How to Maintain Neutral Daylight Illumination with SageGlass® Electrochromic Glazing

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Executive Summary

This White Paper demonstrates how a neutral spectrum of daylight illumination can be maintained in a space fitted with SageGlass® electrochromic (EC) glazing by following a few simple guidelines for their design and operation. The paper gives a brief, non-specialist overview of the relevant colour science needed to understand illumination spectra, e.g. colour temperature, correlated colour temperature, colour rendering index, etc. Data on the visible transmission properties of SageGlass EC glazing are presented. These data are used to show that, even when just a small proportion of EC is kept in the clear state (say, just 1 pane kept clear for each 8 at full-tint), approximately 90% of the daylight entering the space is that which enters through the clear pane – producing a neutral spectrum of illumination in the space. This effect optimizes daylight in a space and will help enhance the occupants' comfort and productivity.

In order to maintain a neutral spectrum of daylight illumination under normal operation it is recommended that the SageGlass EC glazing is zoned so that some of the glass is always kept in the clear state. Additionally, the design of the facade should encourage the redirection and 'mixing' of the light that enters through the clear panes of glass. A number of simple rule-of-thumb guidelines are suggested to help designers achieve effective mixing of the daylight in a space with zoned SageGlass EC glazing. Measurements of the daylight spectra in a space fitted with SageGlass are used to demonstrate the effectiveness of these strategies.

Contents

1 Light and Colour

This section introduces the various measures that are commonly used to characterise the prevailing colour or hue of a source of illumination.

1.1 Black body or incandescent sources

The first electric light bulbs were simply a thin wire or 'filament' in a protective glass enclosure, or bulb. When electrical current passes through the filament its temperature increases and it begins to glow, i.e. it becomes incandescent. At a temperature of about 800 K the filament glows red like the embers of a fire. At higher temperatures (from more electrical current) the intensity of the light increases and the perceived colour changes from red through orange (at ∼1,200 K), then yellow (at ∼2,800 K) to approaching white at a temperature ∼3,500 K. Most filament lamp bulbs have an operating temperature of about 2,800 K.

1.2 Lamp spectra and colour temperature

Incandescent sources emit a continuous spectrum of radiation which closely approximates that of a theoretical 'black body radiator' at the same temperature. Hence, the colour temperature – which effectively characterises the source spectrum – is approximately the same as the operating temperature of the hot filament, e.g. 3,200 K for a tungsten halogen lamp. Non-incandescent lamp types such as florescent or light emitting diodes (LEDs) do not emit a smooth, continuous spectrum of radiation. Their spectra typically contain sharp peaks of emission at a number of particular wavelengths or colours. These lamps are designed so that their emission spectra *appear* to produce white light. Additionally, the light may exhibit a particular hue: 'warm' (yellowish), 'neutral' (no perceived hue) or 'cool' (blueish). Although not incandescent emitters of continuous radiation, the light from the non-incandescent lamps can be characterised by a correlated colour temperature (CCT). The CCT is the temperature of a radiator whose *perceived* colour most closely resembles that of the (non-incandescent) source. For example, a LED can be manufactured to have a CCT the same as that of a tungsten halogen lamp. The spectra from the tungsten halogen and LED lamps will however be quite different, and the colour of objects when illuminated by the two sources in a side-by-side comparison may not appear to be the same. Thus, the CCT when applied to non-incandescent sources should be taken as a guide to the overall character of the perceived light ('warm', 'cool', etc.). Unlike incandescent sources, the spectra of the light from these lamps cannot be determined or estimated from their CCT.

1.3 Daylight spectra and colour temperature

Daylight is light from the sun and the sky. The source of all daylight is the sun. Scattering of sunlight in the atmosphere by air, water vapour, dust, and so on gives the sky the appearance of a self-luminous source of light. Light emitted by the sun closely approximates a black body radiator with a temperature of 5,800 K, i.e. very similar to an incandescent source with the same temperature. Light of all colours is scattered by the atmosphere, but because blue light is scattered slightly more than red light, the clear sky appears blue. When we view the sun directly, this scattering of light (i.e. its removal from the direct beam) we refer to as absorption. And so the sun appears red when at the horizon because the preferential scattering (or 'removal') of blue light from white light leaves red light. A blue sky and a red sunset are therefore produced by the same physical process: the preferential scattering of blue light perceived from different points of view.

These effects combine with meteorological conditions to produce a wide variety of daylight 'phases' based on the time of day, the degree of clearness of the sky, the type of clouds, etc., Figure 1.

Figure 1: Phases of daylight and their 'colours'

The absorption of the direct beam of sunlight by the atmosphere changes the colour (i.e. temperature) of the light, reducing the apparent temperature of the light depending on how much air the light beam has passed through. The colour temperature of direct midsummer sunlight is almost the same as that of the extraterrestrial sunlight, i.e. ∼5,800 K. For average summer sun – when the sun is a little lower in the sky – the colour temperature of the sunlight is about 5,400 K. When the sun is at the horizon the sunlight passes through about twenty-five times more air than when the sun is at an altitude of around 40°. Thus the magnitude of the scattering is much greater, and so the apparent colour temperature of horizon sunlight reduces to that of glowing embers, i.e. less than 1,000 K.

Blue skylight has a higher colour temperature than sunlight – covering a wide range from 9,500 K up to 30,000 K. Although skylight has a continuous spectrum, the light results from a scattering process (acting on lower colour temperature sunlight radiation) and so the shape of the spectrum is only partially similar to that of a black body at the same temperature. An actual black body radiator at a temperature of, say, 30,000 K would emit most strongly at a wavelength of 100 nm, which is in the extreme ultraviolet range – very different from blue skylight.[1] Thus, for light that does not originate directly from incandescence, one should refer to a correlated colour temperature (CCT) rather than colour temperature.

Average summer sunlight (CCT ∼5,400 K) plus blue skylight (CCT ≥9,500) will combine to give light that has a CCT around 6,500 K. This is taken to be the standard reference daylight illuminant, also referred to as $D65$. The CCT of 6,500 K is closer to the CCT for average sunlight (5,400 K) than the ≥9,500 K for blue skylight because, in most situations, illumination from the sun (direct and reflected) will dominate that from the sky. When conditions are cloudy, the sunlight is entirely scattered and none emerges through the atmosphere as direct beam. Under these conditions the CCT is also typically around 6,000 – 6,500 K, i.e. that of the standard reference daylight illuminant. The various "phases" of daylight characterised by their correlated colour temperature are given in Table 1.

1.4 Colour rendering

Colour rendering is defined as the "effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a

[1] Intensely hot stars with a surface temperature of 30,000 K will produce radiation with this spectrum.

