Synergies between Electrochromic Glazing and Tunable White LEDs

View Inc. with analysis and modeling provided by **HLB Lighting Design**

Abstract

Electrochromic (EC) glazing products can control solar transmission by dynamically adjusting the tint level of the glass. The glass tints to control glare and heat when there is direct sun on the façade and clears when the sun is not directly on the façade. This provides unobstructed views and maximizes ambient natural light. Tunable-white LED luminaires can deliver varying spectral distributions, bringing warmth of white light, and greater design flexibility into interior spaces.

What if these two innovative technologies are brought together? This study examines the combined effects of tunable white lighting systems in an interior space with EC glazing (specifically View Dynamic Glass) and provides design guidance on a use case of tunable LEDs in a space with View Dynamic Glass windows.

The results of the study show that the space color quality with View Dynamic Glass can be maintained at good to excellent levels throughout the space, and under all conditions, with the appropriate mixing of electric lighting.

Introduction

Electrochromic (EC) glazing products dynamically tint to block heat and control glare while offering unobstructed views. View Dynamic Glass (VDG) is a commercially available EC glass that has tint states with Visible Transmittance (Tvis) of 1%, 6%, 40% and 58%, and a corresponding Solar Heat Gain Coefficients (SHGCs) of 9%, 11%, 28% & 40%. Tint state selection is fully automated and controlled by a software algorithm designed to manage three functional priorities: glare control, heat control, and daylight maximization. The algorithm is based on several parameters such as the furniture location, architectural features of the building, angle of the sun, cloud cover and glare, temperature, and daylight and light sensor-readings inside.

Tunable LED luminaires are the latest advancement in electric lighting technology and can deliver varying spectral distributions, bringing warmth of white light, and greater design flexibility into interior spaces. Tunable white LEDs are a specific type of electric lighting fixture that allows for changing the color of light from warm to neutral to cool in appearance. Each fixture has two sets of controllable LEDs, one with a warm-white color (usually 2700K), one with a cool-white color (usually 5000K to 6500K). By individually adjusting the output from these two LEDs different white colors can be created. According to the Department of Energy (DOE), this property makes tunable-white LEDs desirable to simulate daylight for a range of applications including offices, medical buildings and other building types.

Objective

The objective of this study is to quantify the ability of an existing tunable white lighting system to complement a space installed with EC glass (in this case VDG), to provide the best color quality. More specifically, this study aims to:

- Measure the color quality of daylight through the various tint states of View Dynamic Glass
- Determine the ability of a tunable white LED lighting system to enhance color quality of the interior space
- Provide a methodology to achieve the target ratio of LED and daylight spectra that will maximize the Color Rendering Index, Gamut Index & Fidelity Index

Metrics of Measurement

The Illuminating Engineering Society's (IES) TM-30 advanced color metric calculator was used to assess the color metrics of the various spectra generated in this study. These include:

- Correlated Color Temperature (CCT) - CCT quantifies the "whiteness" of light, with lower CCT values indicating a warm color and higher indicating a cool color, and there is no established industry standard for CCT in office spaces.

- Color Rendering Index (CRI)- CRI is the current industry-standard metric for evaluating the ability of a light spectrum to render a series of test colors relative to a light spectrum of the same CCT. A higher value is generally better, and industry best practice typically requires a minimum of 80 CRI in office spaces.

- Fidelity (Rf) and Gamut (Rg) - Fidelity and Gamut indexes are from of the IES's TM-30 and represent the next generation of color metrics. Fidelity is similar to the CRI metric but uses a larger color set to broaden the metric. Like CRI, higher values are better with a maximum of 100. The paired Gamut metric evaluates whether a light saturates or desaturates colors, with values over 100 saturating colors and under 100 desaturating colors. The goal, then, with the paired metric is to maximize Fidelity while maintaining at Gamut close to 100.

Illuminance values were also evaluated at for each scenario, to ensure they meet the minimum average threshold levels. For this study, the target minimum average illuminance in the room was set at 25fc, given that is the functional limit of the tunable white luminaires used in this study.

Room Configurations/Modeling

An office space located in Milpitas, CA was used as the rest room for this study (Figure 1). It is a closed office space with VDG on the southside of the building. A Rhinoceros-based 3D model of this room was built and customized. Materials were defined to best capture the actual finishes of the test room and were assigned per Rhinoceros' layers. Material reflectance was also measured on site for validation.

