NEUTRAL DAYLIGHT ILLUMINATION WITH ELECTROCHROMIC GLAZING: SIMULATION OF 'LIGHT MIXING'

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Abstract

Electrochromic glazing generally exhibits a shift in spectral transmission as the glass darkens, e.g. causing it to appear blue as it tints. Occupants however are believed to prefer a neutral spectrum of daylight illumination without any pronounced hue. In this paper the authors show that it is possible to maintain a neutral spectrum of illumination with EC glazing under normal operation provided that just a small proportion of the EC glazing is kept in the clear state. Predictions from a theoretical model are compared with measurements of the daylight spectra in an office with EC glazing under various states of tint. The predicted spectra show excellent agreement with the measurements. The theoretical model is further validated using lighting simulation to demonstrate that, under normal operation, illumination from clear and full-tint EC is well-mixed, with that from clear glazing dominating the overall illumination.

Keywords: Electrochromic Glazing, Daylight, Spectrum.

1 Introduction

The use of daylight in office buildings is generally considered to be a greatly under-exploited resource (Mardaljevic et al., 2009). 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 excessive ingress of daylight. Alternatively, the building may have fixed structures to block, redirect, and/or attenuate the daylight, e.g. light-shelves, brise-soliel, fixed-tint glazing.

With moveable shades, the users rarely make the effort to adjust them once the external condition has changed. Thus the shades are often left deployed for much of the day resulting in the commonplace occurrence of 'blinds down, lights on'. Using traditional approaches there are essentially three ways to control daylight from facade windows:

i. Block the light, e.g. an opaque roller blind.
ii. Redirect the light, e.g. a reflective light-shelf, prismatic glazing, etc.
iii. Attenuate the light, e.g. a fixed-tint glazing.

Many shading devices – fixed and moveable – utilise two of the above mechanisms. For example, a light-shelf is usually designed to block direct sun near to the window and also redirect the (blocked) daylight to the ceiling where it can help to improve daylight penetration. Users can operate venetian blinds to both block and redirect light, though it is more common to see them used with the slats closed.

1.1 The importance of view

Another key consideration is the mode of transmission: specular, diffuse or some mixture of the two. This is particularly important for primary view windows. A specular transmission is one where the light rays exhibit no noticeable deviation, and so the view always appears sharp. For example, even with heavily tinted glass the view to the outside will appear sharp, albeit darkened, during daytime. However, if the glazing is of the diffusing type (e.g. a privacy screen), then the light rays are scattered and there will be no discernible view. Some transparent materials exhibit both specular and diffuse properties, and the quality of the view through them will depend of the relative proportions for the two transmission modes. Note that most occupants find that even a small degree of scattering by glazing is unacceptable for primary view windows. Slatted blinds (i.e. horizontal or vertical) can be adjusted to allow a partially obstructed view out. However, depending on the particular configuration of the slats and the distance from the window, the occupant may find that their focus is drawn to the slats. Thus making it difficult to gain the beneficial relaxation of the eyes that is afforded when they are focused on the distant view beyond. This effective 'shortening' of the distant view can also occur with external shading structures such as brise-soleil.

A glazing with a transmissivity that varies continuously between clear and dark extremes could offer a much greater degree of control over the luminous environment, and avoid many of the drawbacks of the traditional approaches to shading and solar protection (Selkowitz et al., 1998). In contrast to fixed-tint glass, a variable transmission glazing would *modulate* the daylight in response to occurring conditions rather than simply attenuate it by a constant fraction.

1.2 Variable transmission glazing for use in buildings

The principle behind variable transmission glazing (VTG) is straightforward: the transmission properties of the glazing are varied to achieve an 'optimum' luminous and/or thermal environment. The various types of VTG can be grouped into three broad classes: chromogenic coatings, suspended particle device and micro-electromechanical systems (though there are others types also under development).

