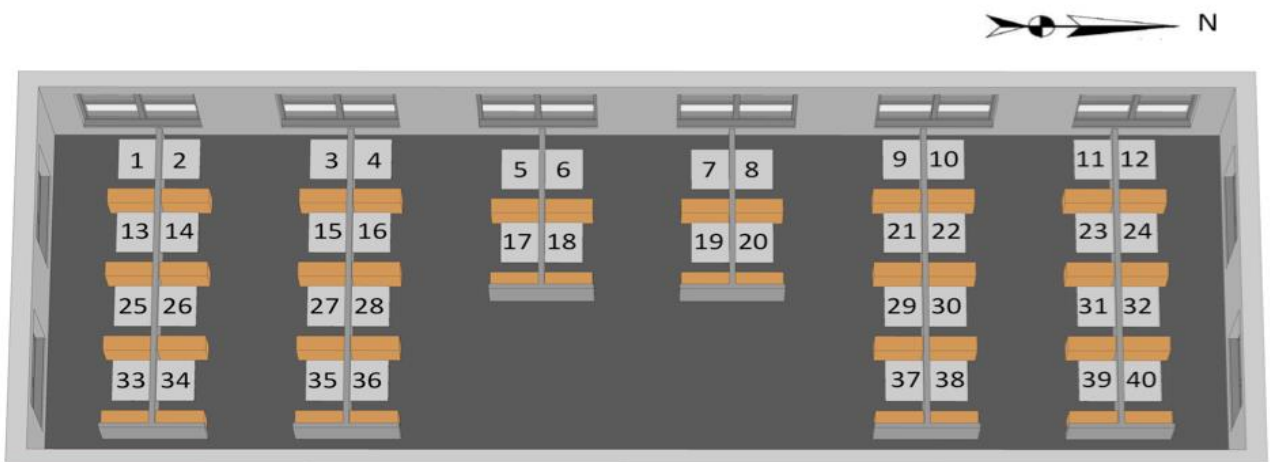


Figure 3: Sensor locations

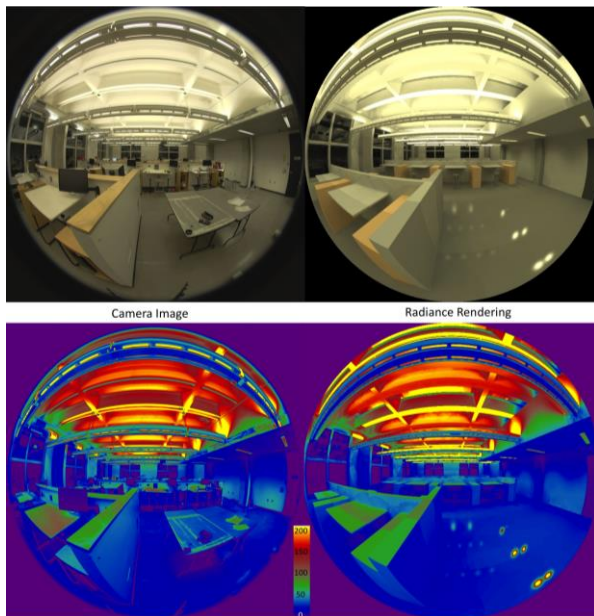


Figure 5: Comparison of the Radiance and camera-generated luminance maps

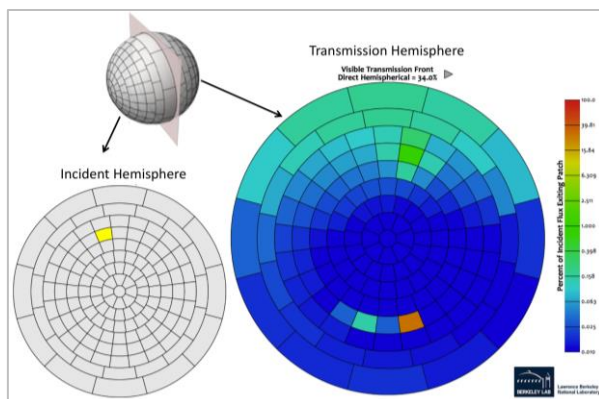


Figure 6: Bidirectional Scattering Distribution Functions relate energy incident on a window and energy leaving a window in Klems directional bins. Image produced by LNBL's BSDF Viewer software (McNeil, 2013a).

