Assessing circadian stimulus potential of lighting systems in office buildings by simulations

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ABSTRACT: Daylighting research has been primarily focused on the visible light spectrum for enhancing the quality and quantity of light in the built environment. Lighting design has been focusing on the reduction of glare and illuminance availability. A new assessment approach has been developed in recent years to address the non-visual effect of light such as circadian entrainment and alertness. The first objective of this study is to evaluate the glazing performance in terms of circadian stimulus potential, visual comfort, and task performance. The second objective is to evaluate the circadian stimulus potential of artificial lights. ALFA is used to measure the three glazing performance at eye-level in office spaces. Equivalent melanopic lux is measured at 1075 virtual nodes over 12 hours on March 21st. Results show that the electrochromic three zones system performs the best among the three glazing options.

KEYWORDS: Daylight; Non-visual effects; Health and Wellbeing; Circadian system; Office building; Electrochromic glazing; ALFA

INTRODUCTION

Given the fact that people in the modern societies spend more than 87% of their time indoors (Konis, 2018), the importance of designing a healthy lighting environment for building occupants becomes more evident (Klepeis,2001). A well-daylit space not only enhances visual comfort and energy efficiency, but also has the potential to improve the non-visual effects of influencing occupants' health and well-being (Hattar et al, 2002)(Amirazar et al,2018). Since the discovery of the third class photoreceptor in the eye - ipRGCs, the impact of the non-visual aspect of light on stimulating the circadian system and consequently affecting the alertness and sense of wellbeing has received increasing attention (Berson et al, 2002) (Hattar et al, 2002). Irregular long-term or short-term exposure to natural light can cause several health issues and disrupt human body mechanisms, such as endocrine function, digestion, core body temperature, sleep-wake cycle, depression, mood, and fatigue (Figueiro et al,2008)(Blask et al, 2005)(Stevens et al, 2013). Considering the importance of the non-visual aspect of (day) lighting, establishing a standardized measurement is critical (Lucas et al, 2014). Therefore, new performance standards, such as EML, CS, and nvRD, are developed to determine the important role of light in maintaining healthy human biological functions. These novel measurements can be adopted along with the conventional metrics for assessing visual task performance and visual discomfort. (Pechacek, et al, 2008) (Amundad ´ ottir, et al 2017)

The circadian stimulus potential attempts to determine where, when and to what extent circadian entrainment and alertness effects are likely to occur in a space. In the other words, it is understood as how often over the year someone looking for a specific view direction at a specific location would experience light levels that are above the threshold for non-visual effects. Because the effect of light on non-visual system is cumulative, instantaneous evaluations are inappropriate due to five fundamental characteristics of the light that stimulates non-visual system over time, namely: quantity, spectrum, timing, duration, and prior light history (Rea, et al, 2002). While the human circadian system is most sensitive to light spectrum at 460 nm (blue region of the visible light spectrum), the visual system is most sensitive to 555nm (green region of the visible light spectrum) (Rea, et al, 2010) (Thapan et al, 2001)

(Brainard et al, 2001). The rods and cones photoreceptors, which are located in the outermost layer of the retina, influence the visual effects (Figueiro, et al, 2016).

However, the recently discovered photoreceptor - intrinsically photosensitive retinal ganglion cells (ipRGCs), contributes with other photoreceptors (cones and rods) to the non-visual mechanisms (Berson et al, 2002) (Hattar et al, 2002). For circadian stimulus potential measurement, the International WELL Building Standard Institute (2017), a “building certification system with the objective of measuring, certifying and monitoring the performance of building features that impact health and well-being”, has developed a metric named Equivalent Melanopic Lux (EML) for evaluating non-visual effect of light. The current version of WELL building Standard (2017) has proposed the threshold of 200 Equivalent Melanopic Lux (EML) and 150 EML measured on the vertical plane facing forward for daylighting and electric lighting spaces, respectively, during the hours between 9:00 and 13:00.
Since the effect of light exposure on the non-visual system is accumulative and dependent on the time of the day and duration of time exposure, Andersen et al (2012) has proposed to divide a day into three time periods, 6:00–10:00 (circadian resetting), 10:00–18:00 (alerting effects of daylight), and 18:00–6:00 (bright light avoidance, dim light only). While the natural light can improve human health and visual comfort, and increase the connectivity to the outside, direct sunlight can create visual discomfort in the form of glare (glare) and overheating of the indoor space (Jakubiec,J.A, et al, 2015)(Asadi et al,2018). Advanced glazing systems, such as electrochromic glazing (EC), are therefore developed to modulate natural light introduced into indoor spaces, and to improve comfort, health and well-being of building occupants. Previous studies on EC glazing have been mostly focused on evaluating light quantity, visual comfort, and energy consumption. Few research has investigated how EC glazing can enhance the non-visual effect of light. There is also a lack of tools. An overview of the ongoing and past research reveals that very few computer tools are available to assess the non-visual effect of light to facilitate the process of building design. The aim of this paper is therefore to employ simulation-based workflow to investigate the circadian effectiveness of indoor spaces illuminated by daylighting and electric lighting. Specifically, the present study is designed to investigate the performance of three different glazing systems in terms of their abilities to deliver circadian potential stimulus by daylight and compare the circadian efficacy of eight different electric lighting systems.