The key to performance for a VTG is a high (visible) transmission in the clear state and a sufficiently low (visible) transmission in the darkened (or tinted) state. To be perceived as acceptable to the majority of occupants in non-residential buildings, the VTG in the clear state should appear like ordinary (un-tinted) double glazing, and so have a visible transmission of 60% or greater. In the darkened state the transmission should be low enough so that additional shading is required only very rarely, or perhaps not at all. In practice this means a minimum visible transmission of around 2% or less. Additionally, the building occupants should have some degree of control of the glazing, e.g. to manually override an automated control setting. So, whilst a 'passive' VTG might seem attractive at first because it allows for autonomous operating behaviour, the corollary of this is a lack of control, e.g. modulation of the glazing transmission by (localised) window temperature will not necessarily offer the luminous environment desired by the occupants.

1.3 Chromogenic glass

There are four distinct types of formulations for coatings that have variable transmission properties. These are: electrochromic, gasochromic, photochromic and thermochromic. The agents causing the change in transmission are: voltage (electrochromic); concentration of pumped gas (gasochromic); localised illumination (photochromic); and, localised temperature (thermochromic). Thermochromic and photochromic are essentially passive devices which respond to changes in the environment, whereas electrochromic and gasochromic are active devices that can be configured to respond to any sensor input, e.g. illumination, temperature, or some combination of the two.

Of the chromogenic types above, only electrochromic (EC) glazing appears to have the necessary optical properties (i.e. wide visible transmission range), is relatively straightforward to install, is already in the marketplace, and undergoing large-scale production (Sanders et al., 2013). The two images in Figure 1 show a large electrochromic glazing installation using SageGlass. For that generation of product the visible transmittance in the clear state was 62% with a minimum of 2% when fully tinted.

User acceptance for any daylight control technology depends on a number of performance and operational characteristics. For EC glazing these include performance with respect to glazing transmission range (i.e. the values for the maximum and minimum visible transmittances), the switching time between the clear and tinted states and the effectiveness of the automated control to minimise user interventions (e.g. manual overrides). Another key factor for user acceptance is the *quality* of the luminous environment produced by EC glazing – for example, the spectral composition of the daylight that is 'filtered' through tinted EC glass. This is because the spectral transmission properties of the EC coating varies as the glass changes state. This can be seen in Figure 1 showing a pair of photographs with EC glass in the clear state (left) and at full-tint (right).

Figure 1 – Images showing electrochromic glazing in clear and darkened state (photos courtesy SAGE Electrochromics Inc.)

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 for SageGlass EC glazing shown in Figure 2. In the clear state the EC glazing has a visible transmittance of 62% and appears effectively neutral to the eye. There is a slight ‘peak’ in the curve around 600mn giving a very slight straw coloured hue, though this is generally not noticeable in normal use. This product has a minimum visible transmittance of 2% 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’ (20%) and ‘mid-tint’ (6%). Note: the transmission curves are those for SageGlass EC glazing manufactured in 2012 and installed in the offices used for the validation described below. The current generation of SageGlass varies in visible transmission between 60% (clear) and 1% (fully-tinted). The findings shown below are equally applicable to the current product.

The peak in the spectral transmission curves gradually shifts from 615nm in the clear state to 455nm 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 1). And of course, the daylight transmitted through the window will be ‘filtered’ according to the spectral properties of the glazing and the character of the illumination incident on the glazing, e.g. ‘warm’ sunlight, ‘blue’ skylight, etc. This presents a number of potential user acceptance issues for any EC glazing installation. In particular, ensuring that the daylight illumination in the space is perceived as ‘neutral’ and adequate for everyday colour rendering purposes. There have been reports that ‘blue’ fixed-tinted glazing had lower approval ratings from test subjects than neutral or warm fixed-tinted glass (Arsenault et al., 2012). Thus the question regarding the neutrality of the illumination spectrum is an important one that needs to be addressed.

2 Neutral daylight spectra with VTG

Personal experience and anecdotal reporting on spaces with EC glazing suggests that a subjectively neutral daylight illumination spectrum can be maintained provided that some of the EC glazing is left in the clear state. However, that needs to be proven with measurements. The illumination spectrum – that is, the daylight that passes through the glazing to illuminate the space – will depend on the spectrum of light that is incident on the glass and the transmission properties of the glazing for the various states of tint.

2.1 Combined transmission model

In principle it is possible to model the combined effect of daylight passing through multiple glazing elements with varying spectral transmission properties provided those are known (e.g. the curves shown in Figure 2). This approach is referred to here as the discrete transmission model, i.e.

