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DAYLIGHT AVAILABILITY AND OCCUPANT VISUAL COMFORT IN SEATTLE MULTI-FAMILY HOUSING

Guanzhou Ji[1]
[1]University of Washington, Seattle, WA

ABSTRACT

The living unit is currently undersized in Seattle multi-family housing. The design decisions for floor layout and unit configuration impact the interior daylight and occupant visual comfort. This study uses the existing daylight/glare metrics and investigates a simulation-based workflow. During schematic design, a series of design alternatives will be compared regarding daylight performance and glare perception. The decision-making process is driven by the results of quantitative and qualitative simulation under the constraints of related design codes. The final results will provide summarized design guidelines that would be instructive for creating well-lit living spaces in Seattle.

INTRODUCTION

In the U.S., housing currently has the most significant proportion among all new construction, and Seattle has the smallest apartment (FMI Corporation 2019, RENTcafe Blog 2019). With the increasing housing demand, Studio/1-Bedroom is the most popular option in Seattle multi-family housing market (Kidder Mathews Corporation 2018). Some under-sized living units follow the minimal dimensions from building codes (SDCI 2015, Neiman 2017, Neiman 2018). However, the limited living space negatively impacts interior daylight and living comfort. Daylight is widely considered and utilized in contemporary buildings (Reinhart et al. 2006). Various daylight metrics (Reinhart et al. 2006, Reinhart et al. 2015, Tregenza et al. 2018) were developed and used in daylight analysis (Reinhart et al. 2001, Nabil et al. 2005, Galasiu et al. 2008, Andersen et al. 2011, Mardaljevic et al. 2012). Nevertheless, most of the current daylight metrics are appropriate for commercial buildings (Dogan et al. 2018). In residences, the flexibility of floor layout and individual differences in visual perception make it challenging to conduct daylight analysis (Boyce 2014). Although the simulation-based analysis (Jakubiec et al. 2011, Reinhart et al. 2011) with daylight/glare metrics are widely used for evaluating daylight performance (Wienold et al. 2006, Pierson et al. 2011, Jakubiec et al. 2015, Jones et al. 2018), the design workflow for creating suitable residential spaces is still in exploration (Mardaljevic et al. 2010, Dogan et al. 2017, Peters et al. 2018). Except for daylight, other constraints (such as spatial efficiency and human comfort) are competing against each other during the decision-making process. Reaching a suitable trade-off for well-being is a practical challenge. The goal of this study is to use daylight availability and occupant visual comfort to guide the design process. Data analysis and graphic visualization will be used for comparing design alternatives.

DAYLIGHT METRICS

Due to technological developments (i.e., lighting fixtures, glazing materials, and daylight apertures), design strategies for utilizing daylight have continuously been updated since the 20th century (Reinhart et al. 2006). Meanwhile, designers' ability in computing the dynamic nature of daylight has also advanced. The daylight simulation tools, like climate-based daylight modelling (CBDM), are universally used in the architectural industry (Reinhart et al. 2015, Tregenza et al. 2018). Point-in-time metric reflects the daylight variation based on specific sky conditions and time points. However, it is impractical to take hourly illuminance simulation to predict long-term daylight performance due to the substantial time/labor cost. In order to respond to the realistic built environment, annual-based metrics are necessary when local meteorological data and occupancy schedules are incorporated into the daylight simulation. Although some rating systems like Assessment Standard for Green Building (GB/T50378-2019) in China still use Daylight Factors (DF) as daylight metric, DF's application is limited (Nabil et al. 2005).

Daylight Autonomy (DA)

Daylight Autonomy (DA) uses the percentage of the entire year's daytime hours to quantify whether a target space (or a measurement point) received sufficient daylight, given a minimum illuminance threshold like 300lux. The target illuminance level depends on building functionality. As DA doesn't enforce an upper threshold (Reinhart et al. 2001, Reinhart et al. 2006), the availability of direct sunlight strongly impacts its result.

Continuous Daylight Autonomy (cDA)

Continuous Daylight Autonomy (cDA) is based on daylight research in a classroom space. The transition of the illuminance threshold between compliance and noncompliance is softened in cDA (Reinhart et al. 2006). Compared to DA, cDA does not exclude the daylight that contributes to the target illuminance. Partial credits will be given to the areas that have slightly lower illuminance than the threshold. As there is no upper threshold in cDA, it does not penalize for glare.

Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy (sDA) is a measurement of daylight illuminance sufficiency in a given area, which reports a percentage of floor area (>50%) that exceeds a specified illuminance (e.g. 300lux) during a specified percentage of the analysis period (IESNA 2012). The value of sDA result ranges from 0 to 100%. If the value is above 75%, the daylight in the given space is regarded "preferred"; if it is in the range of 55%-74%, the daylight is "accepted".