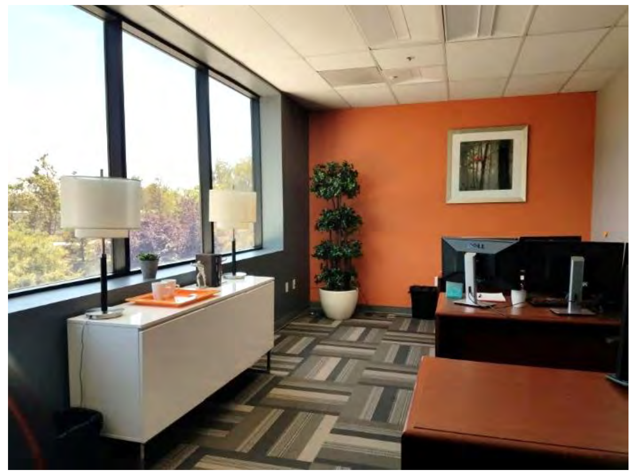


Figure 1 - Closed office space used as test room for the study

Tunable White LED fixture

For this study, two tunable white LED 2x4 ceiling recessed luminaires were installed in the ceiling. The tunable white LED luminaires have a CCT range from 2700K to 6500K with a CRI of 80. Spectral power distribution data (Figure 2) was obtained from the luminaire manufacturer for six nominal color temperatures: 2700K, 3000K, 3500K, 4000K, 5000K and 6500K.

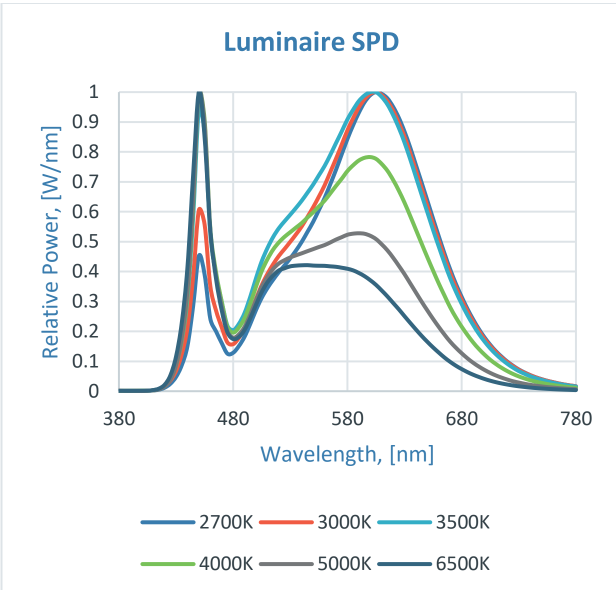


Figure 2 - Luminaire spectral power distribution at various color temperatures

Daylight Spectra

The International Commission on Illumination (CIE) standard D65 daylight illuminant (Figure 3) was used as the reference spectrum for daylight that was then filtered through the spectral transmittance of each tint state. The result was a "transmitted" daylight spectral power distribution for each tint state.

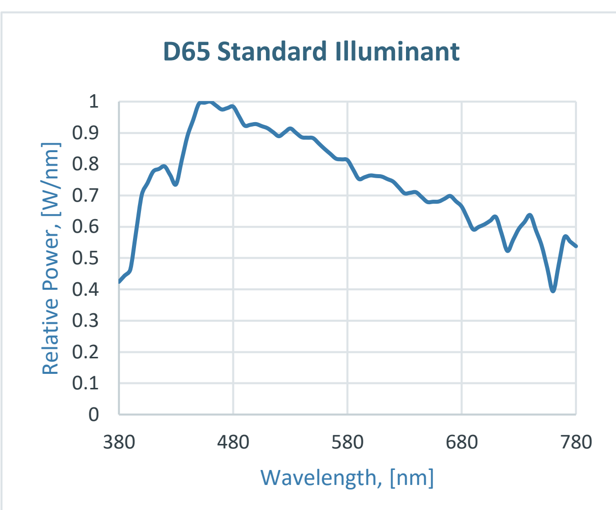


Figure 3 - CIE D65 standard illuminant

EC Glass Spectra

Spectral transmittance data for each of the four tint states of View Dynamic Glass was used (Figure 4). The spectral analysis was limited to a range of 380 – 780 nm due to the relevance of the data. Normalized relative power distributions were used throughout the analysis, which allows for the quantification of spectral characteristics independent of the actual power (or lumens) and can be used with scalar transformations to assess the actual power distribution.