Daylight source	CCT
Sunlight – sunrise or sunset	2,000 K
Sunlight – one Hour After Sunrise	3,500 K
Sunlight – early Morning	4,300 K
Sunlight – late Afternoon	4,300 K
Average summer sunlight at noon (Washington, DC)	5,400 K
Direct midsummer sunlight	5,800 K
Overcast sky	6,000 K
Average summer sunlight (plus blue skylight)	6,500 K
Light summer shade	7,100 K
Average summer shade	8,000 K
Summer skylight	9,500 to 30,000 K

Table 1: Correlated colour temperatures for various daylight sources – Kodak [1].

reference illuminant" [2]. Under normal viewing conditions the perceived colour of an object depends both on the colour of the object and the spectrum of the light under which it is viewed. A photograph taken under illumination from an incandescent source with a colour temperature of 2,800 K will generally appear 'yellowish'. More yellow in fact than the scene appeared at the time the photograph was taken because of a process called chromatic adaptation whereby the the human visual system 'corrects' for shifts in colour appearance caused by illumination or light sources that are not 'neutral', i.e. not typical, white daylight. Although the human visual system has this ability to 'correct' for colour appearance to some degree, tasks involving the critical discrimination of colour will be impaired under illumination that deviates markedly from the reference illuminant which is 'white' daylight with a CCT of 6,500 K.

1.5 Colour rendering index

The colour rendering index (CRI) is intended to be a quantitative measure of the ability of a light source to reproduce the colours of various objects faithfully in comparison with an ideal or natural light source. CRI was formulated at a time when the two most common artificial light sources were incandescent and florescent, and it was the incandescent that was taken as the 'reference' source with a possible maximum CRI rating of 100 – even though colours illuminated by incandescent sources will appear 'yellowish' compared to standard daylight. This is illustrated by the three measured spectra shown in Figure 2. The tungsten halogen and daylight sources both have (measured) CRIs of 98 even though the spectrum of light from the artificial source is very different from natural light. The daylight spectrum was measured in an office with ordinary clear glazing under bright, overcast sky conditions. Note also that CRI has no direct relation to CCT. A lamp with poor colour rendering, say a CRI of 75, could be perceived as providing illumination that is either too 'warm' or too 'cold' depending on the type of lamp – it is impossible to tell which from the CRI alone. In addition to the acknowledged longstanding limitations of CRI, more recently it has been proposed that CRI is not an effective measure to determine colour rendering for LED lamps and that a new formulation is required [3]. CRI therefore should be taken as *indicative* of colour rendering performance rather than an absolute measure of it. CCT and CRI taken together will be a more reliable indicator of colour rendering performance than CRI on its own.

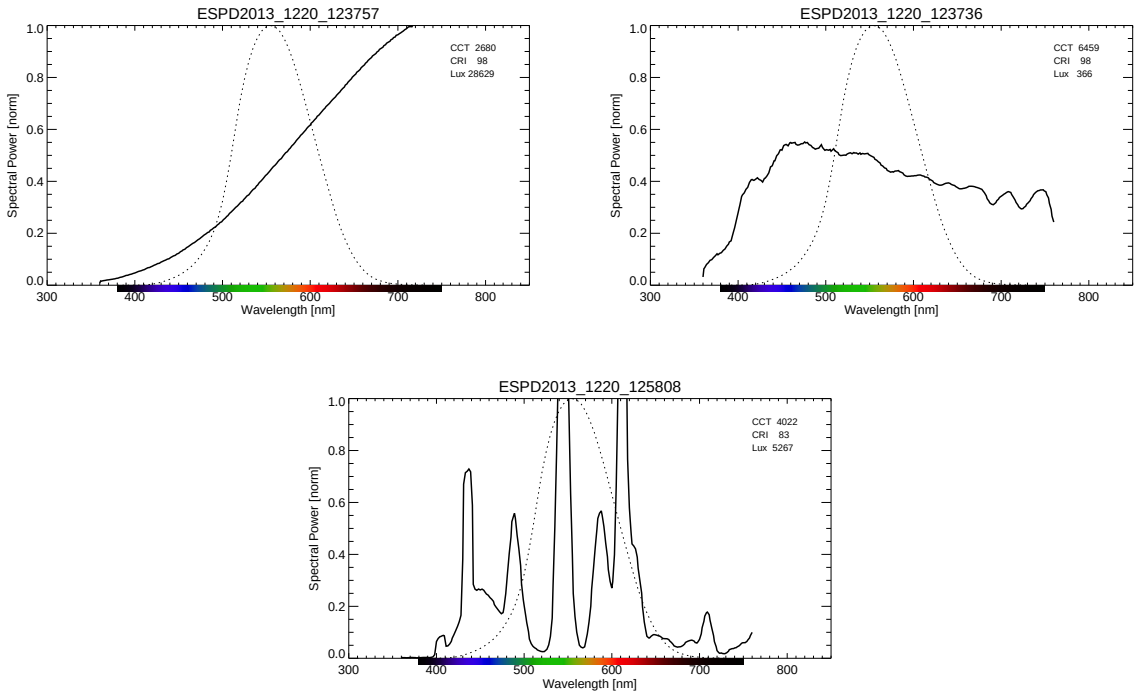

Figure 2: Spectra for tungsten halogen, daylight and florescent light sources

2 Electrochromic Glazing

The use of daylight in office buildings is generally considered to be a greatly under-exploited resource. In large part this is because of the highly variable nature of daylight illumination. The natural, large variability in daylight means that users will often need to use shades to moderate the excessive ingress of daylight. Most shading systems act as a "shutter" that is either open or closed, with users rarely making the effort to optimise the shading for both daylight provision and solar/glare control. And blinds are often left closed long after the external condition has changed. A glazing with a transmissivity that varies continuously between clear and dark extremes offers a much greater degree of control over the luminous environment.

2.1 SageGlass EC glazing

SageGlass produced by SAGE Electrochromics Inc. is an electronically tintable glass for windows, skylights and curtain walls. The transmission properties of the glazing are controlled by a small applied voltage and the control can be based on any measured environmental parameter – often illuminance, temperature, or some combination of the two. The current SAGE product varies in visible transmission between 60% in the clear state to 1% when fully tinted. As the glass darkens (i.e. 'tints') the longer wavelengths are diminished proportionally to a greater degree than the shorter wavelengths, giving the EC glazing good solar control properties to help prevent overheating. Optically, the consequence of this is to shift the peak in visible transmission to the blue end of the spectrum. This can be seen in the transmission curves shown in Figure 3.

In the clear state the glazing has a visible transmittance of 60% and appears effectively neutral to the eye. This example of SageGlass has a minimum visible transmission of

1% when fully tinted and can be varied continuously between this and the clear state. However a small number of intermediate states is considered adequate for most practical installations, e.g. 'light-tint' (18%) and 'mid-tint' (6%).