1.0. METHODOLOGY

This study adopts a simulation-based approach by using newly released simulation software - ALFA to collect light exposures in order to quantify the influence of various light sources on the non-visual (health) needs of occupants. Data related to non-visual effects of light and amount of direct light that hits the sensors are collected by placing sensors on the vertical surface at eye-level height (1.2m) above the floor. Work plane illuminance is measured by virtual sensors located on the horizontal surface 0.76 m above the floor.

2.0. THE SETTING

The study setting is a side-lit open plan office space located in Minneapolis, Minnesota with a window facing south. The dimensions of the space are 22.5 m deep, 14m wide and 3.3m high. The floor is covered with 1075 sensors spaced 0.5 m apart in both directions on the vertical and horizontal measurement grids at 1.2m and 0.76m above the floor, respectively. Sixteen different directions are chosen for each grid point on the vertical plane to represent all possible view directions of seated occupants. The sensor height is set at 1.2 m above the floor to represent users’ eye level height. The space is divided into three zones (zone A, zone B, and zone C) based on their distance to window (see Table 1). The depths of the zones are 5 m, 8 m, 8 m, and respectively. Since typical office schedule is from 7:00 to 18:00, the study only considers the first two time frames (6:00 to 10:00 and 10:00 to 18:00), and the 6:00 -7:00 period is removed from the analysis because typically no occupants work during that hour. The simulation is performed on March 21st from 07:00 to 18:00 with one hour interval. Table 2 shows the specification of the different glazing systems and artificial lighting that are used in this study. EC glazing stands for Electrochromic glazing. The difference between the EC single zone and EC three zones is that for EC single zone the whole glass is tinted or cleared completely, whereas in the EC three zones, the glass is segmented to three equal horizontal rows (zones), and each row is tinted or cleared independently.

Table 1. Model Properties

		Number of Sensors	Depth	Number of Artificial light
Zone	A	250	5 m	6
	B	400	8 m	6
	C	420	8 m	6

Table 2. Glazing and artificial type

	Type
Glazing	Double IGU clear 63% glass, Electrochromic single zone, Electrochromic three zones
Artificial light	FLU0.57, FLU1.28, LED0.29, LED1.00, LED BLUE, LED Green, LED Orange, LED Red

3.0. THE SIMULATION WORKFLOW

The space is modeled in Rhinoceros (Figure 1) (Rhinoceros 3-D Modeling Program). The ALFA software, a plug-in to Rhinoceros, is used to evaluate lighting conditions based on their impact on circadian health and alertness (Solemma, DIVA for Rhino). ALFA assigns radiance materials to all surfaces. The data output indicates the average illuminance in each view direction at each zone. The performance of three glazing strategies is compared in terms of their abilities to provide enough light needed for daytime conditions. The materials' surface reflectance values are shown in Table 3 - melanopic reflectance and photopic reflectance, respectively. The characteristics of the three glazing strategies in terms of melanopic and photopic transmittance are shown in Table 4 with the consideration of the dynamic pattern of electrochromic glazing the tinting state alters glazing transmittance for different time of the day (Malekafzali, 2018).