Annual Sun Exposure (ASE)

Annual Sun Exposure (ASE) is the fraction or percentage of the horizontal work plane that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year over a specified daily schedule with all operable shading devices retracted (IESNA 2012). ASE measures horizontal illuminance on an annual basis, which means it is not a glare metric (Van Den Wymelenberg et al. 2016). However, as it is developed for preventing excessive daylight that could potentially cause glare issues, which serves as a complementing metric for sDA. The sDA value above 75% indicates sufficient daylight, but it cannot predict excessive daylight that might cause glare or overheat issues. ASE restricts direct sunlight penetration into space. Since the overlit areas are near the windows in most cases, it is strict for daylight design (Van Den Wymelenberg et al. 2016, Tregenza et al. 2018). A strict ASE value might be necessary for commercial buildings, but more leniency should be exercised in residential spaces.

Useful Daylight Illuminance (UDI)

Useful Daylight Illuminance (UDI) provides four illuminance ranges: (1) Underlit, UDI (0-100lux). (2) Supplementary, UDI (100-300lux). (3) Autonomous, UDI (300-3000lux). (4) Exceeded, UDI (>3000lux). Other illuminance thresholds, like 100lux or 2000lux, are also discussed (Mardaljevic et al. 2010). When the 300lux is the threshold, DA (300) = UDI (300-3000lux) + UDI (>3000ux) (Mardaljevic et al. 2012). Given a UDI simulation result, a building space with the concentration of low illuminance might achieve the same UDI value with another space that has more extensive illuminance range including a higher maximum illuminance. The illuminance distribution at a single point-in-time across the year cannot be demonstrated from the numerical value of UDI simulation (Dogan et al. 2018).

GLARE METRICS

A glare source typically refers to the visual area with the luminance at least five times higher than the average scene luminance (Jones et al. 2018). Discomfort glare occurs when bright light sources lead to visual irritation or eyestrain. Insufficient visual contrast, direct sunlight, and discomfort glare are three main factors causing visual discomfort. As a subjective phenomenon related to occupants' satisfaction, discomfort glare is common in the interior building spaces (Reinhart et al. 2001, Jakubiec et al. 2011). When window openings are the primary light source, the glazing size, building location, and orientation are all relevant to occupants' perception of discomfort glare (Pierson et al. 2017).

Along with the direct sunlight, the reflections of sunlight from other surfaces could also cause visual discomfort (Mardaljevic et al. 2012). Due to different age, gender, and previous experience in visual tasks, occupants have different perceptions, responses, and preferences to daylight (Boyce 2014). Individuals' perception varies from season to season as well. There is a higher acceptance of sunlight presence in winter, compared to summer (Wienold et al. 2006). This study will predict glare issues for the majority of people in the residential units instead of discussing the individual differences.

Daylight Glare Probability (DGP)

The existing glare metrics include Daylight Glare Index (DGI), CIE Glare Index (CGI), and Visual Comfort Probability (VCP) etc, with merits and shortcomings (Wienold et al. 2006, Jakubiec et al. 2012): (1) The majority of glare metrics are developed from artificial lights. It means they may not be suitable for evaluating glare caused by natural sunlight. (2) Glare is closely related to the subjective view, so the glare sensation changes rapidly depending on occupants' view position/angles and seasonal daylight variations.

Another glare metric is Daylight Glare Probability (DGP). DGP accounts both contrast and brightness, as well as scene luminance. With a view point/direction under specific timepoint, the result of DGP simulation reports the percentage of people who feel the scene glary (Jakubiec et al. 2015). Therefore, DGP is reliable to predict glare issues during daytime. Four glare levels are: (1) Intolerable Glare, DGP$\geqslant$45%. (2) Disturbing Glare, 45%$>$DGP$\geqslant$40%. (3) Perceptible Glare, 40%$>$DGP $\geqslant$ 35%. (4) Imperceptible Glare, 35% $>$ DGP (Giovannini et al. 2019).

Annual Daylight Glare Probability (Annual DGP)

In contrast to the instantaneous glare metric (DGP), Annual Daylight Glare Probability (Annual DGP) provides a graphic chart indicating glare levels. It shows potential periods over the year which are prone to have glare issues. Meanwhile, when sharing the same view setting with DGP, it serves as a supplement for analyzing the long-term glare issues in the given spaces.

METHODOLOGY

Form finding by maximizing adequate daylight is directly relevant to a successful residential design. Current daylight design lacks a precise method to evaluate daylight quality and its effect on human vision (Galasiu et al. 2008). It is advantageous to shape building form (i.e., floor height, floor layout, and window wall ratio) for daylight at the earlier stage. Otherwise, once the unit configuration is determined, it becomes more challenging to optimize interior daylight and occupant visual comfort. The previous study (Jones et al. 2018) has recommended that daylight performance should consider daylight availability and glare issues together. However, different measurements exist in daylight metrics (illuminance) and glare metrics (luminance). For simulation results, the percentage of floor area that achieved target illuminance does not differentiate the interior layout and visual comfort strictly depends on the view position/directions (Jones et al. 2018), the target functional areas are supposed to be outlined more specific in daylight and glare analysis.