The peak in the spectral transmission curves gradually shifts from 565 nm in the clear state to 460 nm at full-tint. Thus the view through the glazing takes on a progressively deeper blue hue as it transitions from clear to full-tint (Figure 4). And of course, the daylight transmitted through the window will be 'filtered' according to the spectral properties of the glazing and the nature of the illumination incident on the glazing.

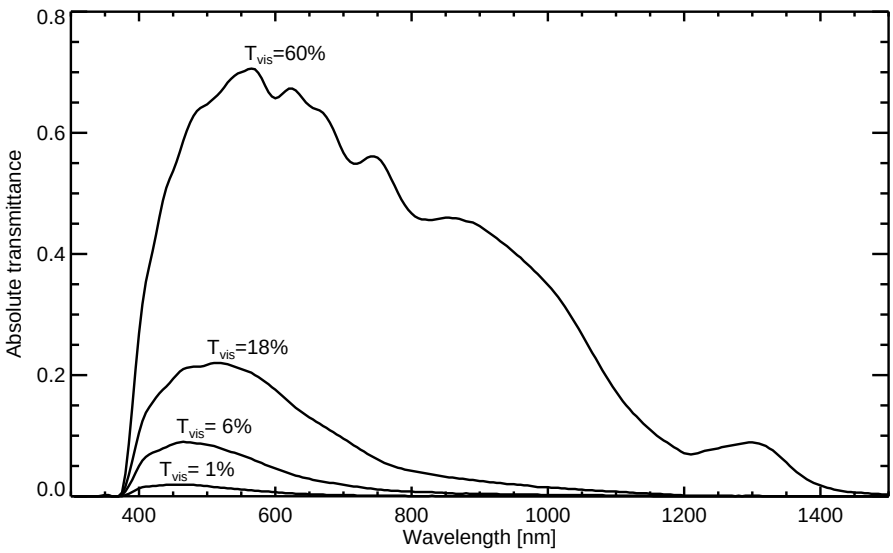

Figure 3: Absolute spectral transmission curves for SageGlass in clear (60%), fully tinted (1%) and two intermediate states. Note, the curves are for monolithic coated EC glass whilst the labels refer to the visible transmittance when used in conjunction with clear glass in an insulating glazed unit.

Figure 4: Images showing SageGlass electrochromic glazing in clear and tinted states

Note the EC glazing shown in Figure 4 and that installed in the space used for the validation study (Section 4) are a previous generation where the range in visible transmission was 62% in the clear state and 2% when fully tinted.

2.2 Occupant preferences

The occupants of buildings are known to prefer daylight with a neutral spectrum over any other form of illumination. Fixed tint glass has been shown to have lower approval rating than clear glass, particularly on overcast days when the tint will make a dull sky appear even duller, thereby exacerbating any sense of drabness regarding the illumination. Additionally, tints with a hue may be in discord with user expectations with regard to actual weather conditions. For example, on an overcast day we would not expect sky seen through the windows to appear blue. With SageGlass electrochromic glazing under normal operation it is possible to avoid the all the undesirable effects associated with fixed-tint glass. This is achieved through optimum control and zoning of the glass: (a) having the glass transition to full tint only when required; and, (b) ensuring that a proportion of the glass remains in the clear state.

2.3 The spectrum of natural light indoors

The spectrum, or perceived hue, of natural illumination inside a space depends on three key factors:

i. the spectrum of daylight incident on the external surface of the glass;

ii. the spectral transmission curve of the glass; and,

iii. the colours of the interior surfaces, e.g. walls, floor, ceiling, etc.

The incident spectrum of illumination will depend on the phase of daylight, e.g. sunny conditions. The spectral transmission properties of the glass are described by curves such as those shown in Figure 3. For any arbitrary combination of clear and tinted EC panes, it is possible to derive a single transmission curve which characterises the transmission properties of the ensemble of panes. This assumes that all the light from the panes in the various states of tint are effectively 'mixed' following reflections within the space. For most interior spaces, particularly offices and other non-residential settings, the surface finishes typically have a fairly neutral hue. It is rare to have walls with highly saturated colours, rarer still for ceilings. Thus, for most practical applications it is possible to ignore this third factor when evaluating the spectrum of daylight inside building spaces. This has been confirmed by measurements in an office space with EC glazing (see Section 4).

The transformations of the spectra of natural light from outside to inside of the building are illustrated in Figure 5. The illumination incident on the windows has a particular spectral power distribution (SPD) depending on the phase of daylight under consideration. The SPD of light entering the space is the SPD of the incident daylight multiplied by the spectral transmission curve for the glazing. The SPD of light at any point in the space will be some combination of illumination received directly from the windows (if they can be 'seen' from that point) and light arriving at that point following multiple reflections within the space. As noted above, with typical decor the change in SPD due to reflections in the space is not significant and can usually be ignored. Thus, the SPD of illumination anywhere in the space will be approximately equal to the SPD of the light entering the space through the glazing.

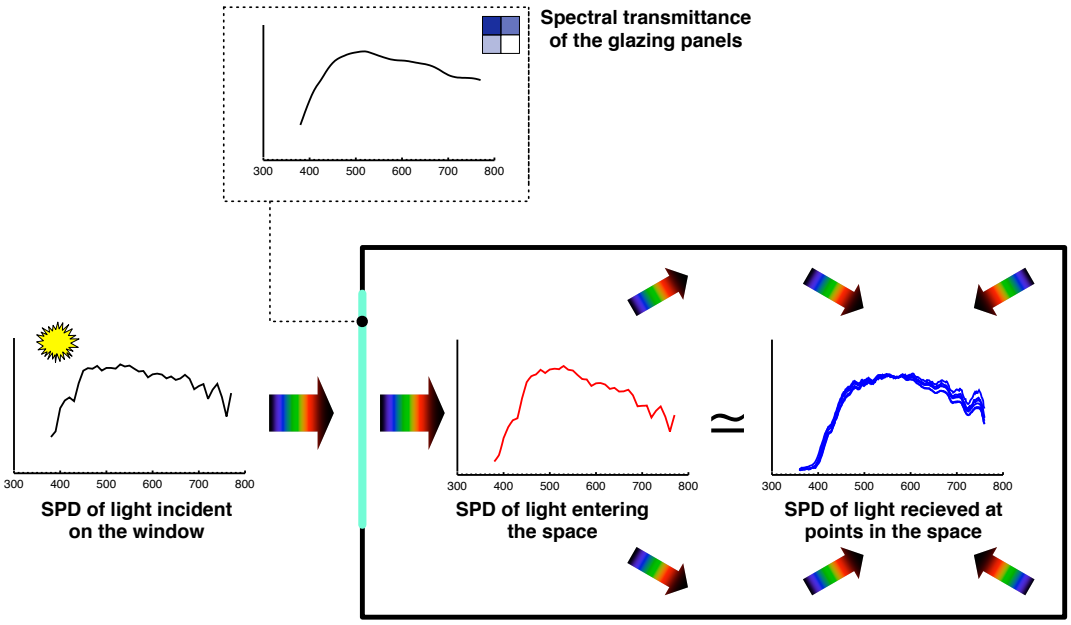

Figure 5: The spectrum of natural illumination inside a space is essentially the product of the incident light spectrum and the spectral transmission curve of the glazing.