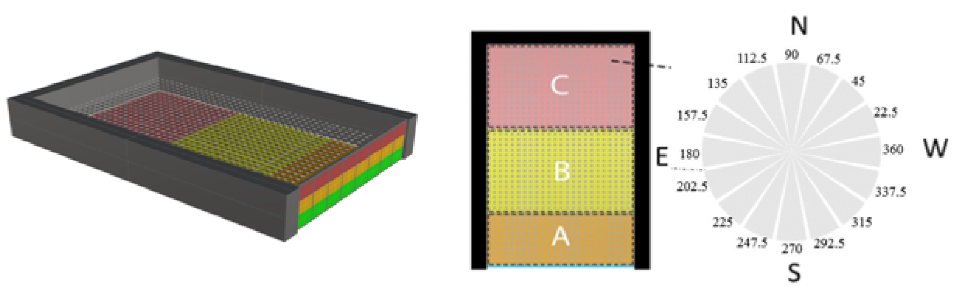

Figure 1. The 3D Model of the Office Space Created in Rhino

Table 3. Material reflectance

	Ceiling	Column	Interior wall	Floor
Melanopic reflectance (%)	76.8	76.8	76.8	37.6
Photopic reflectance (%)	81.2	81.2	81.2	41.8

4.0. RESULT AND DISCUSSION

The analysis is conducted into two parts: daylit and non-daylit. In the daylit section, the glazing performance is estimated in terms of the daylight quality on vertical and horizontal surfaces, task performance, visual comfort, and health effect (circadian stimulus potential). In the non-daylit section, different artificial lights are compared in terms of the health effect (circadian stimulus potential) during the non-daylit period. Based on the WELL Building Standard (2017) the desirable circadian stimulus potential should be above 200 EML, the vertical direct illuminance in a view should be under 1500 lux to minimize glare risk,(Jakubiec, J. A, et al, 2012) (Jakubiec, J. A, et al, 2015) and the work plane illuminance should more than 300 Lux according to the established daylight performance metric - Daylight Autonomy (DA300) (Reinhart, et al, 2006).

Table 4. Characteristics of three glazing systems

Glazing	Melanopic transmittance	Photopic transmittance
Electrochromic Glazing Fully tinted state	1.6	0.9
Electrochromic glazing 2nd intermediate state	7.4	5.6
Electrochromic glazing 1st intermediate state	18.7	17.6
Electrochromic glazing Clear state	55	60
Double IGU clear Tvis 63%	61.7	63.3

4.1. Daylit

Figure 2 - 5 summarize the glazing performance in terms of circadian stimulus potential, visual comfort, and task performance. In Figure 2, although the best performance in terms of melanopic illuminance EML is with the double glazing system, the EC three zone provides the balance between the range of photopic illuminance (daylight availability) and melanopic illuminance (health performance). Although the range of photopic illuminance with the double glazing system is most desirable, the daylight intensity is significantly higher than the "comfort" level. The two versions of EC glazing (EC single zone and three zone) perform well in controlling the incident daylight. Moreover, the performance of EC three zones is better than that of the EC single zone in terms of health performance - the percentage of the circadian stimulus potential in EC three zone is higher than the single zone version. In the double glazing, the percentage of the views with vertical direct illuminance under 1500 lux collected during the first time period (7:00- 10:00) is low in all zones. Moving away from the window, the percentage of views with vertical direct illuminance under 1500 lux is increased, which means zone C has better lighting condition in terms of visual comfort. In EC single zone, the percentage of views with vertical direct illuminance under 1500 lux in zone B and C are 100% in both time periods. In zone A, the graph indicates that the view direction ranging from the 45'- 135' facing the window in the second time period, and the view direction ranging from 45'-225' facing the window in the first time period are about 70% under 1500 lux. As expected, the distance from the window in the daylit space is found to have a significant impact on the predicted stimulus potential. In terms of the circadian stimulus potential, by moving away from the window the percentage of views above 200 EML is decreased. In EC three zones, by moving away from the window the percentage of views with vertical illuminance under 1500 lux is significantly increased. In comparing EC single zone with EC three zones in zone A, the percentage of the direct sun entering through the single zone EC glazing is higher. The EC three zones system performs better in creating the balance in daylight availability between visual comfort and work plane illuminance. In EC three zones, the zones that are far from the window have less percentage of views about 200 EML than those close to the window.

As mentioned above, the WELL Building Standard measures the circadian stimulus potential by the percentage of views (min. 75%) that have at least 200 equivalent melanopic lux. Circadian stimulus potential is assessed for at least the hours between 9:00 and 13:00 on the vertical plane facing forward 1.2 m above the floor to simulate the view of the occupant. Based on this standard, Clear IGU 63% has above 75% percentage of views in term of circadian stimulus potential. In EC single zone, the percentage of views in zone B, and C is negligible, and in zone A, the percentage of the view directions ranging from 225' to 315' facing the window is above the minimum requirement. In EC three zones, the percentage of views is higher than the WELL Building Standard at the zone close to the window, but by moving away from the window (zone C), the percentage drops under the desirable range. In zone B, the view directions ranging from 0' to 180' facing the window provides enough EML to stimulate human circadian system.