Meanwhile, desirable illuminance thresholds for residential buildings are still in debate (Mardaljevic et al. 2010, Dogan et al. 2017, Peter et al. 2018). BREEAM (BRE Global Ltd 2014), LEED (USGBC 2019), and WELL (IWBI 2019) take 300 lux as the benchmark for general visual tasks. 3000lux is a typical upper threshold for the overlit issue. Therefore, taking the 300-3000lux in daylight analysis will exclude most of the illuminance that is either underlit (0-300lux) or overlit (>3000lux). Considering the target surfaces for most visual tasks (such as kitchen counter, dining table, and reading desk) is at 2'-6" height, this height is set up for the target surfaces in residences.

Sky cover in Seattle stays at a high level during the entire year with a changeable range. Thus, point-in-time and annual-based metrics are both necessary to predict daylight performance. Due to the complexity of developing a new metric for residential daylight, using current daylights metrics will be more feasible (Dogan et al. 2017, Dogan et al. 2018). In this study, for daylight availability, UDI (300-3000lux) is adopted as the desirable illuminance range for making design decisions. 8:00 AM-6:00 PM is selected as the occupancy schedule. September 21st (equinox) (clear sky condition) is selected as the typical date for shading design, and then the shading period could cover from March 21st to September 21st. Besides, DGP is used to test the impact of shading on visual comfort inside living unit at 9:00 AM and 12:00 PM, September 21st. As the glare metrics (DGP and Annual DGP) share the same view settings, Annual DGP analyzes shading strategy for improving visual comfort on an annual basis.

The simulation objects are all modelled with NURBS geometry in Rhino and Grasshopper plug-in. DIVA-for-Rhino (Version 4.1) conducts annual-based simulations (UDI and Annual DGP) with Radiance simulation engine. Point-in-Time simulations (hourly illuminance and DGP) are supported by DIVA-Grasshopper in Rhino interface for quick feedback/testing of different design alternatives. In the 3D model objects, the radiance material property (diffuse reflectance) includes: surrounding buildings - 35%, ceiling - 80%, floor - 20%, roof - 35%, ground - 20%, wall - 70%, interior door - 50%, shading device - 35%, window - 80% transmittance.

Floor-Floor Height

The author selected a North-South facing site in Capitol Hill, Seattle. Under current 75'-0" height limitation (SDPD 2006), a series of floor-floor height options are tested for multi-family housing (Figure 1), with 1'-0" height reserved inside for ceiling/structure space. The street-level floor heights are all set in 14'-0" for commercial use (SDCI 2016). Crossed walls are added to represent the interior wall partitions (Figure 2). Because the alternatives have different floor-floor heights and floor elevations, the second floor is selected for comparison to minimize irrelevant variables.

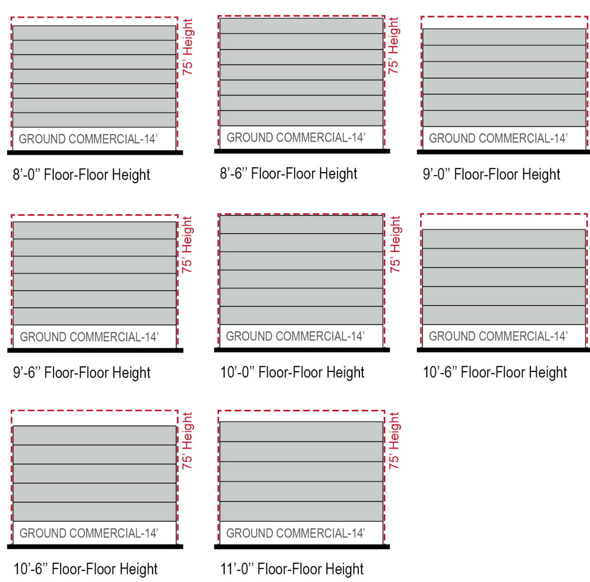

Figure 1 Floor-Floor Height

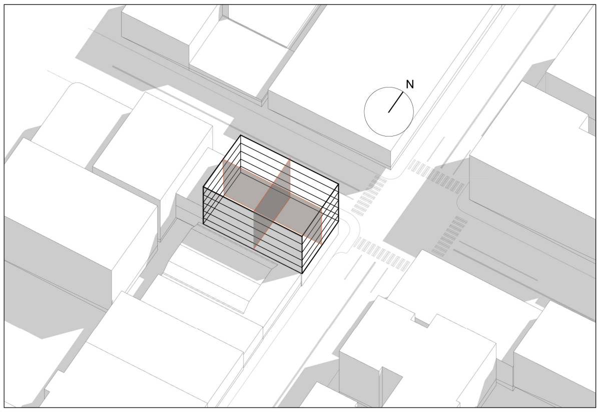

Figure 2 Scenario for Floor-Floor Height Simulation

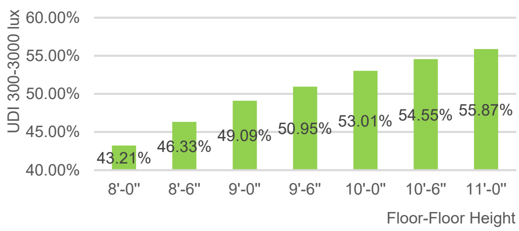

Figure 3 UDI (300-3000lux) and Floor-Floor Height

The result (Figure 3) shows a greater floor-floor height brings a greater UDI (300-3000lux) value. In this case, it is difficult to determine the most suitable floor-floor height.