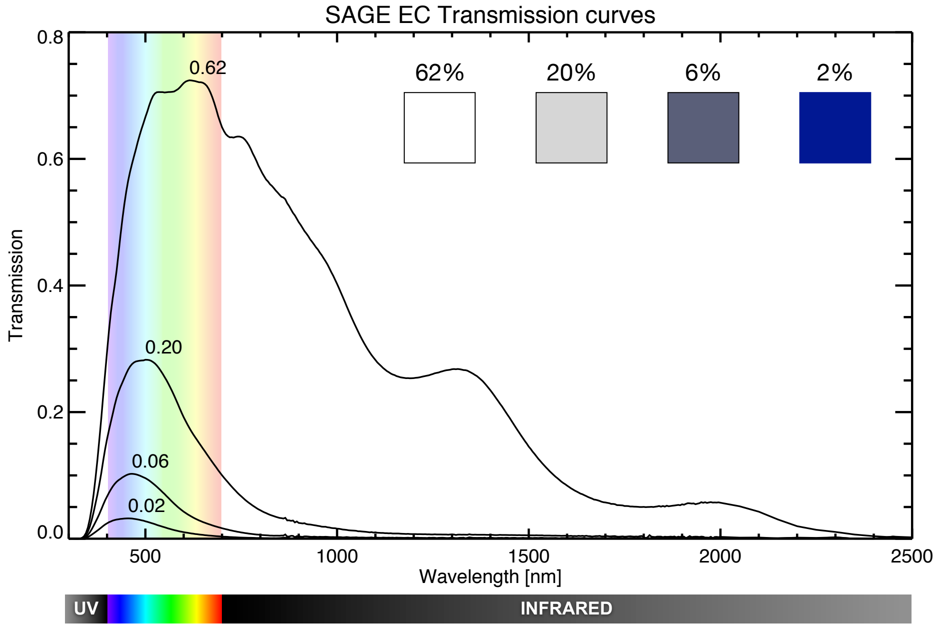

Figure 2 – Absolute spectral transmission curves for SAGE electrochromic glass in clear (62%), fully tinted (2%) and two intermediate states. Data from the IGDB files supplied by SAGE Glass.

illumination from each glazing element model independently. The problem however can be greatly simplified if the different transmission properties for each glazing element are combined into a single transmission model for all the elements in the group. A schematic illustrating this is shown in Figure 3. A paper describing this model and its validation is currently in press (Mardaljevic et al., 2015). The combination spectral curves (Figure 4) are shown each normalised to peak value equals 1 because, for this part of the evaluation, it is the shape of the spectra rather than their absolute values which are of importance. Additionally, the plot shows the transmittance curves for EC glass in the clear state (dashed line) and at full-tint (dotted line), Figure 4. For reference, the plot also includes the visual sensitivity curve $V(\lambda)$ (also normalised to peak equals 1). Matrix notation is used to describe the number N of equal-area glazing elements in each of the four states of tint. This is given given by the vector $\mathbf{R}$ where:

$$\mathbf{R} = \begin{bmatrix} N_a & N_b & N_c & N_d \end{bmatrix} \tag{1}$$

For example, if one panel 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 curve for $\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix}$ (i.e. 1 clear panel and 1 at full-tint) is shown in yellow. With gradually increasing values for N_d, the colour used for the curve transitions from yellow 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 panels is quite pronounced and ‘orderly’. Firstly, for the case with 1 clear and 1 full-tint panel, the combined spectral transmittance curve (yellow) 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 500 nm (i.e. the ‘red’ end of the visible spectrum), and a slight enhancement of wavelengths shorter than 500 nm (i.e. the ‘blue’ end). With each additional full-tint panel this trend persists, with the crossover point around 500 nm seeming to act as a ‘pivot’.

Consider now the absolute values for transmission. A two panel combination with one set to fully clear (62%) and one to full-tint (2%) has an equivalent visible transmittance of 32%, i.e. $(62 + 2)/2$. However, approximately 97% of that equivalent visible transmittance is due to the panel in the clear state, because of course the clear state panel has $31\times$ the visible transmittance of the glass at full-tint.