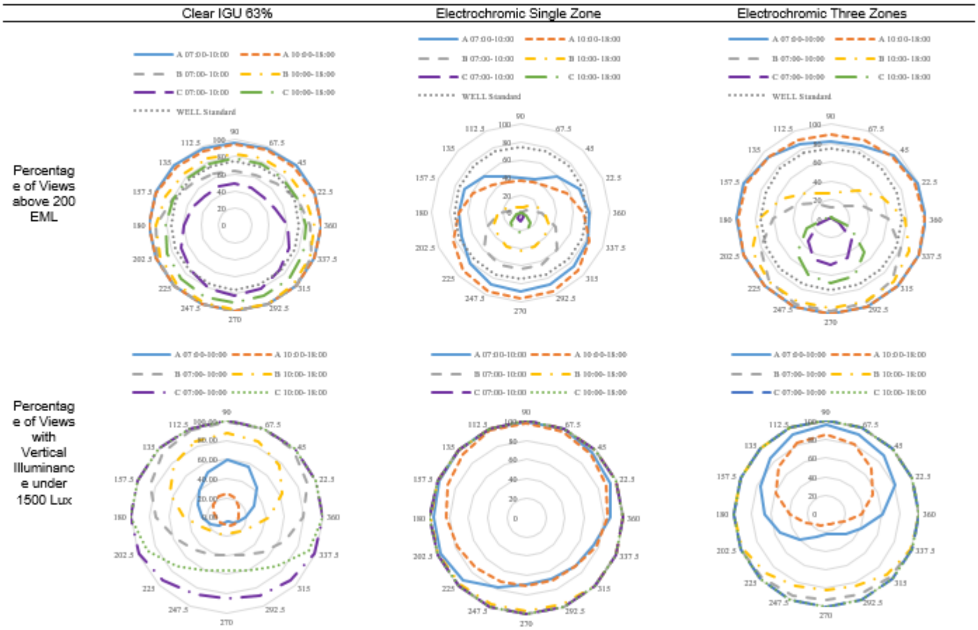

Figure 2. Compare the daylight performance of three glazing strategies within two-time period for three zones (zone A, Zone B, and Zone C) at the south facing façade

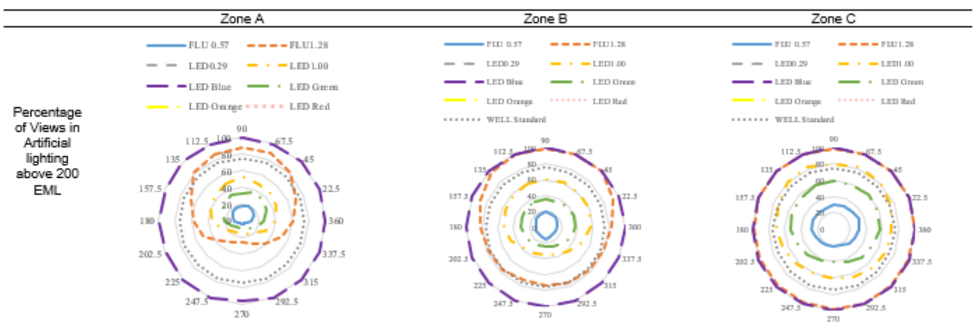

Figure 3. Compare the circadian stimulus potential of three glazing strategies based on the WELL Building Standard in time period from 9:00 - 13:00 for three zones (zone A, Zone B, and Zone C) at the south facing façade

Figure 3 shows that the best glazing performance is EC three zones regarding the desirable melanopic illuminance range, which is minimum 200 EML, and the desirable photopic illuminance range, which is maximum 1500 lux. . It is critical to balance between circadian stimulus potential and vertical illuminance (visual comfort) Figure 3 shows that the vertical illuminance of the Clear IGU 63% is too high, although its melanopic illuminance range is desirable, This glazing provides minimum 200 EML for nearly 100 percentage of views in two time periods in zone A. In zone B and C, the second time period has better performance than the first one. The double glazing performs better in term of the circadian stimulus potential than the advanced glazing systems - the percentage of the melanopic illuminance in all zones A, B, and C is higher than 75%. However, the melanopic illuminance is not the only metric to assess the glazing performance. The EC three zone works better than the single zone version. In zone A, the percentage of the EML is higher than the minimum threshold, but in zone C the percentage of the EML is under the threshold.