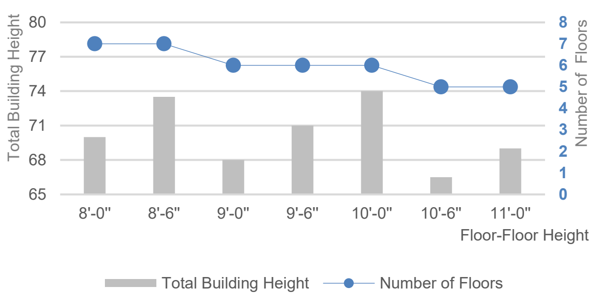

Figure 4 Total Building Height, Number of Floors and Floor-Floor Height

The floor-floor height in 8’-0” or 8’-6” brings the maximum seven stories (Figure 4). However, because of the reserved 1’-0” ceiling height, the actual floor-ceiling heights (7’-0” and 7’-6”) are not feasible for living unit. Choosing 10’-0” as floor-floor height sacrifices one floor compared to 8’-0” or 8’-6”, but it would realize the maximum building height and achieve a relatively better daylight performance. Therefore, 10’-0” is selected as floor-floor height.

Floor Typology

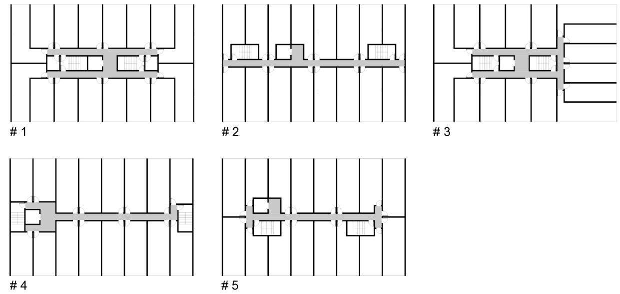

Figure 5 Floor Typology

The alphabet was previously used to simplify floor layout (Holl 1987, Dogan et al. 2015). In this study, five floor plates are developed (Figure 5) with different internal circulation. The size of the living unit is controlled between 220 sq.ft and 300 sq.ft. Due to the existing building on the west side, this study will not include windows openings there. For maximizing the number of living units, the floor boundary follows the property line without building setback in floor layout alternatives. The interior space uses the minimum dimensions from the design code (SDCI 2015). To get quick feedbacks, the simulation starting this step will be conducted with a single floor plate model without surrounding context. The floor plate models at this step temporarily take 7’-6” as floor-ceiling height as the code notes (SDCI 2015), with fully-glazed window. Figure 6 shows UDI (300-3000lux) does not exceed 42% in all floor typologies. Thus, the minimum interior height (7’-6”) from the code is not favorable for interior daylight. Based on the highest UDI (300-3000 lux) value, floor #3 is selected with 10’-0” floor-floor height.

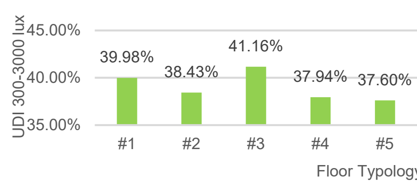

Figure 6 UDI (300-3000lux) and Floor Typology

Table 1 Building Efficiency Analysis

Floor Typology	Total Number of Units	Average Unit Size	Average Unit Width	Average Unit Depth	Ratio: (Total Unit Area)/(Corridor Area)
#1	16	273 sq.ft	11'-1/4"	23'-1/4"	9.58
#2	16	284 sq.ft	11'-3"	26'-11"	12.10
#3	16	279 sq.ft	13'-8"	23'-5"	9.75
#4	16	282 sq.ft	11'-3"	24'-10"	11.09
#5	16	286 sq.ft	11'-3"	26'-11"	13.03

In Table 1, Floor #3 has a smaller value in the Ratio: (Total Unit Area)/(Corridor Area) than some of the other alternatives, but it’s average unit width and Depth better daylight.

Unit Layout

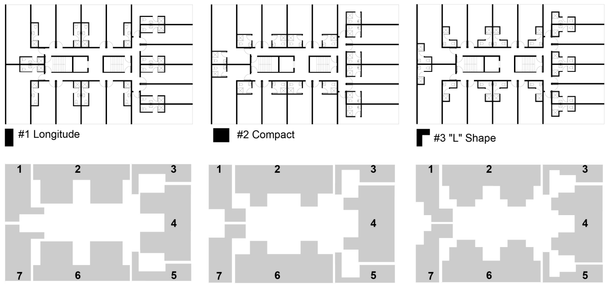

Figure 7 Interior Partitions and Simulation Zones

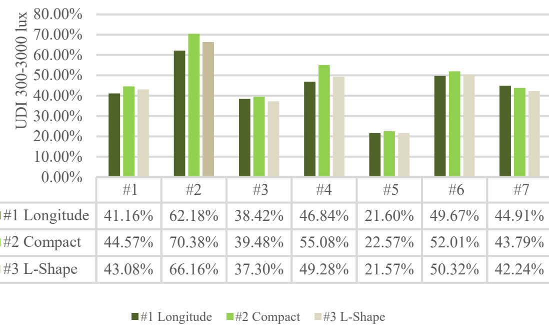

Figure 8 UDI (300-3000lux) and Interior Partition

Three types of interior partitions are developed based on floor #3 (with fully-glazed window). The same unit layouts are grouped into one simulation zone. As #2 Compact has the overall highest values of UDI (300-3000lux) (Figure 8), thus, #2 Compact is selected.