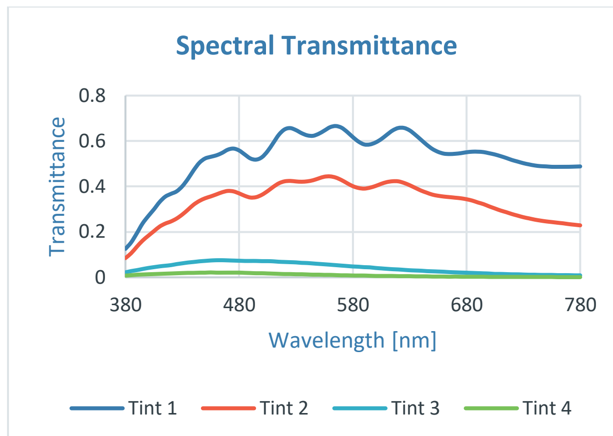


Figure 4 - Spectral transmittance of VDG at four tint states

Analysis Details

To set up the modeling of this study, a series of daylight illuminance calculations were performed which provided information about daylight penetration at different times of day and year through the different tint states. These were completed using Diva for Grasshopper through Rhinoceros 5, which served as the interface for Radiance-based calculations. The 3D model plan view is show in Figure 5.

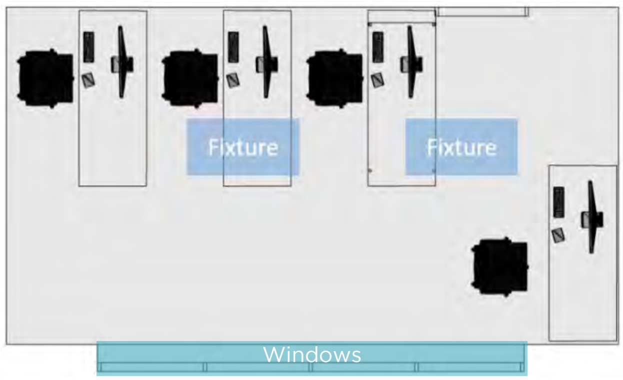


Figure 5 - 3D model plan view with LED fixture locations

The 3D model was also used to examine the point-by-point illuminance achieved by the tunable white luminaire in the space. Sixty-five (65) points were evenly distributed through the space and were calculated at 2.5' AFF[1]. Figure 5 shows the plan view of the test room.

The point-by-point electric lighting analysis used luminaire photometric data (IES files) from the luminaire manufacturer and assumed a maintained lighting condition (LLF[2] = 0.9). Electric lighting calculations were performed in AGI32 software. These points also formed the basis of calculation of the various color metrics of analysis scenarios, discussed in the results section.

Scenarios

In order to have a diverse representation of the solar and sky conditions as well as of the tint states, a variety of typical times of day and year were selected for clear sky or overcast sky conditions. Given that under overcast conditions, tint state 1 is the prevailing condition based on the algorithm, only one time was selected for overcast sky condition.

Table 1 summarizes the five scenarios considered and the corresponding date, sky condition, and tint states of the three window locations/orientations:

Table 1: Study scenarios

Scenarios	Date and Time	Sky Condition	VDG Tint	VLT
S1	9/21 8am	Clear + Sun	1	58%
S2	9/21 10am	Clear + Sun	2	40%
S3	9/21 12pm	Clear + Sun	3	6%
S4	9/21 2pm	Clear + Sun	4	1%
S5	12/21 12pm	Overcast	1	58%

Methodology

The focus of the analysis was to assess the ability of the tunable white LED fixtures to complement the color quality metrics. The goal is to select the tunable white LED settings that would maximize the average CRI of the test room while also ensure that fidelity and gamut indexes are high.

For each scenario, the following steps were taken:

1. **Create the modified spectrum to establish the baseline color metrics** – The first step involved creating the modified spectrum of daylight, which is the light spectrum that passes through the windows. As mentioned before, the CIE standard D65 illuminant was assumed as the normalized spectrum of daylighting, which was then "filtered" by the various tint state spectral transmittance to result in a transmitted spectral power distribution. Combining the daylight illuminance and the spectral power distribution, the point-by-point absolute