Bidirectional Scattering Distribution Functions (BSDF), proposed by Klems (1994), determine the light transmission pattern through an object for all incident directions (Fig. 6). The BSDF data are produced either in laboratory using a Goniophotometer or virtually through raytracing tools. The resultant data is stored in a matrix form.

The 5-phase method combines daylight coefficient concept with BSDF data for fast and accurate modelling of innovative fenestration systems. The 5-phase method is an extension of the three-phase method in which the flux transfer from the sky to the point in the space is broken into three phases:

1. Sky to exterior of fenestration
2. Transmission through fenestration
3. Interior of fenestration into the simulated space (McNeil, 2013a).

Each phase of light transport is simulated independently and stored in a matrix form. The resultant illumination is obtained using matrix multiplication (McNeil & Lee, 2013). Since the three-phase method did not model direct sun distribution accurately (McNeil, 2013b), the 5-phase method was developed with these two additional steps:

1. Subtracting the direct solar contribution from the three-phase method computations
2. Adding a more accurately simulated direct solar contribution to the model (McNeil, 2013b).

Figure 7 illustrates the terms of the 5-phase method. Since the automatic and manual shades in this study were on different control algorithms, the 3 window systems resulted in 32 different scenarios to be modeled in Radiance (Table 2). A full year simulation was performed for each scenario through the 5-phase method. The Radiance simulations resulted in 32 sets of annual hourly illuminance data as well as annual hourly rendered images. In an excel spreadsheet, the control algorithms were used to filter and consolidate the data down to 3 sets. Finally, annual daylight performance and visual comfort metrics were computed for each design.

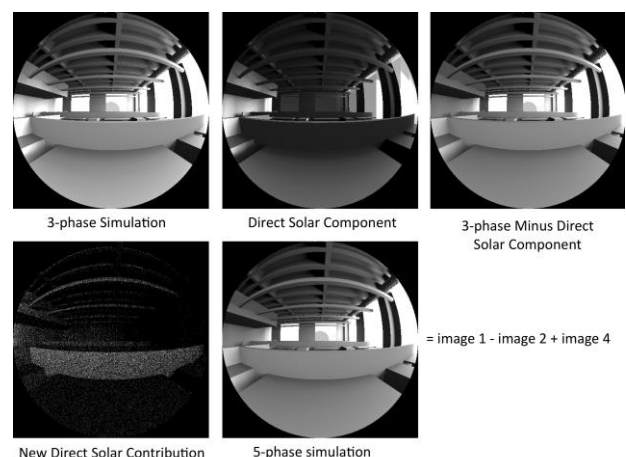


Figure 7: The 5-phase method simulation terms

## Shade Control Algorithms

### Control Algorithm for Venetian Blinds

There are a number of shade control behavior models available to use in building energy simulation. Some examples are Lee and Selkowitz's model (1995), Lightswitch 2002, LEED (2012), Inkarojrit (2005), and IES-LM83 (2013). Konis (2012) observed occupants' shade control behavior in an office building and concluded that the "active operator" shade control models underestimate the window occlusion, and the "worse case" models overestimate the level of window occlusion, but they predict it more closely.

Nezamdoost and Van Den Wymelenberg (2016) examined the shade control behavior model adopted by IES-LM83 and found that it was too active relative to occupants' actual behavior. In the absence of a realistic shade control behavior model, author used Reinhart's

(2004) lightswitch model for its simplicity and moderate criteria.

The model assumes two types of users. The “active operator” deploys the venetian blinds when the transmitted solar radiation exceeds 50 W/m<sup>2</sup>. Once lowered, the shades stay down for the rest of the day and are opened in the next morning. The “passive operator” adjusts the shades based on the same criteria but on a weekly basis. For the existing window design, the annual illuminance data were once filtered with the active operator model and once with the passive operator model, which was the current state of the room.

The active user mode in such space can be achieved by either encouraging the occupants to open the venetian blinds every morning upon arrival or adding a spring system to the venetian blind that retracts the shades overnight. For subdivided windows, however, only active operator model was used to process the data since a field observation had shown occupants control the shades more actively on subdivided windows (Sanati & Utzinger, 2013).