Fenestration

Three fenestration types are considered with different window-wall ratio (WWR): (1) WWR Top: the top of the window attaches to the interior ceiling height. (2) WWR Center: the center point of the window matches the center point of the exterior unit wall. (3) WWR Side: one side of the window attaches to one side of the exterior unit wall. Some options are excluded due to the maximum sill height (44”) (SDCI 2017).

Table 2 UDI (300-3000lux) and Window-Wall Ratio

WWR	#1	#2	#3	#4	#5	#6	#7
WWR 90% Top	**37.15%**	**66.48%**	44.61%	**50.52%**	25.07%	55.19%	**40.47%**
WWR 80% Top	35.56%	65.53%	46.18%	48.82%	26.06%	56.62%	39.74%
WWR 70% Top	33.75%	63.79%	50.61%	46.89%	29.42%	57.57%	38.46%
WWR 60% Top	31.62%	60.25%	**58.28%**	44.91%	37.90%	**60.00%**	37.88%
WWR 90% Center	35.08%	64.87%	46.53%	48.33%	25.93%	55.25%	38.98%
WWR 80% Center	31.75%	61.59%	50.05%	44.59%	28.26%	55.65%	36.09%
WWR 70% Center	28.20%	55.16%	53.58%	40.60%	32.22%	54.73%	33.13%
WWR 60% Center	24.29%	44.67%	55.72%	36.13%	37.61%	51.57%	29.38%
WWR 50% Center	19.73%	35.15%	56.81%	30.60%	43.64%	45.32%	25.08%
WWR 40% Center	14.48%	25.37%	56.35%	23.81%	**48.19%**	35.81%	19.56%
WWR 30% Center	8.59%	14.45%	48.94%	15.92%	46.63%	22.90%	13.31%
WWR 90% Side	35.00%	64.73%	43.95%	48.32%	24.48%	55.31%	39.13%
WWR 80% Side	31.27%	60.44%	44.17%	44.30%	24.23%	55.54%	36.35%
WWR 70% Side	26.72%	52.41%	45.19%	39.82%	25.34%	53.98%	32.73%
WWR 60% Side	21.08%	39.12%	46.13%	34.10%	28.08%	49.20%	28.02%
WWR 50% Side	15.01%	26.65%	45.16%	26.86%	31.83%	40.52%	22.05%
WWR 40% Side	10.24%	18.27%	42.14%	18.76%	34.73%	28.62%	15.37%
WWR 30% Side	6.74%	11.33%	32.45%	11.25%	30.51%	16.78%	9.89%

Table 2 represents the UDI (300-3000lux) values with different fenestration types and floor zones: (1) When the interior walls are unified in the same material, there is no significant daylight improvement when the window attaches to the side of the exterior unit wall (WWR Side). (2) The window’s head height is an influential factor for interior daylight. When two fenestration types share the same WWR value, the higher window’s head achieves the greater UDI (300-3000lux) value. Design decisions on fenestration are determined by the highest values of UDI (300-3000lux), highlighted with a bold black color in Table 2.

Table 3 UDI (>3000lux) and Window-Wall Ratio

WWR	#1	#2	#3	#4	#5	#6	#7
WWR 90% Top	**4.75%**	**8.25%**	41.16%	**14.74%**	64.45%	29.23%	**16.91%**
WWR 80% Top	3.83%	6.66%	36.83%	12.84%	60.39%	26.01%	15.13%
WWR 70% Top	2.84%	4.87%	28.94%	10.08%	53.06%	22.51%	13.10%
WWR 60% Top	0.74%	1.29%	**15.51%**	6.72%	39.40%	**15.77%**	9.35%
WWR 90% Center	4.51%	7.82%	38.77%	13.95%	63.02%	27.64%	16.01%
WWR 80% Center	3.42%	5.92%	32.01%	11.36%	57.07%	23.20%	13.41%
WWR 70% Center	2.52%	4.41%	24.63%	9.04%	48.94%	18.94%	10.95%
WWR 60% Center	1.80%	3.21%	18.07%	7.05%	39.10%	14.97%	8.57%
WWR 50% Center	1.25%	2.23%	12.64%	5.25%	28.52%	11.40%	6.51%
WWR 40% Center	0.73%	1.29%	6.51%	2.37%	**18.05%**	8.05%	4.67%
WWR 30% Center	0.14%	0.11%	2.80%	1.77%	11.27%	3.98%	2.57%
WWR 90% Side	4.41%	7.74%	38.91%	13.85%	61.68%	27.36%	15.82%
WWR 80% Side	3.46%	6.02%	32.27%	11.30%	55.00%	22.68%	13.07%
WWR 70% Side	2.63%	4.68%	25.75%	8.84%	47.91%	18.18%	10.51%
WWR 60% Side	1.95%	3.52%	19.77%	6.91%	39.68%	14.21%	8.06%
WWR 50% Side	1.41%	2.52%	14.54%	4.93%	29.92%	10.70%	6.00%
WWR 40% Side	0.84%	1.51%	7.54%	3.57%	19.09%	7.26%	4.13%
WWR 30% Side	0.22%	0.20%	3.35%	1.49%	10.95%	3.45%	2.33%

In the selected WWR (Table 3), the overlit issues primarily occurred in the East-facing and South-facing zones (#3, #4, #5, #6, #7). It suggests that shading devices need to be considered for those spaces.