3 Zoning and the 'Mixing' of Light

Zoning is the term used to describe the operation of electrochromic glazing when different tint settings are used on different panes or groups of panes at any one instant in a room or space. This is often desirable for a number of reasons:

(a) to ensure that glare control can be achieved (needing $\leq$2% T_{vis});

(b) to provide sufficient daylight illumination in the space;

(c) to ensure that the spectrum of illumination in the space remains neutral; and,

(d) to maximise the opportunity to save energy through photoelectric dimming of lights and/or reduction in cooling loads.

Consider the following example for EC glazing in horizontal rows. A window extending from the sill to the ceiling could be comprised of three glass panes (in three frames) or a single pane in one frame which has been 'zoned' to create three sections that tint independently – referred to as 'between pane' and 'in-pane' zoning respectively. In either case, it is possible to control the zones independently. A common zoning arrangement that works effectively for much of the year when skies are clear is shown in Figure 6. In this example, zones 2 and 3 are set to full-tint to moderate the ingress of high angle sun, whilst for zone 1 the glazing is set to be fully clear.

In addition to allowing for an (un-tinted) view to the outside, a zone pane set to fully clear (T_{vis} = 60%) will allow in about sixty times more daylight than a zone pane of the same size set to full tint where T_{vis} = 1%. This huge difference in absolute visible transmittance between clear and fully tinted means that, with just a relatively small proportion of the EC glazing set to clear (the rest at full tint), the daylight illumination in the space is dominated by the neutral light entering through the clear glazing. For

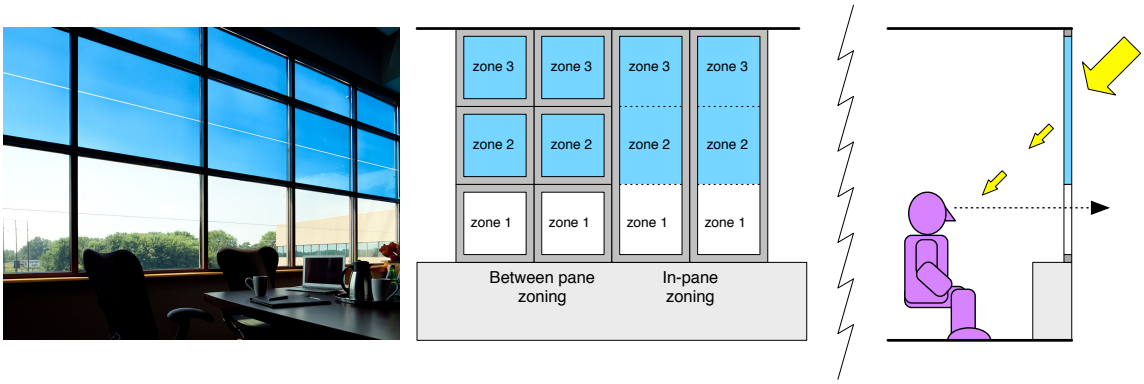

Figure 6: Zoning of electrochromic glazing by individual panes or within-pane zoning

example, consider the case where there is just one pane set to clear ($T_{vis} = 60\%$) for every eight set to full-tint ($T_{vis} = 1\%$). In this state, the clear glass occupies only 1/9 of the glazed area, but it accounts for $\sim 9/10$ of the overall visible transmittance of all nine panes of glass, Figure 7. Additionally, the overall visible transmittance for all nine panes is just 8%. This explains why the illumination in a space with EC glazing controlled in this manner generally appears neutral – as is evident in Figure 4 where less than one third of the glass is clear (the remainder at full-tint).

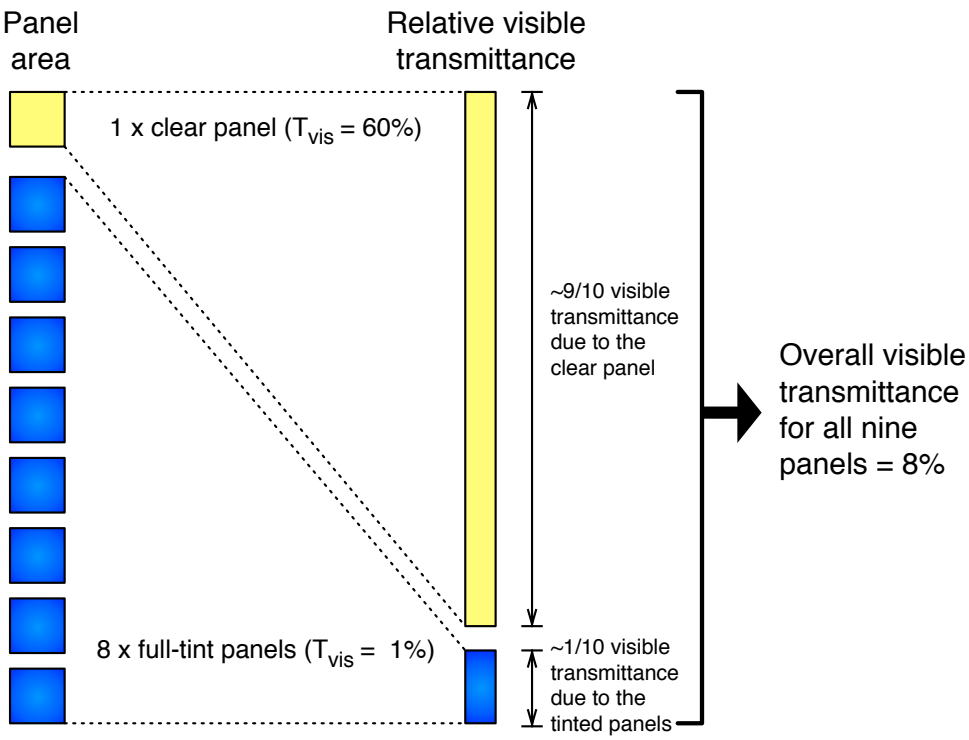

Figure 7: Combination of one EC pane set to clear and eight set to full-tint. The bulk of the visible transmittance is that due to clear glass, resulting in neutral daylight dominating the illumination of the space.