Transmitted vertical irradiance through the west and south facing windows were obtained using TRNSYS software. The same TMY data used for daylight

calculations served as the input data for solar radiation calculations in TRNSYS. The resultant hourly transmitted solar radiation data for the west and south windows was used to determine the venetian blinds’ operation.

#### Control Algorithm for Automatic Louvers

The control algorithm for automatic shading devices was based on the presence of direct sunlight. Table 3 shows the criteria for determining the sky condition from direct normal and diffuse irradiance data (Fernandes, Lee, & Ward, 2013). In this study, it was assumed that the motorized louvers would be extended when direct normal irradiance was equal or greater than 50% of diffuse horizontal irradiance. Based on table 3 values, this represents a sky with 70 percent or less cloud cover. In other words, the automatic shading devices are deployed when 0 to 70 percent of the sky is covered with clouds. The louvers remained in their extended state for at least one hour before reopening. For west facing windows however there was an additional criteria, and that was the time of day. The automatic louvers in west facing windows would be activated in the afternoons only.

*Table 3: Predicting sky condition based on direct normal and diffuse horizontal irradiance (Fernandes, Lee, & Ward, 2013)*

Sky type	Condition
Clear	Direct normal irradiance is more than 200% of diffuse horizontal irradiance
Intermediate	Direct normal is between 5% and 200% of diffuse horizontal irradiance
Overcast	Direct normal is less than 5% of diffuse horizontal irradiance

*Table 2: Radiance modeling scenarios*

N	Shading System	South Louvers	South Venetian Blinds	West Louvers	West Venetian Blinds
1	Option 1	Open	Open	Open	Open
2	Option 1	Open	Open	Open	Closed
3	Option 1	Open	Open	Closed	Closed
4	Option 1	Open	Closed	Closed	Closed
5	Option 1	Closed	Closed	Closed	Closed
6	Option 1	Closed	Closed	Closed	Open
7	Option 1	Closed	Closed	Open	Open
8	Option 1	Closed	Open	Open	Open
9	Option 1	Open	Closed	Open	Closed
10	Option 1	Closed	Open	Closed	Open
11	Option 1	Closed	Open	Closed	Closed
12	Option 1	Closed	Closed	Open	Closed
13	Option 1	Open	Closed	Open	Open
14	Option 1	Open	Open	Closed	Open
15	Option 2	Open	Open	Open	Open
16	Option 2	Open	Open	Open	Closed
17	Option 2	Open	Open	Closed	Closed
18	Option 2	Open	Closed	Closed	Closed
19	Option 2	Closed	Closed	Closed	Closed
20	Option 2	Closed	Closed	Closed	Open
21	Option 2	Closed	Closed	Open	Open
22	Option 2	Closed	Open	Open	Open
23	Option 2	Open	Closed	Open	Closed
24	Option 2	Closed	Open	Closed	Open
25	Option 2	Closed	Open	Closed	Closed
26	Option 2	Closed	Closed	Open	Closed
27	Option 2	Open	Closed	Open	Open
28	Option 2	Open	Open	Closed	Open
29	Existing	-	Open	-	Open
30	Existing	-	Closed	-	Closed
31	Existing	-	Closed	-	Open
32	Existing	-	Open	-	Closed

#### Occupancy Schedules

Daylight performance metrics were calculated based on daylight hours since the architecture studio is occupied all day long.

## Results

#### Daylight Performance Results

Three dynamic daylight metrics of Useful Daylight Illuminance (UDI<sub>200-2000</sub>), Daylight Autonomy (DA<sub>300</sub>), and Maximum Daylight Autonomy (DAMax) were calculated from the hourly illuminance data at sensor points. Figures 8-11 show the UDI values for four different shading conditions in the room. Figures 12-15 show the Daylight Autonomy results.