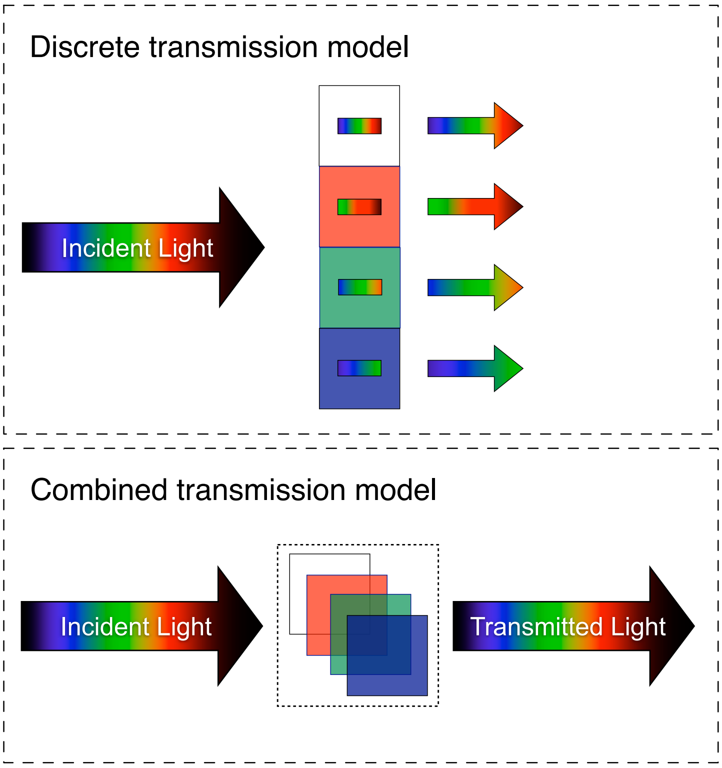

Figure 3 – Discrete and combined transmission models

2.2 A hypothesis regarding 'light mixing'

For the combined transmission model to have practical application for spaces with, say, electrochromic glazing, a hypothesis is made regarding the 'mixing' of daylight illumination in the space. The daylight illumination incident on a window will have a spectral power distribution (SPD) which depends on the sun/sky conditions and the reflection properties of the local environment, Figure 5. The SPD for the daylight illumination entering the space will be the element-by-element (or Hadamard) product of the incident SPD and the transmission curve for the window – in this case, a transmission curve for a combination of EC glazing elements in different states of tint.

As the entrant daylight illumination undergoes multiple reflections off the various surfaces inside the space, the SPD will, at each reflection, undergo some modification according to the spectral reflectance properties of the respective surfaces, e.g. walls, ceiling, floor, and, to a lesser degree, other fixtures. The majority of office spaces tend to have fairly neutral decor, especially for the walls and ceiling. It is proposed that, for these types of spaces, the important reflections do not significantly modify the entrant illumination spectrum. Furthermore, the daylight in these spaces is generally well-mixed with a homogenous/isotropic SPD, Figure 5.

2.3 Validation of transmission and light mixing models by measurement

The models described above were validated by comparing the spectrum of illumination predicted by the theoretical model against measurements taken in an office space fitted with production electrochromic glazing (Mardaljevic et al., 2015). Although EC glass has been available for a number of years and evaluated under various experimental conditions (e.g. test cells), the first commercial installation in the UK happened only in late 2012. Two offices at De Montfort University (Leicester, UK) were fitted with EC glazing produced by SAGE Electrochromics Inc. 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 (Kelly et al., 2013).

The space used for the validation has 8 panels of EC glass grouped into 5 zones. Daylight SPDs in the space were measured at six locations in the space. Four of these corresponded to the view