Shading Device

The objective at this design phase is to address around 15%-20% overlit issues (UDI (>3000lux)) in the East-facing and South-facing zones. Two shading strategies are introduced (Figure 9).

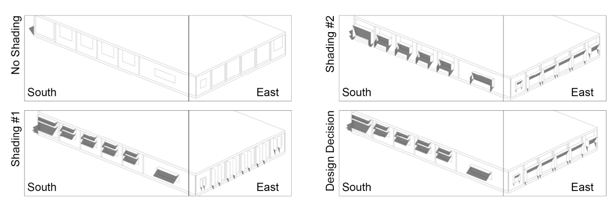

Figure 9 Shading Options

For Shading #1, two separate panels are placed horizontally in the South-facing rooms. The lower panel is placed at 6’-8” to ensure occupants’ view access to the exterior. For the East-facing rooms, two vertical panels are placed at the window’s South side and midline. The length of vertical panels is equal to window’s height. The shading depth (either 1’-0” or 1’-6”) depends on different floor zones. In terms of Shading #2, for South-facing and East-facing windows, it adopts integrated shading devices. The top of the shading device is placed at 6’-8”. The shading depth includes 1’-0”, 1’-6”, and 2’-0”, depending on the shading effects. In point-in-time illuminance analysis, September 21st is selected as the typical date. 9:00 AM is chosen for East-facing zones, and 12:00 PM is selected for South-facing zones.

Table 4 Point-in-Time Illuminance Simulation and Shading Scenarios

Scenario	Time	#3	#4	#5	#6	#7
No shading	9:00 AM	3718.2	9059.25			
	12:00 PM			6250.81	7680.03	10453.2
Shading #1	9:00 AM	2240.2	6592.94			
	12:00 PM			3451.11	4884.60	5600.32
Shading #2	9:00 AM	1724.0	5549.13			
	12:00 PM			4618.31	5043.62	7976.30

(unit: lux)

Table 4 shows a nuanced difference between two shading strategies. In the East-facing zones (#3, #4), Shading #2 works better in lowering the average illuminance at 9:00 AM. Shading #1 is more effective at 12:00 PM for the South-facing rooms (#5, #6, #7). The design decision for the exterior shading is a combination determined by the best shading effects (Figure 9).

Visual Comfort

In the DGP simulation, four perspectives are established (Figure 10). The view heights are all fixed in 6’-0” height (the length of the camera in Rhino is 15). For Corresponding to the point-in-time illuminance setting in the shading design, September 21st, 9:00 AM is selected for the East-facing zone (View A, View B). September 21st, 12:00 PM is selected for the South-facing zone (View C, View D).

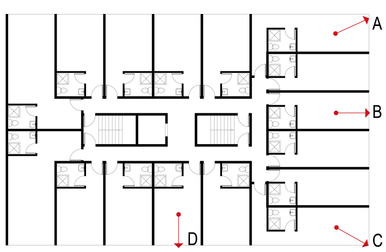

Figure 10 DGP View Setting

After adding Shading #1, the glare level in the View-B is alleviated from “Intolerable” (47% DGP) into “Disturbing” (42% DGP). The DGP values in the View-A and View-D slightly also decreased. Although the DGP value in the View-C stays consistent, the false-color imagery indicates that the interior glary area is decreased. When Shading #2 is added, it alleviates the glare level in View-B from “Intolerable” (47% DGP) into “Disturbing” (44% DGP). Although the DGP values in the other three views remain in the “Imperceptible” level, the shading device blocked some direct sunlight. No matter which shading device is adopted, direct sunlight always accesses into the interior spaces. The next step is to consider interior roller shades for achieving a more subtle visual comfort.