#### Electric Light Usage

The studied space currently contains 77 two-lamp 32 W fluorescent luminaires. Separate manual switches control the perimeter and core area luminaires. In order to estimate energy saving potential of each window shading design, it was assumed that the luminaires were equipped with photoelectric lighting controls. Table 4 shows the number of hours the core area and perimeter area lights



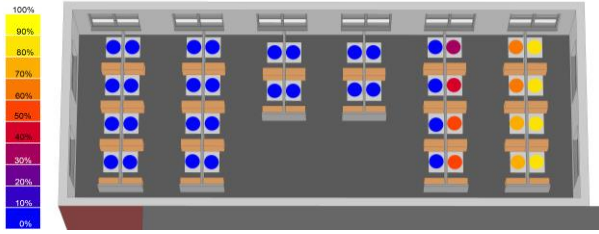


Figure 8: The UDI results for existing windows with passive users

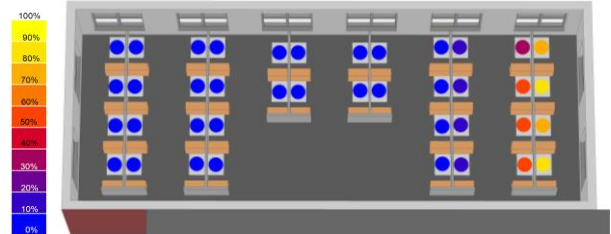


Figure 12: The DA results for existing windows, passive users

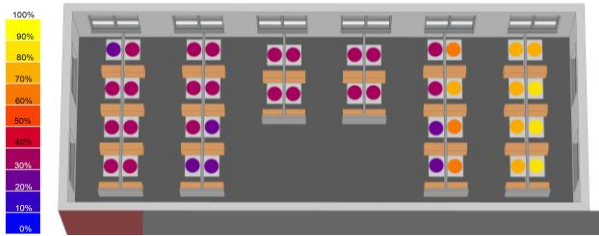


Figure 9: The UDI results for existing windows with active users

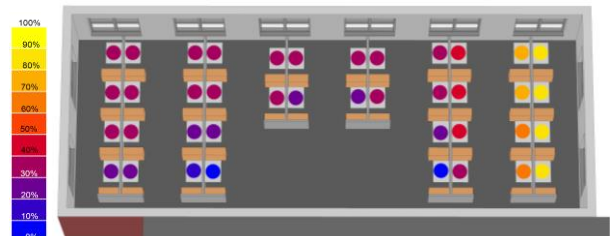


Figure 13: The DA results for existing windows, active users

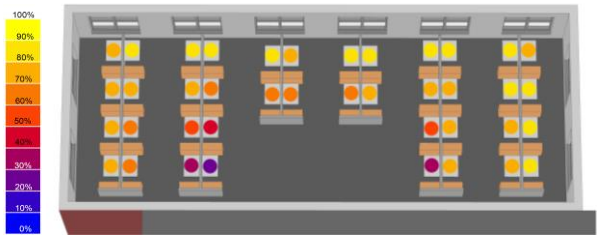


Figure 10: The UDI results for subdivided windows with interior shading.

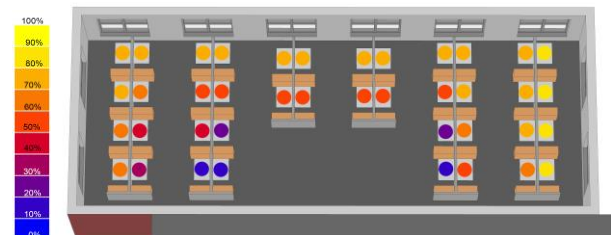


Figure 14: The DA Results for subdivided windows with interior shading.

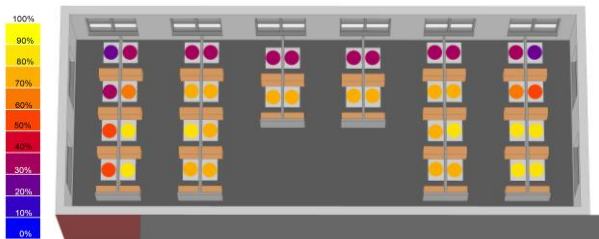


Figure 11: The UDI results for subdivided windows with exterior louvers.