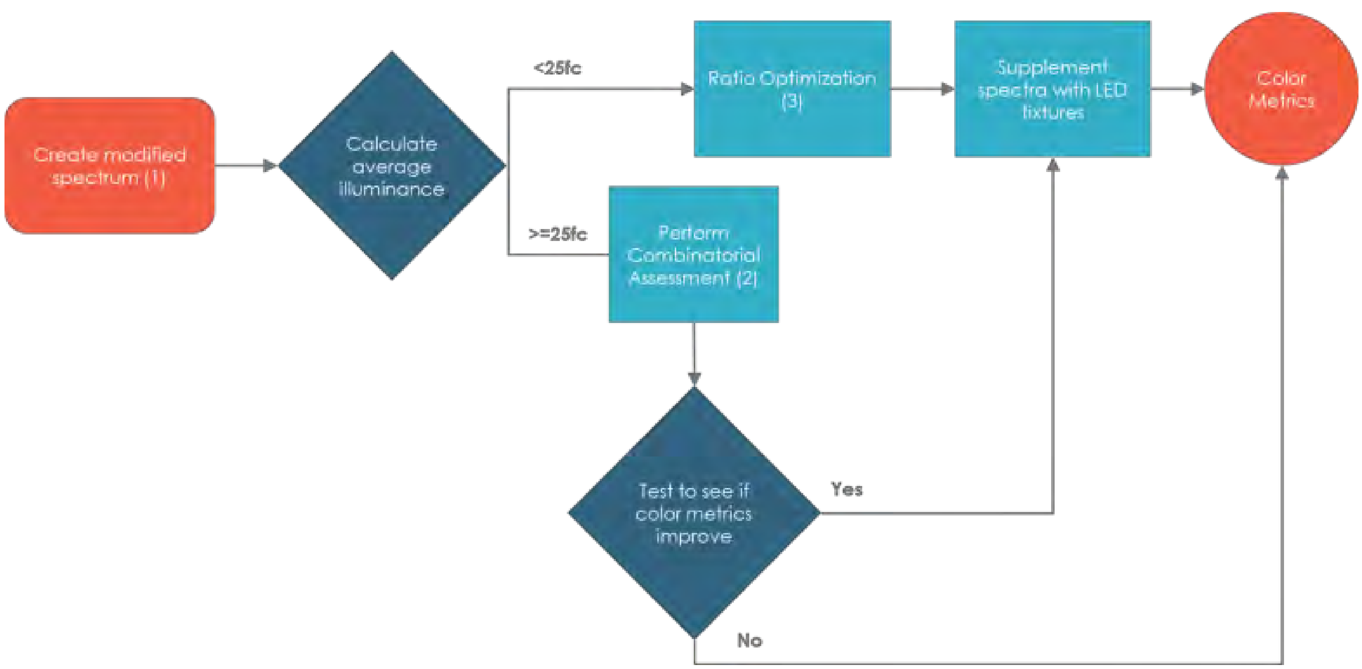
[1] Above Finished Floor, a way of defining the height in a space.
[2] LLF: Light Loss Factor, a factor applied to luminaire photometric data to account for cumulative reductions in light output due to environmental conditions (e.g. dust, ambient temperature) and normal light source depreciation.

spectral power distribution from daylight was determined. The IES TM-30 calculator was used to assess all four-color metrics of the resultant combined spectrum for each calculation point at each point in time.

2. **Determine what color of LED lighting to use (combinatorial assessment**) – A preliminary analysis was performed to test the robustness of the tunable white LED lighting to positively or negatively influence the color quality of the LED lighting proportionally mixed with the filtered daylight. The resulting proportional influence of the electric lighting was used in the next step to establish the optimal CCT and light level setting for the electric lighting.

3. **Add tunable white LED light to the space** (Ratio Optimization) – Point-by-point electric light levels were then used with the optimal color and quantity of tunable white LED to determine the point-by-point spectrum of electric light. The point-by-point daylight spectrum was then added to the point-by-point electric light spectrum to result in the point-by-point absolute spectral power distribution. Again, the IES TM-30 calculator was used to assess all four-color metrics of the resultant combined spectrum for each calculation point.

Figure 6 depicts the methodology in a flow chart format.



(1) D65 daylight illuminant + tint state transmittance
(2) Point-by-point irradiance of daylight + electric light
(3) Ratio of daylight to electric light

Figure 6 - Flow Chart of Methodology: Depicts the process undertaken to determine the recommended tunable white LED mixing levels

Results

Scenarios 1 and Scenario 5 (VDG in Tint State 1)

For scenarios 1 and 5, it was determined that, when the daylighting exceeded the target of 25 fc average and that the windows were in tint state 1, no supplemental electric lighting was required. Since there is abundant daylight in the space, the daylight alone provided plentiful illuminance and excellent color quality. Addition of any electric lighting only worsened the color quality since the CRI of the electric lighting is lower than that of daylight. Figure 7 shows a representative image of the tint state.