The majority of office and similar spaces have fairly bright, neutral decor. In large part this is to encourage the penetration of daylight deep into the core of the space by

the reflection from 'bright' surfaces, e.g. walls and ceilings typically have reflectivities of 60% and 80% respectively. Another consequence of the multiple reflections occurring in the space is that daylight arriving at any point is often well-mixed, i.e. it is a 'blend' of all the daylight entering the space from all of the glazing. This helps to ensure that the dominant neutral daylight from the clear glass is well mixed with the daylight that is filtered through the tinted glass, resulting in a neutral daylight spectrum throughout the space.

4 Measured Daylight Spectra

Two offices at De Montfort University (Leicester, UK) were fitted with SageGlass EC glazing in late 2012. As noted, the EC glazing was a previous generation SageGlass product where the range in visible transmission was 62% in the clear state with a minimum of 2% when fully tinted. The findings shown below however are equally applicable to the current product. The lighting in the offices was upgraded at the same time, but otherwise the offices and the occupants were as before. The user acceptance of the installation is being evaluated as part of a long-term case study [4].

Photographs of one of the offices (Room 0.30) and the external facade are given in Figure 8. The two offices (Rooms 0.30 and 0.29) comprise three large window bays, each with six panes. However, the dividing wall between the two offices bisects the central bay. Additionally, the false ceiling in the offices meets the facade wall at the shared window and the window exclusive to 0.29. Thus the upper panes for these two bays are either for ventilation or are 'false' windows, i.e. they do not provide any illumination to the offices. For the remaining bay in 0.30, the false ceiling is stepped back from the window, and all six panes can illuminate the space – though the false ceiling does offer some shading depending on the sun angle. Thus, there are eight EC panes in room 0.30 and six in room 0.29 – they were all set to full-tint when the external photograph was taken (Figure 8). The installation was a retrofit of previously remodelled spaces in what was originally a Victorian-era factory building.

Figure 8: Photograph of Room 0.30 and the external facade.

The zoning arrangement used to control the glazing in room 0.30 is shown in Figure 9 (zones 1–4 were assigned to the the four zones in Room 0.29). In the full-height six pane window, each row-pair of panes constitutes a zone – thus there are five zones in total. Alongside the zoning graphic is a sketch showing the approximate positions of the four occupants and their typical view directions (A–D) whilst working. View E is a general view from the back of the room looking towards the glazing, and F is the view from the

window wall towards the back of the room. Illumination spectra were measured at each of these six view points/directions for every combination of glazing state described below. To avoid contamination of the spectra, all electric lighting and computer monitors were switched off.

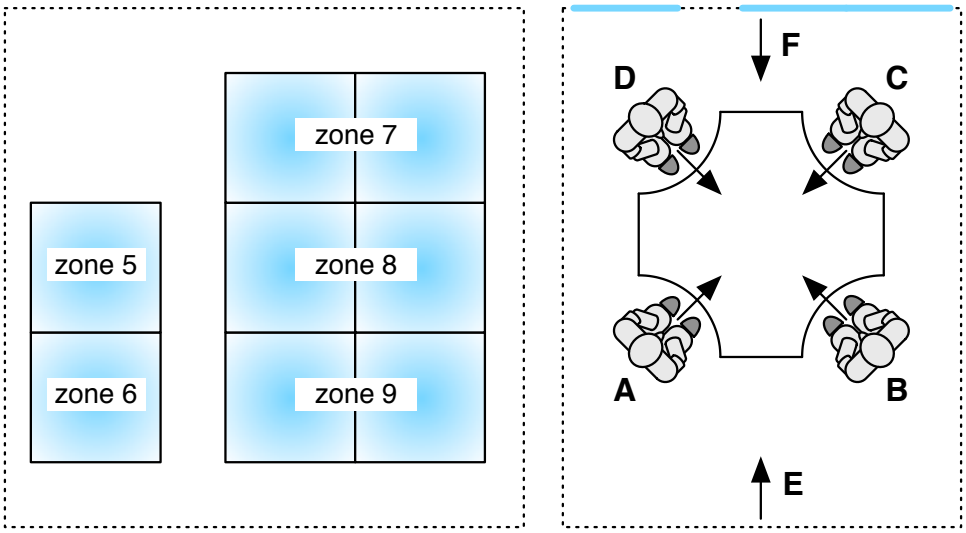

Figure 9: Zoning of the EC glass in Office 0.30 and a schematic (not to scale) of the office layout showing the occupant workstation positions and the six view directions (A–F) at which spectra were measured.

Spectra at the six points A to F were measured using a calibrated handheld spectrometer which covers the range 360 to 760 nm. The spectrometer sensor was 'pointing' in the direction of view of the eye position in each case, i.e. seated for A–D and directed at the task (the computer display which was switched off), standing with a horizontal view to the opposite wall for E and F. The measured spectra are for the light that would be received by the eye when located at the various measurement positions and view directions indicated in Figure 9. The spectrometer also records illuminance and various derived quantities including correlated colour temperature (CCT) and colour rendering index (CRI).

The measurements were taken under sunny, clear sky conditions on a weekend day in order to not disrupt the normal occupants. The conditions were very stable with an almost total absence of clouds. The measured spectra were normalised so that each would produce the same illuminance, allowing for a like-for-like comparison of the shapes of the spectral curves. In the example shown below, five panes were set to full-tint ($T_{vis} = 2\%$) and three were set to fully-clear ($T_{vis} = 62\%$). Normalised spectra measured at the six view points/directions A to F are the blue curves plotted in Figure 10. The visual sensitivity curve $V(\lambda)$ is shown in green (normalised to peak equals 1). Inset photographs show two views of the space at the time of measurement. Also plotted is a prediction (red curve) of the daylight spectrum inside the space determined from a theoretical model (see Appendix).

4.1 Key findings

The following observations are made:

(a) The six spectra measured at points A to E are very similar confirming the hypothesis that the daylight illumination in the space is well-mixed.

(b) The spectra reveal that the daylight illumination is essentially neutral, i.e. without any noticeable tint.

(c) This is further confirmed by the CCTs for the daylight illumination in the space – all very similar with a mean of 4970 K.

(d) The measurements reported by the spectrometer (mean CRI of 93) indicate good colour rendering.

(e) The measured spectra and CCT for the zoned EC case reveal the daylight illumination to be *less* 'blue' than the overcast sky daylight spectra through ordinary clear glass shown in Figure 2.

(f) The theoretical model showed very good agreement with the measurements. The mean of the Pearson correlation coefficient (r) between the theoretical illumination spectrum and each of the six measured spectra was 0.980, indicating an extremely good fit.