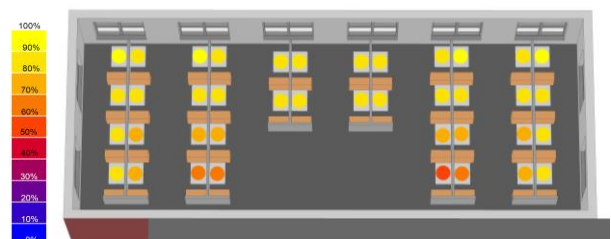


Figure 15: The DA Results for subdivided windows with exterior louvers.

need to be turned on based on Daylight Autonomy data. The lights were assumed to be turned on when illuminance level dropped below 300 lux at sensor 37 and sensor 19 representing the core and perimeter areas respectively. The two selected sensors had the lowest DA in their area.

The annual electric light usage in the room (table 5) was obtained by multiplying table 4 values by the power demand of each group of luminaires (Equations 1). It can be observed in table 5 that the subdivided windows with exterior louvers produce the lowest annual electric light usage. It is notable that the performance of the subdivided window system with interior louvers is relatively close to that of the existing windows with active users.

Table 4: Number of hours during the daytime when electric lights need to be turned on.

Shading System	Number of hours when illuminance is below 300 lux at sensor 19	Number of hours when illuminance is below 300 lux at sensor 37
Existing (Passive User)	4686	4686
Existing (Active User)	3290	4229
Subdivided with Exterior Louver	919	1929
Subdivided with Interior Louver	2315	4400

Luminaire specification: 2 lamp T8 32W  
Number of luminaries in Perimeter area: 26  
Number of luminaries in the core area: 51  
Perimeter area lighting energy demand: (1)  
 $26 \times 2 \times 32 = 1664 \text{ W}$   
Core area lighting energy demand:  
 $51 \times 2 \times 32 = 3264 \text{ W}$

Table 5: Annual electric light usage during daytime

Shading System	Electric light usage at the perimeter area (kWh)	Electric light usage at the core area (kWh)	Total Electric light usage (kWh)
Existing (Passive User)	7797.50	15295.10	23092.61
Existing (Active User)	5474.56	13803.46	19278.02
Subdivided Ext. Louver	1529.22	6296.26	7825.47
Subdivided Int. Louver	3852.16	14361.60	18213.76

### Total Electricity Consumption

In energy saving calculations, one factor to consider is that the automatic shading devices use electricity to operate. Therefore the energy use of the motor needs to be included in the calculations. To obtain the annual electricity consumption of the motorized louvers, the energy demand of the motor was multiplied by the number of louver adjustments (Equations 2). The annual electricity consumption of louvers was found to be about 6 kWh, which is very minimal compared to the annual electric light usage. Figure 16 shows the total electricity use in the room due to each window design. The subdivided window with exterior louvers and lightshelf still outperforms other options by a huge margin. With such system, the annual electricity usage can be reduced to one third of the existing situation. This could partly be due to the fact that the fixed lightshelf reduces occupants' chance of closing the blinds and hence increases the interior daylight level. According to the transmitted irradiance data produced by TRNSYS, the number of hours per year when occupants close the venetian blinds on west-facing windows is 578 with the exterior lightshelf and 1668 without the lightshelf. For the south-facing windows the numbers are 1448 and 1990 respectively. Evidently, the lower shade closing incidents result in higher daylight availability in the room.

Motorized louvers' motor Specification: 110 V AC, 150 Watts, 2in/sec lift speed

The upper window height: 53 inches  
The lift duration:  $53 / 2 = 26.5 \text{ sec}$   
Automatic louvers' energy demand per lift:  
 $150 \text{ Watts} \times 27/3600 \text{ h} = 1.125 \text{ Wh per lift}$

Number of times when south louvers need to be adjusted: 768  
South louvers' annual energy use: (2)  
 $2 \times 1.125 \times 768 = 1726 \text{ Wh}$

Number of times when west louvers need to be adjusted: 638  
West louvers' annual energy use:  
 $6 \times 1.125 \times 638 = 4306.5 \text{ Wh}$

Automatic louvers' annual energy use:  
 $1726 + 4306 = 6032.5 \text{ Wh} = 6.03 \text{ kWh}$