Given that no LED lighting are needed, the resultant color metrics are reported below (Table 2).

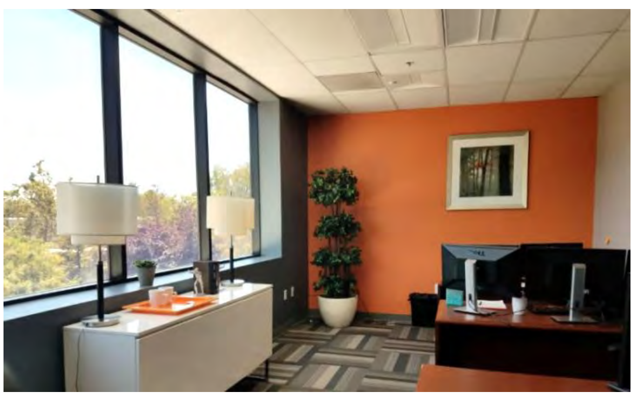


Figure 7 - Tint state 1 in the test room. Image is representative of the tint state only and do not correlate with the calculated value.

Table 2: Tint state 1 resultant average color metrics

Average Daylight Illuminance	~1,000fc
Average LED Illuminance	0
Average Total Illuminance	~1,000fc
Mixing ratio (daylight/LED)	100%/0%
Average CCT	5,717K
Average CRI	94
Average Fidelity	95
Average Gamut	97
Recommended LED Setting	No LED

Scenario 2 (VDG in Tint State 2)

For scenario 2, the south-facing window in the test room was set to tint state 2 (Figure 8). The daylight alone was determined to provide an average in the space of 580 fc, which is abundant. Based on the mixing graphs and the maximum electric light output, the maximum mixing ratio possible was determined to be closest to 90%/10%. and that the optimal light color quality is achieved with the electric lighting set at 3000K and maximum output (Figure 9).

Daylight was found to significantly penetrate the space, with even the rear of the room having daylight-dominated illuminances. Given the high color quality properties of tint state 2 and the dominance of daylight in the space, the color metrics remain uniform throughout the space.

The addition of the 3000K LEDs helped to lower the CCT further into the space, and to somewhat improve CRI. However, in the areas like the northeast section of the room where the light is dominated by the LED fixtures alone, the color metrics are made worse. This, and given that the illuminance is abundant in the space, for all practical purposes no LEDs are needed for this scenario with the existing LEDs. It should be noted that, LED fixture CRI vary significantly and therefore there could be many other tunable LEDs that would improve the CRI in this instance.

The average color metrics, as shown in Table 3, are all excellent with no LEDs added.

Figure 8 – Tint state 2 in the test room. Image is representative of the tint state only and do not correlate with the calculated value.

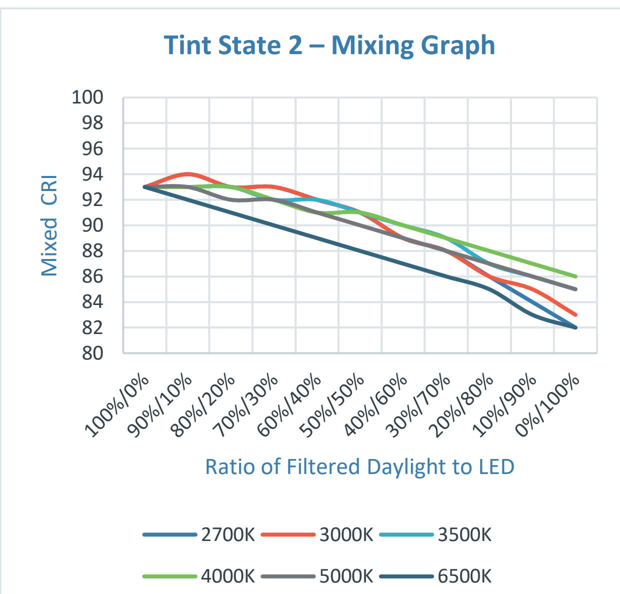


Figure 9 - Tint state 2 mixing graph

Table 3: Tint state 2 resultant average color metrics

Average Daylight Illuminance	580fc
Average LED Illuminance	0
Average Total Illuminance	580fc
Mixing ratio (daylight/LED)	100%/0%
Average CCT	5,828K
Average CRI	93
Average Fidelity	94
Average Gamut	96
LED Setting Needed	No LED needed