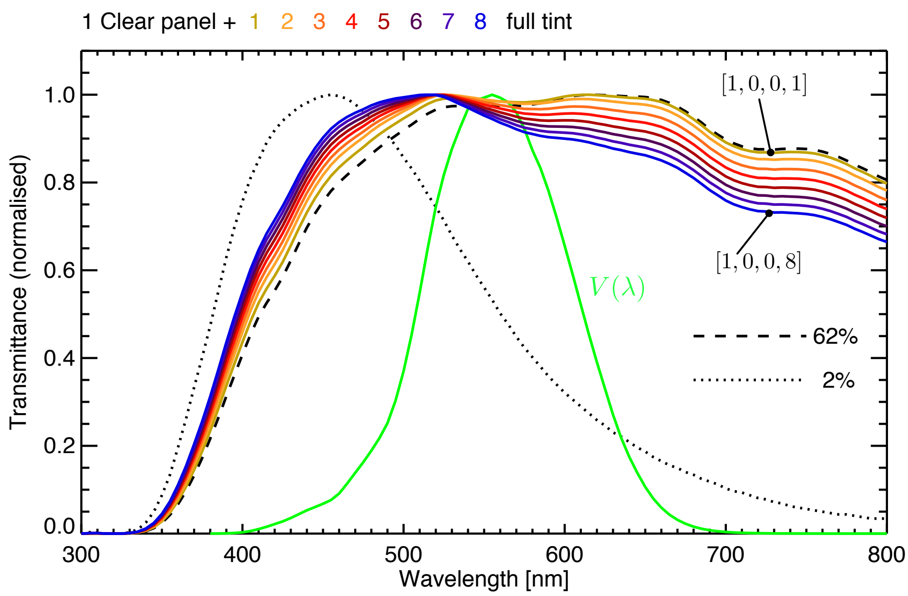

Figure 4 – Eight spectral transmittance curves for EC glass in the combinations 1 clear to (1 to 8) at full tint

directions of the seated occupants working in the space. The other two ‘views’ were from the back of the space towards the glazing, and from the glazing wall towards the back of the room.

Spectra were measured using an MK350 handheld spectrometer produced by UPRtek. The spectra cover the range 360 to 760 nm and are output as normalised curves (peak equals 1). The sensor has an approximate cosine response, and so the spectra recorded are equivalent to spectral irradiance by a device that measures absolute units. The measured spectra are therefore also similar to what would be received by the eye when located at the various measurement positions and view directions. The MK350 also records illuminance and various derived quantities including correlated colour temperature (CCT) and colour rendering index (CRI). Tests showed that repeatability was very good and there was no practical advantage in taking multiple spectra at individual measurement points – an important consideration since we did not want the sun position to change significantly during each set of measurements. Comparison of daylight and artificial light spectra measured simultaneously with a ‘laboratory grade’ spectrometer (PhotoResearch 655) showed very good agreement.

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. Thus, standard illuminant D_{55} was chosen as the source used in the theoretical model to predict the illumination spectrum for the office space. Predicted and measured spectra were normalised to $V(\lambda)$ such that the area under the normalised curve was the same for each, i.e. each of the spectra would produce the same illuminance. Results for two of the cases evaluated are shown in Figure 6.

Firstly, all six measured spectra were remarkably similar in each case, supporting the hypothesis that SPDs in the space are largely homogeneous/isotropic. This was so for all six cases examined (Mardaljevic et al., 2015). For the case $\begin{bmatrix}3 & 0 & 0 & 5\end{bmatrix}$, three EC panels were set to clear (T_{vis}=62%) and the remaining five set to full tint (T_{vis}=2%). For $\begin{bmatrix}0 & 0 & 3 & 5\end{bmatrix}$, three EC panels were set to tinted state T_{vis}=6% and the remaining five set to full tint. For the case with clear glazing the measured correlated colour temperature (mean of 6 values) was 4,970 K and the illumination of the space appeared neutral, notwithstanding the evident blue tint of the glazing – see Figure 7. Also, the spectrum and measured CCT are typical of those measured in spaces with ordinary clear glazing (Mardaljevic et al., 2015). In contrast, the measured CCT for the other space was 11,557 K and the space had a noticeable blue hue (Figure 7). Also, the spectrum is clearly divergent from