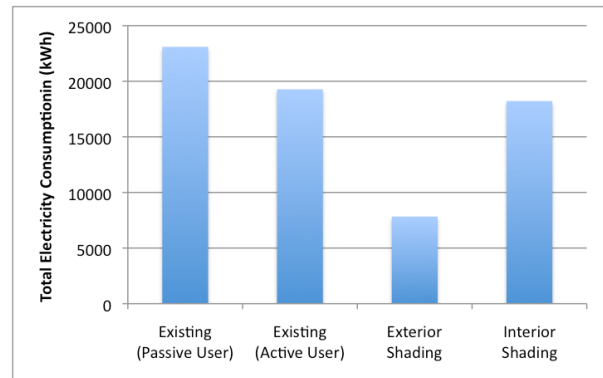


Figure 16: Annual electricity consumption in the room due to each window shading design.

### Daylight Glare Probability (DGP)

The 5-phase method simulations resulted in 14076 rendered images of a single viewpoint after filtering and consolidation. Figure 17 shows some examples of the rendered images. A bash script was created to run Evalglare on all of the images and compute the hourly DGP values for each shading system. Daylight Glare Probability, developed by Wienold and Christofferson (2006), represents "percent of people disturbed". Before calculating the DGP value for each image, Evalglare requires a criterion for determining potential sources of glare. In this study the criterion was set as any part of the image with a luminance value of 2000 cd/m<sup>2</sup> or above.

The resultant DGP values were subsequently processed in a spreadsheet to calculate the annual daylight glare probability for each window shading design. The annual Daylight Glare Probability is simply the percentage of the daylight hours throughout the year when the DGP value is above 0.35. Table 6 shows that almost no discomfort glare was detected with any of the shading designs at the studied field of view.

Table 6: Annual Daylight Glare Probability

Shading System	Annual DGP
Existing (Passive User)	0%
Existing (Active User)	0%
Exterior Louver	0.06%
Interior Louver	0%

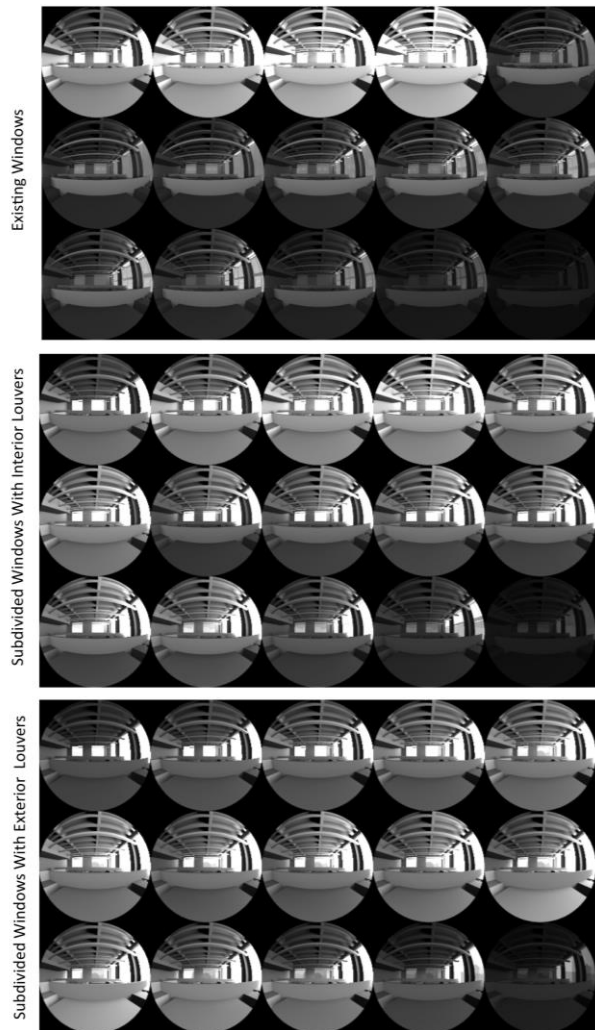


Figure 17: The hourly renderings of the room on summer solstice (6 A.M. to 8 P.M.). The top left image in each group represents 6 AM on Jun 21st, and the lower right image represents 8 PM on the same day.