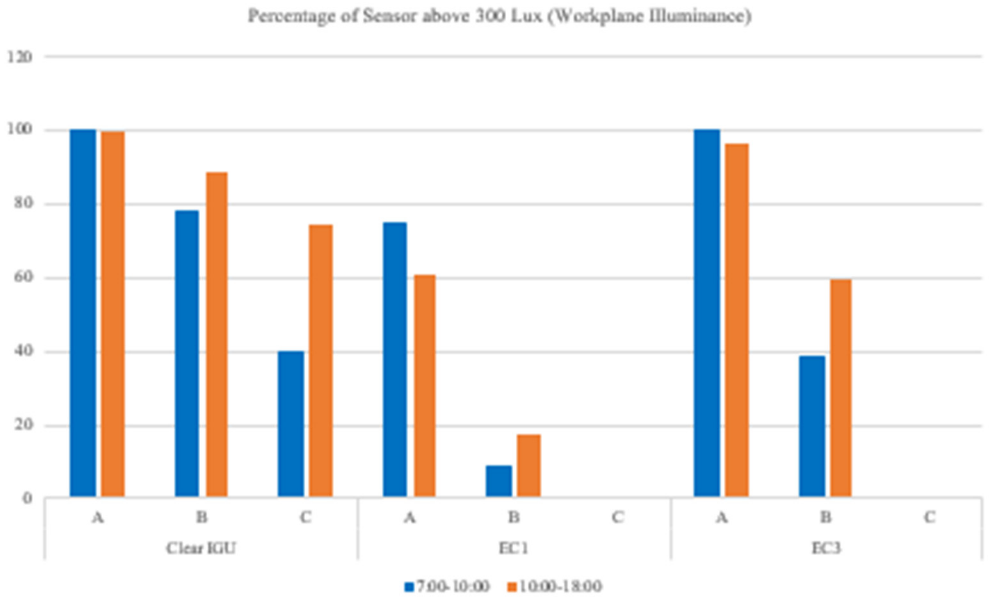

Figure 4. Compare the daylight performance of three glazing strategies within two-time period for interior and perimeter zones at the south facing facade

Figure 4 shows the percentage of daylight illuminance more than 300 Lux in the work plane. The performance of the new EC glazing (EC three zones) performs better than the old version (EC single zone) regarding the daylight availability in the workplace in both zone A and B and in both time periods, by considering the balance between visual comfort (vertical views under 1500 lux) and workplane illuminance. To summarize, three glazing types are compared in terms of daylight availability in horizontal illuminance (workplane), vertical illuminance (visual comfort), and the non-visual aspect (health aspect). A parallel coordinate chart (Figure 5) is created to illustrate the following points:

- **Photopic illuminance**
  The range of the photopic illuminance in EC three zones and EC single zone in all zones (A, B, C) between 7:00- 18:00 are under 1500 lux. In Double glazing system just in zone A the range of the photopic illuminance is above 1500 lux. In zone B and C, the photopic illuminance is under 1500 lux.
- **Melanopic lux**
  In zone A, the double Glazing system, EC three zones and EC single zones all provide melanopic lux level above 200 EML in all time periods and in all view directions. In the double glazing system the level of photopic illuminance is above 200 EML in all zones. EC three zones provides 200 EML or higher and provides acceptable photopic illuminance range between 7:00 and 17:00 in view direction facing the window (45'- 135') in zone B. In zone C, it provides 200 EML or higher between 7:00 and 8:00 and between 15:00 and 17:00 in view direction facing the window (22.5'- 157').
- **Workplane illuminance**
  The zone A of the double glazing system provides 300 lux or higher for office tasks. However, in zone B and C the illuminance level is lower than 300 Lux during 7:00- 17:00 and 9:00- 16:00. In both EC glazing systems, the range of the workplane illuminance is lower than 300 lux in all the time periods in zone C. The zone A of the EC three zones system achieves the desirable daylighting range in all time periods, but in zone B it only achieves the range between 8:00 and 17:00.

- **Melanopic lux EML> 200, Photopic Illuminance < 1500**

In zone A, both versions of the EC glazing achieve this balance, but the double glazing does not meet this condition. Although the double glazing performance is relatively poor in zone A, it performs better in zones away from the window.