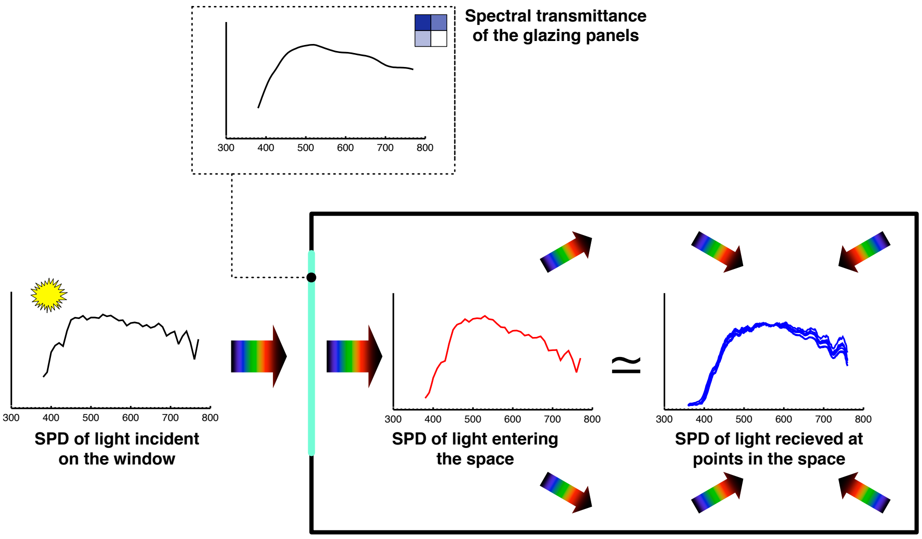

Figure 5 – Hypothesis regarding light-mixing

any that would normally be encountered in a space with ordinary clear glazing.

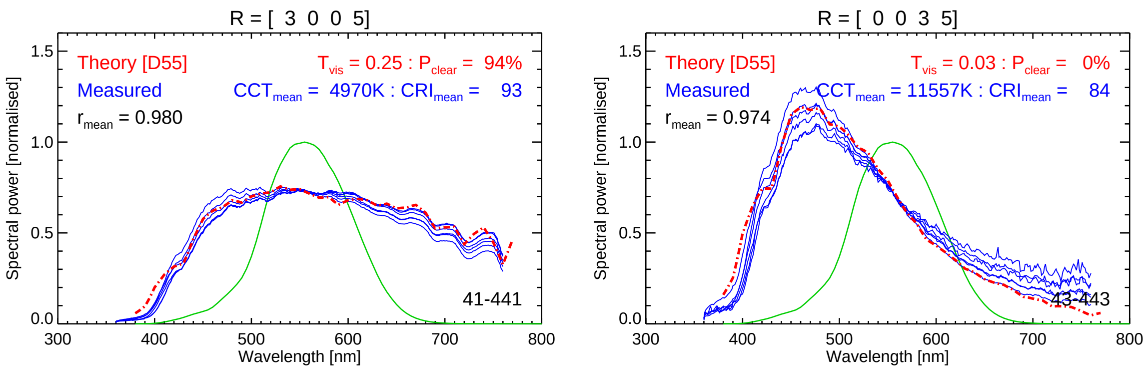

Figure 6 – Theoretical and measured SPDs in a space with EC glazing

The theoretical model for the daylight SPD in the office (red curve) shows remarkably good agreement with the measurements. This demonstrates that combined transmission model for EC glazing is a good (if not very good) representation of EC performance in real spaces. The plots in Figure 6 are also annotated with: the mean of the six measurements of colour rendering index (CRI); the effective visible transmittance of all EC panels combined (predicted); and, the predicted fraction of the total daylight passing through the windows resulting from EC in the clear state (expressed as a percentage).

3 Simulation of light mixing

In this section the hypothesis regarding the spatial homogeneity of mixed light from combination clear and tinted EC glazing is examined in more detail using the *Radiance* lighting simulation system (Ward Larson et al., 1998).

3.1 The building model

A 9 m square generic office space was created for this evaluation. A particularly deep space was chosen to determine if this imposed limits on the hypothesis regarding well-mixed light. The window was described as three equal height strips of EC glass. In the rendering shown in

$$\begin{bmatrix} 3 & 0 & 0 & 5 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 0 & 3 & 5 \end{bmatrix}$$

Figure 7 – Photos of the office for two of the EC tint state combinations

Figure 8 the upper two strips were set to full tint and lower strip to clear. The floor to ceiling height was 3.2 m, and space was empty apart from a 0.5 m deep sill which had a height of 0.8 m. The reflectance values for the ceiling, walls/sill, and floor/ground were 80%, 60% and 20% respectively.