## Conclusion

The merits of a subdivided window have long been acknowledged by daylighting experts, however a subdivided window that incorporates both manual and automatic shading devices has not been adequately studied. The purpose of such system is to provide occupants with a high sense of perceived control over their environment while ensuring daylight admission into the space. This study examined two design options for a subdivided window using an advanced simulation method. The results show that a subdivided window consisting of a manual venetian blind on the lower half,

an exterior lightshelf in the middle, and an automatic exterior louver system on the upper half has a better chance of daylighting a space than a subdivided window with interior motorized louver and venetian blind. The results however pertain to one climate type, and the performance of the systems needs to be examined in multiple climate zones and building designs.

The fixed exterior lightshelf seems to have an important role in the performance of the exterior shading system, in that it reduces the chance of venetian blinds being closed by the occupants. The additional advantages of an exterior system are lower solar heat gain and less motor noise. However, the exterior shading devices will be exposed to outdoor elements and may require more maintenance compared to the interior solutions.

## Acknowledgement

This study was part of doctoral research conducted by the author at the University of Wisconsin-Milwaukee under the supervision of Prof. Michael Utzinger. The author is also grateful to Greg Ward, Andy McNeil, and Radiance mailing list members who provided guidance on the Five Phase Method Simulation with Radiance.

## References

- Fernandes, L. L., Lee, E. S., & Ward, G. (2013). Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort. *Energy and Buildings*. 61 (2013), 8-20.
- Inkarojrit, V. (2005). *Balancing comfort: Occupants' control of window blinds in private offices* (Doctoral dissertation, University of California, Berkeley).
- Klems, J.H., 1994. A new method for predicting the solar heat gain of complex fenestration systems: I. Overview and derivation of the matrix layer calculation, *ASHRAE Transactions* 100 (1): 1065-1072.
- Konis, K. S. (2012). *Effective Daylighting: Evaluating Daylighting Performance in the San Francisco Federal Building from the Perspective of Building Occupants* (Doctoral dissertation, University of California, Berkeley).
- Lee E. S., & Selkowitz S. E., (1995). The Design and Evaluation of integrated envelope and lighting control strategies for commercial buildings. *ASHRAE Transactions*, Chicago, IL 101[1], 326-342. January 28-February 1.
- McNeil, A. (2013a). The Three-Phase Method for Simulating Complex Fenestration with Radiance. LBNL. Available at: <http://www.radiance-online.org/learning/tutorials/Tutorial-ThreePhaseMethod.pdf>
- McNeil, A. (2013b). The Five-Phase Method for Simulating Complex Fenestration with Radiance. LBNL. Available at: [http://www.radiance-online.org/learning/tutorials/fivephasetutorialfiles/Tutorial-FivePhaseMethod\\_v2.pdf](http://www.radiance-online.org/learning/tutorials/fivephasetutorialfiles/Tutorial-FivePhaseMethod_v2.pdf)

- McNeil, A., & Lee, E. S. (2013). A validation of the Radiance three-phase simulation method for modeling annual daylight performance of optically complex fenestration systems. *Journal of Building Performance Simulation*, 6(1), 24-37
- Nezamdoost, A., & Van Den Wymelenberg, K. G. (2016). Revisiting the Daylit Area: Examining Daylighting Performance Using Subjective Human Evaluations and Simulated Compliance with the LEED Version 4 Daylight Credit. *LEUKOS*, 1-17.
- O'Brien, W., Kapsis, K., & Athienitis, A. K. (2013). Manually-operated window shade patterns in office buildings: A critical review. *Building and Environment*, 60, 319-338.
- Perez, R., Seals, R., & Michalsky, J. (1993). All-weather model for sky luminance distribution-preliminary configuration and validation. *Solar energy*, 50(3), 235-245.
- Reinhart, C. F. (2004). Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. *Solar Energy*, 77(1), 15-28.
- Sanati, L., & Utzinger, M. (2013). The effect of window shading design on occupant use of blinds and electric lighting. *Building and environment*, 64, 67-76.
- Tregenza, P.R., 1983. Daylight coefficients. *Lighting Research and Technology*, 15(2), 65-71.
- Ward, G., Mistrick, R., Lee, E. S., McNeil, A., & Jonsson, J., (2011). Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance. *Leukos* 7(4), 241-261.
- Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38, 743-757.