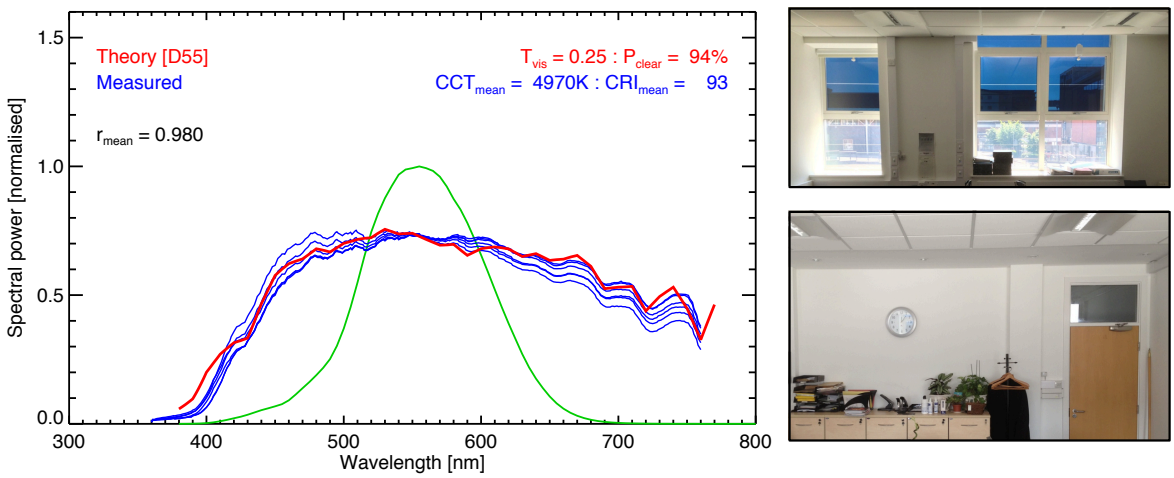

Figure 10: Measured illumination spectra (blue curves) for zoned EC space (five fully tinted and three fully clear panes). Photographs of the front and rear of the office taken at the time of measurement.

5 Rule-of-thumb Design Guidelines for SageGlass EC Glazing

When planning a new-build or retrofit installation with SageGlass, observing a few simple guidelines for the design and operation of the EC glazing will benefit the space. The two key 'take home' messages are:

(1) Design a zoning arrangement and control strategy such that some of the glazing is always in kept in the clear state; and,

(2) The facade design/detailing and the interior decor should encourage the diffuse reflection of direct sun entering the space through glazing in the clear state.

Keeping some of the glazing in the clear state is required to maintain a neutral spectrum of illumination in the space. However, it is also necessary to ensure that daylight through glass in the clear state is well-mixed with the filtered light through the tinted glass.

It will generally be the case that maximum control will only be required when direct sun enters the space.

5.1 Perimeter EC glazing

Designers often specify floor-to-ceiling glazing, particularly for office buildings. Depending on the prevailing climate and the aspect of the facade, floor-to-ceiling glazing can produce a high occurrence of visual and/or thermal discomfort, causing the occupants to deploy shades, blinds, etc. And, in cooling dominated locales, greatly adding to the energy expended in preventing overheating. Effective zoning of SageGlass EC glazing can help to achieve a balance between solar protection to minimise heat gain and the requirement for a neutral spectrum of illumination. Thus, the zoned area intended to be left clear should be small enough to adequately control heat gains, but still be sufficient to dominate the internal daylight conditions and so provide a neutral spectrum.

The following illustrations are for how effective mixing can be achieved for a space with perimeter EC glazing when the sun angles and both high and low. For high-angle sun the reflection/redirection of direct sunlight from a white sill is one way to encourage the mixing of neutral and filtered illumination – the upper panes would be fully tinted whilst the row above the sill would be clear (e.g. Figure 6). Another approach could be a perimeter of lightish floor covering to achieve the same effect. However, when the sun angle is low it may be necessary to set the lower panes to full tint. In which case, keeping a few of the panes near a wall in the clear state can allow some direct sun to reflect off the wall and so mix with the filtered light in the space (e.g. Figure 8).

5.2 Rooflights

For rooflight installations the design and/or zoning strategy should be tailored to achieve the same effect. For most typical rooflight configurations, keeping the upper parts of the EC glass clear will help to facilitate the mixing of light by redirection and also protect the occupants from direct sun. For thin roof sections, the areas on the opposing roof slope where (transmitted) direct sun is likely to strike should be given a bright, diffusing finish to encourage the reflection/distribution of sunlight in the space below. For panes set in a thick roof, the glazing could be zoned so that the upper part of the rooflight remains clear. Thus direct sun has the opportunity to strike the deep 'reveal' and so be redirected into the space where it can mix with the filtered light, Figure 11.

5.3 Light-wells

With light-well and similar structures an effective design may not require a particular zoning pattern of clear and fully tinted panes provided that the light-well is sufficiently deep. With such designs the direct and filtered light will undergo multiple reflections within the light-well and emerge into the space already well-mixed. In fact, for arrangements where there is no direct view of the tinted panes, the occupants may not realise that any panes are in the tinted state. Such arrangements could be particularly effective for art galleries and other spaces requiring critical viewing under neutral daylight illumination and, at the same time, effective control of absolute levels of illumination to comply with long-term exposure recommendations for paintings, fabrics, etc.

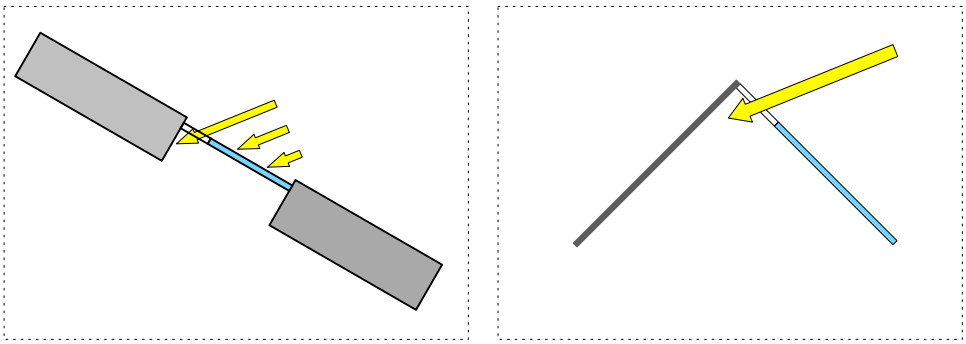

Figure 11: Zoning for rooflights

6 Summary

The procedures described above can be used to predict the daylight illumination spectrum in spaces with any combination of clear and tinted SageGlass EC glazing. The spectrum for the zoned arrangement described in Section 4 was predicted using the method described above. The prediction showed very good agreement with the measured spectra for that case (Figure 10). The method was tested in the same space for five other unique zoning configurations with very similar good agreement in each case [5].