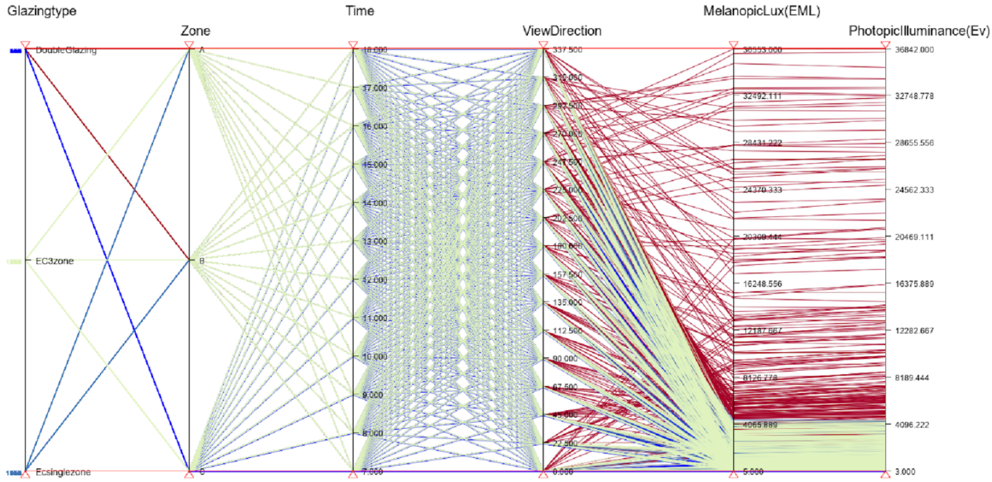

Figure 5. Parallel Coordinates plot of daylighting assessment metrics, melanopic and photopic of three glazing in t three zones (zone A, Zone B, and Zone C) from 7:00 - 18:00 at the south facing facade

4.2. Non-daylit

As the previous study concluded, electrical lighting can affect circadian rhythm disorder. Moreover, artificial lighting can also improve indoor environment by providing sufficient light stimulus to residents. Regarding the second study objective, different types of artificial lighting in terms of their non-visual effects are evaluated. In addition, artificial light source is introduced as an additional source to assistant glazing to enhance healthy circadian. In this section 8 different artificial light sources are compared in three zones during the non daylit time period. The number of artificial lights installed in model is 18 in total with 6 in each zone. In zone A, based on the Well Building Standard, only LED Blue achieves the range higher than the minimum EML standard. In zone B and C, both LED Blue and FLU 1.28 has EML level higher than 75%.

The results suggest that for all views and all zones LED Blue meets the threshold of 200 EML. In contrast, the EML ranges of LED Red and LED Orange are negligible. This finding aligns with the previous literature (REF) that non-visual system is more sensitive to blue-enriched light.

CONCLUSION

The comparison among different glazing systems and artificial light sources in terms of circadian stimulus potential, task performance and visual comfort are conducted in this paper by using computer simulations. The outcome is dependent on distance from windows. Due to the discovery of the novel photoreceptor and the melanopic sensitive wavelength, photopic illuminance is found to be an inappropriate measurement for circadian stimulus potential. Findings from this study show that the electrochromic three zones glazing provides the best performance in creating the balance among the metrics.

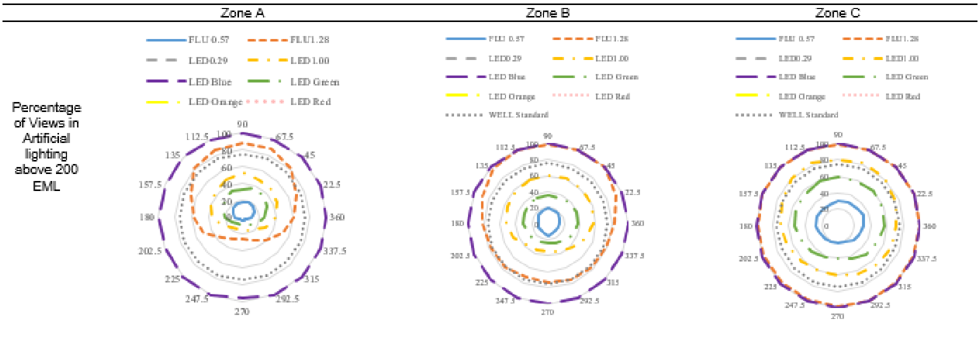

Figure 6. Compare the circadian stimulus potential of three glazing strategies based on the WELL Building Standard in time period from 9:00 - 13:00 for three zones (zone A, Zone B, and Zone C) at the south facing façade

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