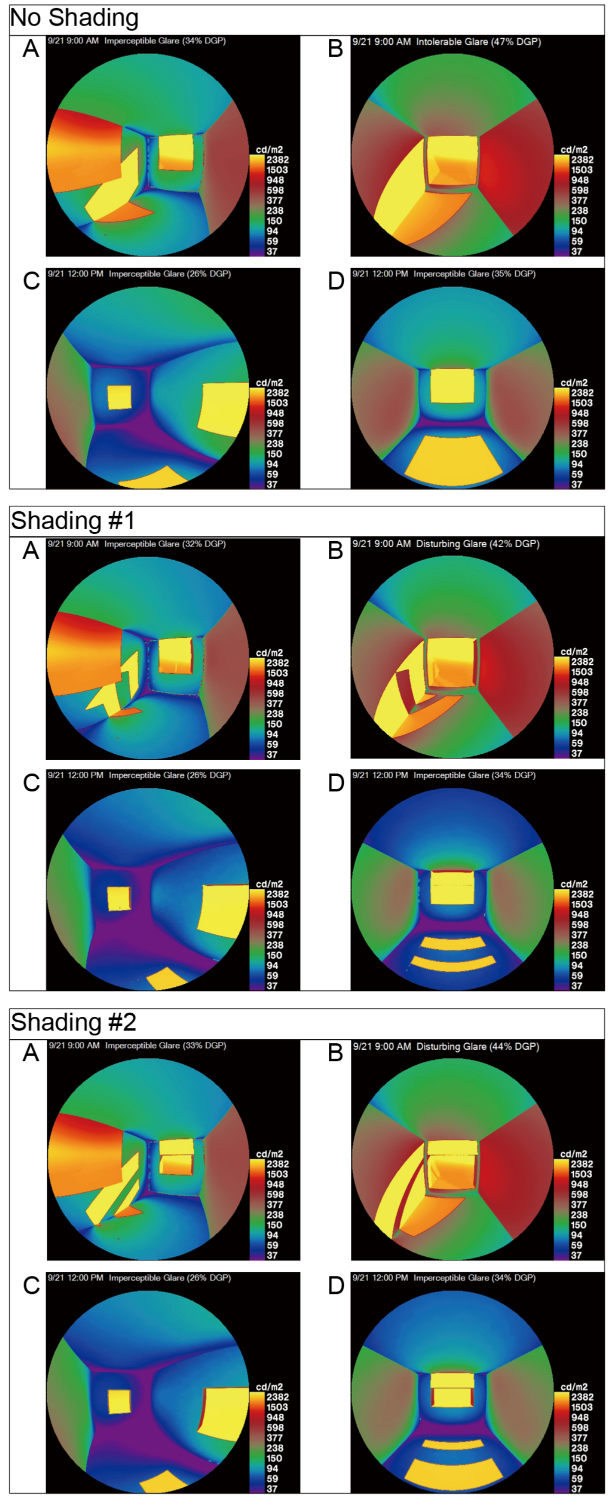

Figure 11 DGP Simulation and Shading Options

Table 5 UDI (300-3000lux) and Shading Scenarios

Scenario	**#3**	**#4**	**#5**	**#6**	**#7**
No shading	57.97%	50.46%	48.03%	59.67%	47.60%
Shading #1	58.88%	50.31%	47.62%	57.70%	46.78%
Shading #2	59.47%	51.19%	46.82%	58.90%	49.02%
Shading #3 + auto 300-3000 lux	63.89%	40.04%	9.45%	34.10%	30.76%
Shading #3 + auto 300-4000 lux	**63.79%**	**45.21%**	**23.64%**	**43.18%**	**38.46%**
Shading #3 + auto 300-5000 lux	63.95%	40.76%	11.94%	36.06%	32.44%
Shading #3 + auto 2000-3000 lux	63.80%	39.92%	9.16%	33.98%	30.55%
Shading #3 + auto 3000-4000 lux	63.93%	40.62%	11.84%	36.26%	32.19%