Prospective users of SageGlass EC glazing are encouraged to follow the 'rule-of-thumb' design guidelines outlined in Section 5 to help ensure that a neutral spectrum of daylight illumination is maintained in the space under normal operation of the EC glazing. SAGE Electrochromics can offer advice on predicting the daylight spectra in spaces for specialist applications, e.g. museums, art galleries, etc.

References

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Appendix

A Predictive Model of the Daylight Illumination Spectrum

A predictive model for the daylight illumination spectrum in spaces with arbitrary combinations of tinted and/or clear glass was formulated by the author (Mardaljevic) and validated using measurements in a space fitted with SageGlass EC glazing. The predictive model is founded on the following principles/hypotheses:

(a) The individual spectral transmittance curves of any arbitrary combination of SageGlass EC glazing can be 'merged' to give a single spectral transmittance curve which characterises the ensemble.

(b) The spectrum of illumination in a space is the product of the spectral power distribution of the daylight incident on the glazing and the 'merged' spectral transmission curve for the glazing ensemble.

(c) For spaces that are not too large and that have 'typical' neutral decor, the daylight illumination spectrum will be fairly constant across the space.

As noted in Section 4, the predictive model showed excellent agreement with the measurements, confirming the validity of the principles/hypotheses noted above [6].

A.1 SageGlass combination clear-tinted spectral transmission curves

The procedure to derive the overall transmittance curve for an arbitrary combination of EC panes in various states is as follows [5]. The row vector $\mathbf{V}$ of the visible transmittance of the glazing in four possible states of tint a, b, c and d is:

$$\mathbf{V} = \begin{bmatrix} V_a & V_b & V_c & V_d \end{bmatrix}$$

In the commonly used states for the current SageGlass product this vector would equal $\begin{bmatrix} 0.60 & 0.18 & 0.06 & 0.01 \end{bmatrix}$, i.e. 60% visible transmittance in the clear state, 1% when fully tinted, and the two intermediate states of 18% and 6%. Next, the row vector $\mathbf{R}$ gives the ratio or number of equal-sized panes in each of the states of tint:

$$\mathbf{R} = \begin{bmatrix} N_a & N_b & N_c & N_d \end{bmatrix}$$

For example, if one pane was in the clear state, two at light-tint, three at mid-tint and four at full-tint, the vector would equal $\begin{bmatrix} 1 & 2 & 3 & 4 \end{bmatrix}$.

The effective visible transmittance of the combination V_R is determined from the following equation:

$$V_R = \frac{\begin{bmatrix} V_a & V_b & V_c & V_d \end{bmatrix} \cdot \begin{bmatrix} N_a & N_b & N_c & N_d \end{bmatrix}^\top}{(N_a + N_b + N_c + N_d)} \tag{1}$$

where $^\top$ denotes the transpose from row to column vector. The same more compactly is:

$$V_R = \frac{\mathbf{V} \cdot \mathbf{R}^\top}{\sum \mathbf{R}} \tag{2}$$

Of particular interest for this illustration is the fraction of the total transmittance that is from glass in the clear state (i.e. where $V_a = 0.60$) since this will be a key determinant

in achieving neutral daylight illumination inside the space. The fraction P_a is determined as follows:

$$P_a = \frac{V_a R_a}{\sum_{i=1}^{4} V_i R_i} \tag{3}$$

The overall spectral transmittance curve for any arbitrary combination of (equal-sized) EC panes is determined using similar matrix operations. For example, the vector $\mathbf{T_a}$ of spectral transmittance data for EC glass in state a is given by:

$$\mathbf{T_a} = \begin{bmatrix} t_{a_1} & t_{a_2} & \cdots & t_{a_m} \end{bmatrix} \tag{4}$$

where, for the IGDB data used here, t_{a_1} is the transmittance at the short wavelength limit (e.g. 300 nm) and t_{a_m} the transmittance at the long wavelength limit (e.g. 1,500 nm). The four individual row vectors comprising the four spectral transmittance curves shown in Figure 3 are concatenated to form a matrix:

$$\begin{bmatrix} t_{a_1} & t_{a_2} & \cdots & t_{a_m} \\ t_{b_1} & t_{b_2} & \cdots & t_{b_m} \\ t_{c_1} & t_{c_2} & \cdots & t_{c_m} \\ t_{d_1} & t_{d_2} & \cdots & t_{d_m} \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} \mathbf{T}_a \\ \mathbf{T}_b \\ \mathbf{T}_c \\ \mathbf{T}_d \end{bmatrix} \tag{5}$$

The vector $\mathbf{T_R}$ containing the spectral transmittance curve data for an arbitrary combination $\mathbf{R}$ of EC panes in various states is given by:

$$\mathbf{T_R} = \begin{bmatrix} N_a & N_b & N_c & N_d \end{bmatrix} \cdot \begin{bmatrix} t_{a_1} & t_{a_2} & \cdots & t_{a_m} \\ t_{b_1} & t_{b_2} & \cdots & t_{b_m} \\ t_{c_1} & t_{c_2} & \cdots & t_{c_m} \\ t_{d_1} & t_{d_2} & \cdots & t_{d_m} \end{bmatrix} / \left(N_a + N_b + N_c + N_d\right) \tag{6}$$

Or, more compactly:

$$\mathbf{T_R} = \frac{\mathbf{R} \cdot \begin{bmatrix} \mathbf{T}_a & \mathbf{T}_b & \mathbf{T}_c & \mathbf{T}_d \end{bmatrix}^\top}{\sum \mathbf{R}} \tag{7}$$

This equation is used to derive the combined spectral transmittance curve for arbitrary combinations of (equal-sized) EC panes in various states. For panes of dissimilar sizes, an additional (vector) term needs to be incorporated into the above equations to weight the individual contributions to the combination curve accordingly.

A.2 Example combined transmission curves for clear and tinted panes

With even a small number of independently controlled EC panes there are many unique combinations of tint state possible. Initial tests showed that to achieve high levels of overall daylight control, whilst maintaing at the same time the potential for neutral daylight illumination, a combination of clear and fully tinted panes is particularly effective. For example, a two pane combination with one set to fully clear (60%) and one to full-tint (1%) has an equivalent visible transmittance of 30.5%, i.e. $(60 + 1)/2$. However, approximately 97% of that equivalent visible transmittance is due to the pane in the clear state, because of course the clear state pane has 60× the visible transmittance of the glass at full-tint.