Scenario 3 (VDG in Tint State 3)

For this scenario, the south-facing window in the test room was set to tint state 3 (Figure 10). The daylight alone during this test was determined to provide an average of 49 fc, so the maximum possible mixing ratio of daylight to illuminance in the space was between 60%/40% and 70%/30%; however, the goal was to minimize the supplemental electric lighting. The mixing properties on the mixing graphs were reviewed, and it was determined that a 70%/30% mixing ratio at 3000K would optimize CRI and Fidelity while minimizing the amount of electric lighting required (Figure 11). Table 4 reports the color metrics.

During this time and with this tint state, the daylight did not penetrate the space as strongly during other assessed times, leaving the illuminance in the back of the room dominated by the LED fixture; the CCTs then mix accordingly, with high CCTs close to the window mitigated by lower, warmer CCTs at the back of the room. Point-by-point calculations of CRI are above 80 throughout the room, as shown in Figure 12.

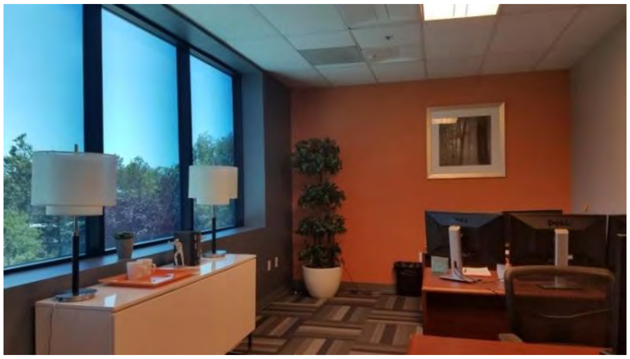


Figure 10 - Tint state 3 in the test room. Image is representative of the tint state only and do not correlate with the calculated value.

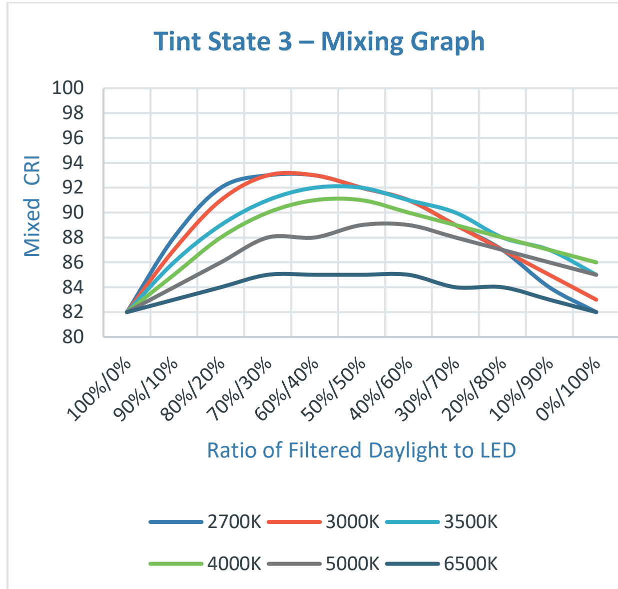
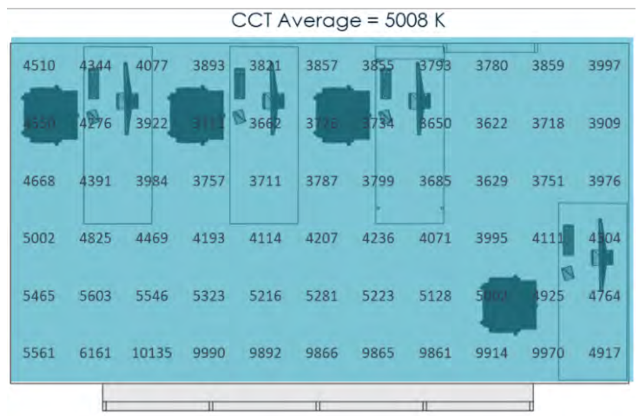