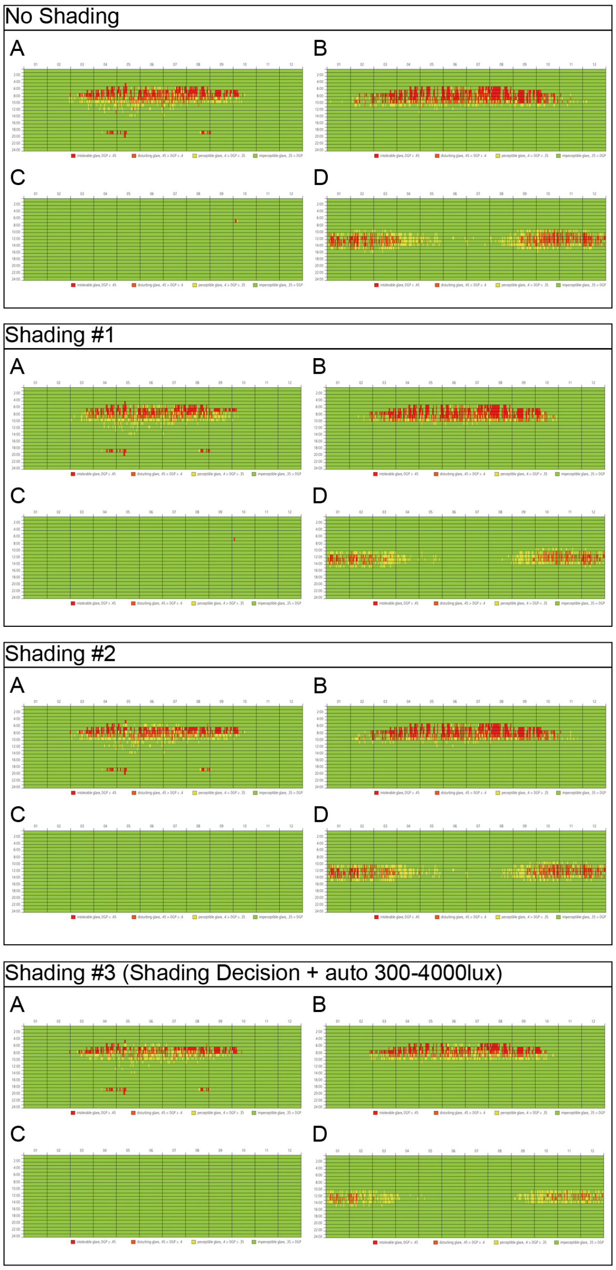

Figure 12 Annual DGP Simulation Shading Options

Based on the selected exterior shading device, automated glare control (interior roller shades) with different illuminance thresholds are tested by using UDI (300-3000lux) simulation (Table 5). The interior roller shades could block sunlight indeed, but it also results in overshading effects that decreased desirable daylight range (UDI (300-3000lux)). However, for Northeast-facing room #3, the interior roller shades could improve the interior daylight. For the given five thresholds, the ideal option is to set it in 300-4000lux, which means the interior shading device would not deploy until the illuminance reaches 4000lux. In contrast, UDI starts penalizing when the values above 3000lux. Due to the flexibility of occupant movement in residence, it is acceptable to operate the shading device in a higher illuminance setting. Therefore, using interior roller shades is a practical approach for occupants.

Using the same view settings in DGP simulation, the Annual DGP simulation (Figure 12) shows that for the View-D, the glare issue appears around noon from September to March. In the View-A and View-B, glare issues mainly appear between morning and noon from March to October. There is no glare issue in the View-C. In those three shading strategies, shading #3 (shading decision + automated interior shades (300-4000lux)) works the best in responding to the annual glare issues, comparing to other two shading strategies. It also indicates that some glare issues (especially "Intolerable Glare") persist at limited time frames throughout the entire year.

Therefore, shading device and interior roller shades (300-4000lux threshold) will be both recommended.

CONCLUSION

Design Guidelines

After computational simulation and discussion, a series of design guidelines are finalized for Seattle multi-family housing: (1) Floor-Floor Height: Under 75'-0" height limitation, 10'-0" is optimal for floor-floor height, with 1'-0" height reserved inside for ceiling/structure. The minimum height (7'-6") in the related codes is not favorable for daylight. (2) Unit Depth: During the entire year, the South-facing rooms have more common overlit issues (UDI (>3000lux)) and less underlit issues (UDI (0-300lux)) than the North-facing rooms. Given the same unit width, if the overlit area around window region is acceptable, minimizing the unit depth in the North and extending the unit depth in the South will improve the overall daylight distribution. (3) Fenestration: When the interior wall materials are unified, placing the window at one side of the wall does not significantly improve interior daylight. The most effective approach is to raise the window's head to the ceiling height, or as high as possible. (4) Shading Strategy: The South-facing and the East-facing rooms typically need shading devices (the West orientation is excluded in this study). The rooms in the Southeast and the Northeast corners require more effective shading strategies than other orientations. For the exterior shading, the horizontal shading device is more efficient in decreasing hourly illuminance in the South-facing rooms. The integrated shading device works better for the East orientation. If the outdoor shading is not feasible due to the strict building setback, interior roller shades could be a feasible option. (5) Glare Control: interior roller shades could be a reliable shading strategy in addressing annual-based glare issues. Especially movable shading device can be customized for different individual preferences and site contexts.

Final Floor Plan

The final floor plan (Figure 13) includes the design decisions in this study. The daylight-oriented workflow has a well fit to local building code (SDCI 2015), which prescribes 7'-0" by 7'-0" habitable area inside living units. The ideal unit layout for daylight has relatively wider unit width and shorter unit depth, which also brings an integrated habitable space.

Future Study

The main challenge in residential daylight design is the different target illuminance depending on visual tasks, age, and gender (Peters et al. 2018), while a lack of daylight metric for residential building. In this study, UDI (300-3000lux) is prioritized as the desirable daylight range to guide the design decisions, and UDI (>3000lux) indicates potential overlit areas that need shading and glare control. As a daylight metric, UDI is powerful to provide annual daylight performance, but its simulation results are compressed. Generating both false-color imagery and quantitative values for all design proposals repetitively could be overwhelming.

In further research, except for September 21st (9:00 AM, 12:00 PM), other time points need to be tested for comprehensive shading strategy. The result of this study only shows the glare perception generated from the chosen view directions/positions. Due to the flexibility of occupant activities and daily schedules, more view settings would be necessary. Apart from floor-floor height, the rest of the simulation does not have surrounding contexts. The realistic environment may impact fenestration selection. The daylight performance in the west orientation and illuminance variation in different floor elevations also need to be explored further. The roller shades might be useful to address the illuminance variation from different floors. This study could be expanded to explore more specific illuminance thresholds for residential building. A higher illuminance threshold may be suitable for residential units, but more research is needed to determine how it could impact living comfort.

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Figure 13 Final Floor Plan

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