To illustrate this we compare the overall spectral transmittance curve for one clear pane with up to eight panes at full-tint (with none set to either of the intermediate states), e.g:

$$\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & N_{01} \end{bmatrix} \text{ where } N_{01} = 1, 2, 3, 4, 5, 6, 7 \text{ or } 8 \tag{8}$$

For each of the eight values of N_{01} in $\mathbf{R}$, the transmission model described above was used to determine the spectral transmittance curve $\mathbf{T_R}$ of the combination.

Any comparison of spectral transmittance curves will depend to a degree on how the data are normalised. The combination spectral curves (Figure 12) are shown in two ways: (i) each normalised to peak value equals 1; and, (ii) relative to the transmittance curve for EC glass in the clear state (i.e. peak value for clear equals 1). Additionally, the plot shows the transmittance curves for EC glass in the clear state (dashed line) and at full-tint (dotted line), Figure 12. For reference, the plot also includes the visual sensitivity curve $V(\lambda)$ (also normalised to peak equals 1).

The curve for $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix}$ (i.e. 1 clear pane and 1 at full-tint) is shown in olive. With gradually increasing values for N_d, the colour used for the curve transitions from olive through red to blue, i.e. for $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 8 \end{bmatrix}$. Although containing many curves, the plot is quite easy to interpret when viewed in colour since the progression with increasing number of full-tint panes is quite pronounced and orderly. Firstly, for the case with 1 clear and 1 full-tint pane, the combined spectral transmittance curve (olive) is almost identical to that for the glass in the clear sate (dashed line). Relative to the clear state, there is a very slight suppression of wavelengths longer than 550 nm (i.e. the 'red' end of the visible spectrum), and a slight enhancement of wavelengths shorter than 550 nm (i.e. the 'blue' end). With each additional full-tint pane this trend persists. Even with 8 full-tint panes for each 1 clear, the combined spectral transmittance curve is very close to that for the clear pane alone.

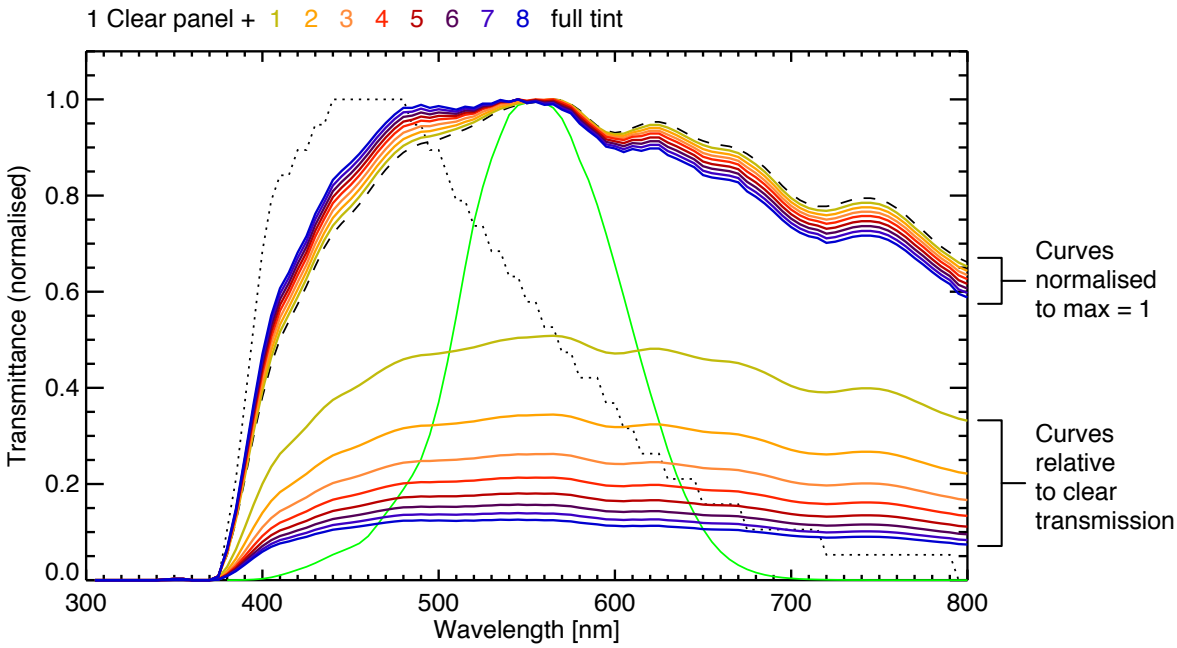

Figure 12: Eight spectral transmittance curves for SageGlass EC glazing in the combinations given in Equation (8).

A.3 The illumination spectrum

In addition to the transmittance spectrum of the glazing, the illumination spectrum – that is, the daylight that passes through the glazing to illuminate the space – will depend

also on the spectrum of light that is incident on the glass. The illumination spectrum is the product of the transmittance spectrum $\mathbf{T_R}$ and the spectral power distribution for the daylight incident on the glass $\mathbf{D_K}$.

For any particular combination of clear and tinted SageGlass, the spectral transmittance curve is derived using the method outlined above. For an arrangement where there is one clear pane for each eight fully tinted, the combined spectral transmittance curve for all nine panes $\mathbf{T_R}$ would the the respective curve in Figure 12 converted to absolute units. In normal operation, the EC glazing would be set to full tint when direct sun is incident on the facade. In which case, sunlight will be the dominant source of illumination on the facade and the SDP for incident daylight can approximated to D_{55} which is the CIE standard illuminant for sunlight. Thus, the illumination spectrum for daylight entering the space would be:

$$\mathbf{I_{space}} = \mathbf{T_R} \circ \mathbf{D_{55}} \tag{9}$$

where $\circ$ is the symbol for the element-by-element or Hadamard product.

The daylight spectrum predicted using the methods described above was shown to have excellent agreement with measured spectra for a variety of combinations of clear and tinted SageGlass EC glazing [5][6].

About the author

John Mardaljevic PhD FSLL is Professor of Building Daylight Modelling at the School of Civil & Building Engineering, Loughborough University. Mardaljevic pioneered what is now known as Climate-Based Daylight Modelling (CBDM). Founded on rigorous validation work, CBDM is now the basis for research and, increasingly, industry practice worldwide. Mardaljevic's practice-based research and consultancy includes major projects such as the New York Times Building and The Hermitage (St. Petersburg). He currently (2014) serves as the 'UK Principal Expert on Daylight' for the European Committee for Standardisation CEN / TC 169 WG11, and on a number of International Commission on Illumination (CIE) technical committees. In 2012 Mardaljevic was presented the annual UK lighting award by the Society for Light and Lighting (SLL). He is CIE-UK Representative for Division 3 (Interior Environment), and Chair of the CIBSE Daylight Group.

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