Figure 11 - Tint state 3 mixing graph

Table 4: Tint state 3 resultant average color metrics

Average Daylight Illuminance	49fc
Average LED Illuminance	21fc
Average Total Illuminance	70fc
Mixing ratio (daylight/LED)	70%/30%
Average CCT	5,008K
Average CRI	90
Average Fidelity	89
Average Gamut	96
Average % Daylight	49%
Recommended LED Setting	3,000K at 87.5% Brightness



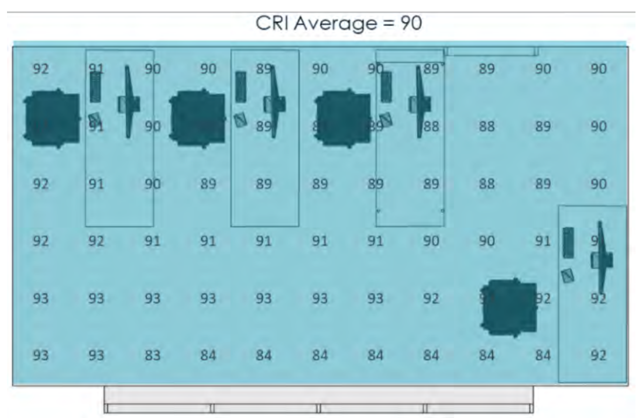


Figure 12 - Point-by-Point calculations of CCT and CRI

Scenario 4 (VDG in Tint State 4)

For this scenario, the south-facing window was set to tint state 4 (Figure 13), with an average illuminance from daylight at approximately 5 fc, since its primary purpose is to control glare by blocking 99% of the light (1% transmission). Given the target work-plane illuminance of 25 fc, the maximum mixing ratio was determined to be between 20%/80% and 10%/90%. Based on the mixing graph (Figure 14), it was determined that at maximum illuminance, a 4000K setting on the tunable white lighting would maximize CRI at approximately 88 based on the average assessment. The average color metrics are shown in Table 5.

While the daylight directly adjacent to the window is highly dominated by the tint state 4 illuminance, the interior space is dominated by the color properties of the electric lighting. Point-by-point calculations of CCT and CRI are shown in Figure 15.

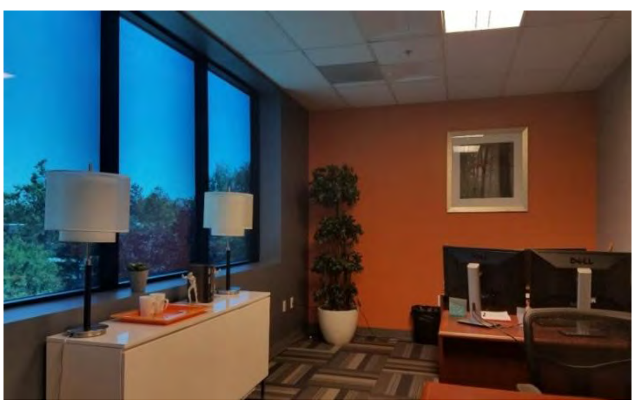


Figure 13 - Tint state 4 in the test room. Image is representative of the tint state only and do not correlate with the calculated value.

Table 5: Tint state 4 resultant average color metrics

Average Daylight Illuminance	5fc
Average LED Illuminance	20fc
Average Total Illuminance	25fc
Mixing ratio (daylight/LED)	20%/80%
Average CCT	4,912K
Average CRI	88
Average Fidelity	85
Average Gamut	98
Recommended LED Setting	4,000K at 83% Brightness

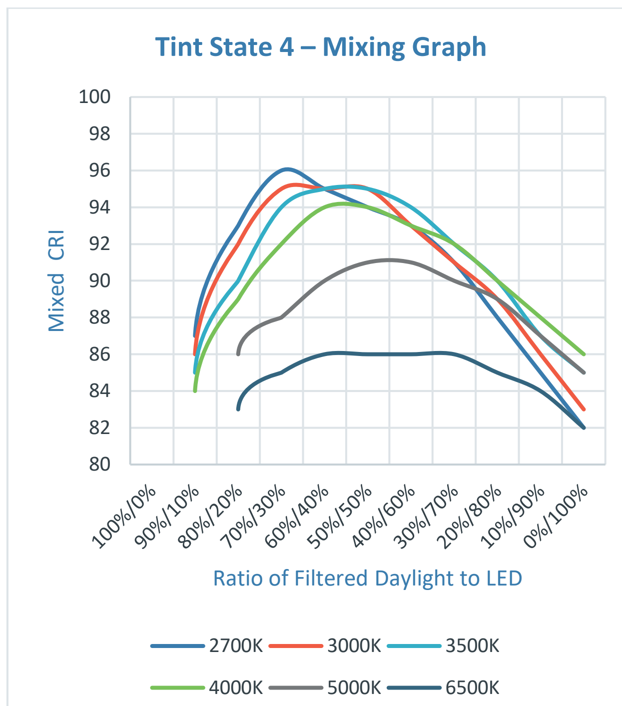


Figure 14 - Tint state 4 mixing graph

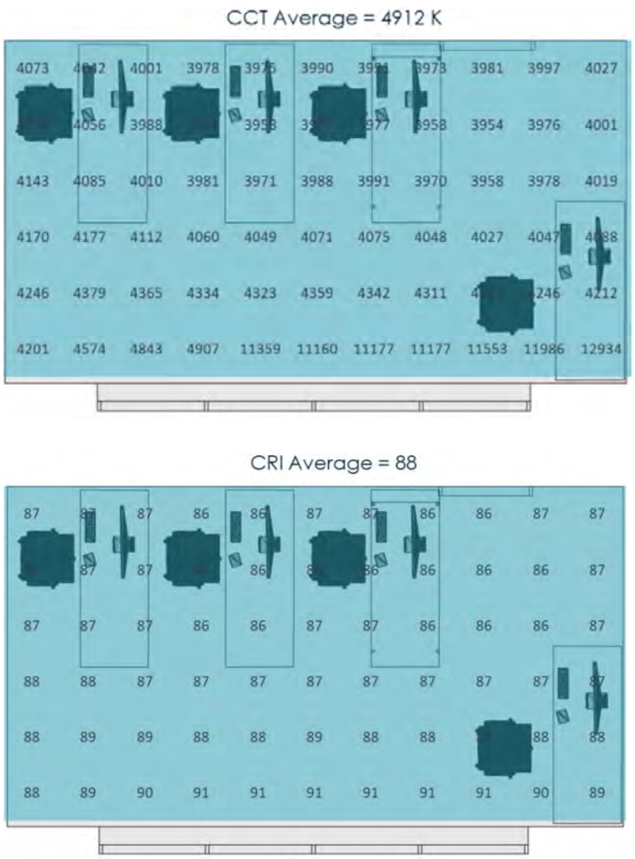


Figure 15 - Point-by-Point calculations of CCT and CRI

Conclusions

Based on this study, the space color quality of View Dynamic Glass can be maintained at good to excellent levels throughout the test room space with the appropriate mixing of electric lighting. Specifically,

1. In **tint states 1 and 2**, the light color quality is excellent – no supplemental electric lighting needed

2. In **tint state 3**, the space color quality is considered good and meets industry recommendations. Tunable white LEDs can improve color quality by lowering CCT and maintaining high CRI.

3. In **tint state 4**, View Dynamic Glass provides glare control. During this time, the space color quality is dominated by the electric light and can be enhanced by using tunable white LEDs with high color-rendering properties

The recommended LED settings for each scenario are shown in Table 6.

One of the most important findings is that the ability of a tunable white lighting system to enhance the color quality of the transmitted spectrum is dependent on the quality of the LED lights themselves. Choosing an LED light with a higher CRI will significantly improve the color metrics when the EC is in more tinted states.

Another important point is that while tunable white LED offers the best enhancement to color quality, dimmable LEDs can also be used to achieve very similar results. This simply involves picking a fixed CCT level from the results above, and then applies the dimming percentages. Based on the results of this study, a fixed CCT dimmable LED at 4000K will generate comparable results to one at 3000K (resulting in only an approximately 2% improvement in CRI). Given that dimmable LED fixtures are the default LED product on the market for construction-grade fixtures, this is a great option.

Finally, it should be noted that the results can vary for spaces with different setup and electric lighting fixtures. While this study proposes a methodology, customized analyses must be done for each individual space.

Table 6: Summary of color metrics and recommended tunable white LED settings

	Tint State 1	Tint State 2	Tint State 3	Tint State 4
Recommended LED Setting	No artificial lighting needed when light levels are sufficient	No artificial lighting needed when light levels are sufficient	3,000K at 87.5% Brightness*	4,000K at 83% Brightness
Average CCT	5,717K	5,828K	5,008K	4,912K
Average CRI	94	93	90	88
Average Fidelity	95	94	89	85
Average Gamut	97	96	96	98