3.2 Simulation of the discrete transmission model

The spatial homogeneity of light from combination clear and tinted EC glass was predicted using the discrete transmission model. In other words, light from each of the three strips of EC glass was predicted on a strip by strip basis and then combined. Thus it was possible to track and quantify the contribution to total illumination from each strip whatever its state of tint.

The glazing strips were modelled as neutral glass with the appropriate visible transmittance value, i.e. 62% and 2%. When simulating the illumination from one strip, the other two were modelled as zero transmission glass rather than opaque panels. Thus, the specular reflection of light *back* into the space from the other two (non-transmitting) strips was correctly accounted for. Even though this probably accounts for a fairly small part of the total, the need to accurately track other small contributions (i.e. from strips set to full-tint) made this worthwhile. This paper gives the results for a single case of a sunny sky condition.

3.3 Results

The results showing the simulated daylight distribution for the office space are presented in Figure9. The sensor grid was as normal desk height (0.8 m) and covered the entire area less a 0.5 m perimeter space. The spaces were simulated with the number of ambient bounces set to seven to ensure that the values were close to a fully converged (i.e. realistic) ‘infinite’ light reflection condition. The upper plots show the illuminance distribution for the case with:

1. Lower strip clear (62%), the two upper strips set to zero transmission. Note, the high-angle sun cannot shine directly onto the sensor grid through the lower strip.
2. Lower strip set to zero with the upper two set to full tint (2%). Direct sun can illuminate the sensor grid through the upper strips, but at full tint the illumination is heavily attenuated and does not exceed 2000 lux.

The plot annotations show mean illuminance for the front and rear halves of the space. The lower plot shows the percentage contribution to total illumination that results from the EC strip in the clear state. Again, the plot annotations show mean percentage contribution for the front and rear halves of the space.

For all except the direct sun illuminated area, the illumination from the clear glazing strip contributes more than 95% of the total (horizontal) illumination arriving at the sensor grid (i.e. desk or workplane). Even for the direct sun illuminated area, that contribution doesn't drop below the 80% mark. Note, for this 1:2 ratio of clear to full-tint EC glazing, the theoretical model predicted that 93% of the overall visible transmittance was that due to the clear part.

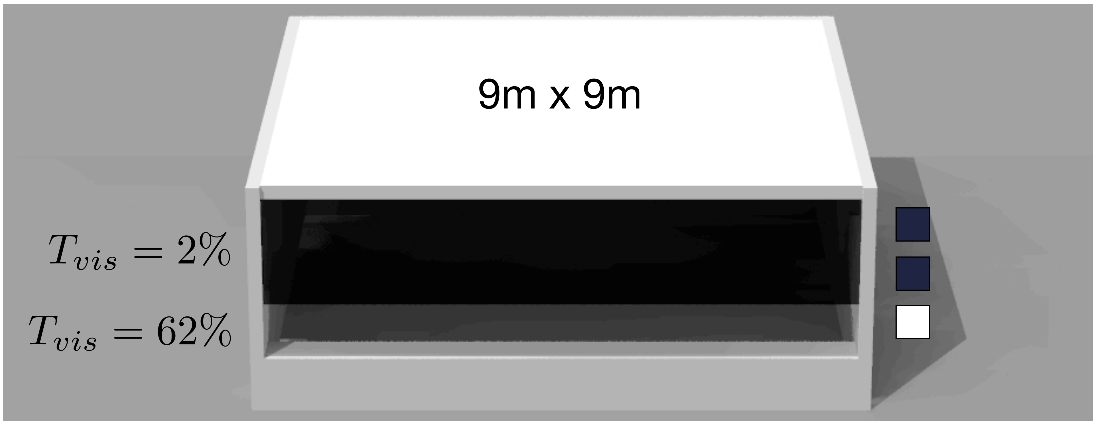

Figure 8 – Rendering of the 9 m square office space

4 Discussion

The simulation of the illuminance contribution of clear and full-tint strips of EC glazing using the discrete transmission model has provided additional supporting evidence for the validity of the combined transmission model. This work will be extended to examine annual profiles of light mixing using climate-based daylight modelling. For that work, currently in progress, the EC controls strategy to adjust the glazing transmittance in response to changing external conditions will be based on the control algorithms used in actual EC installations.

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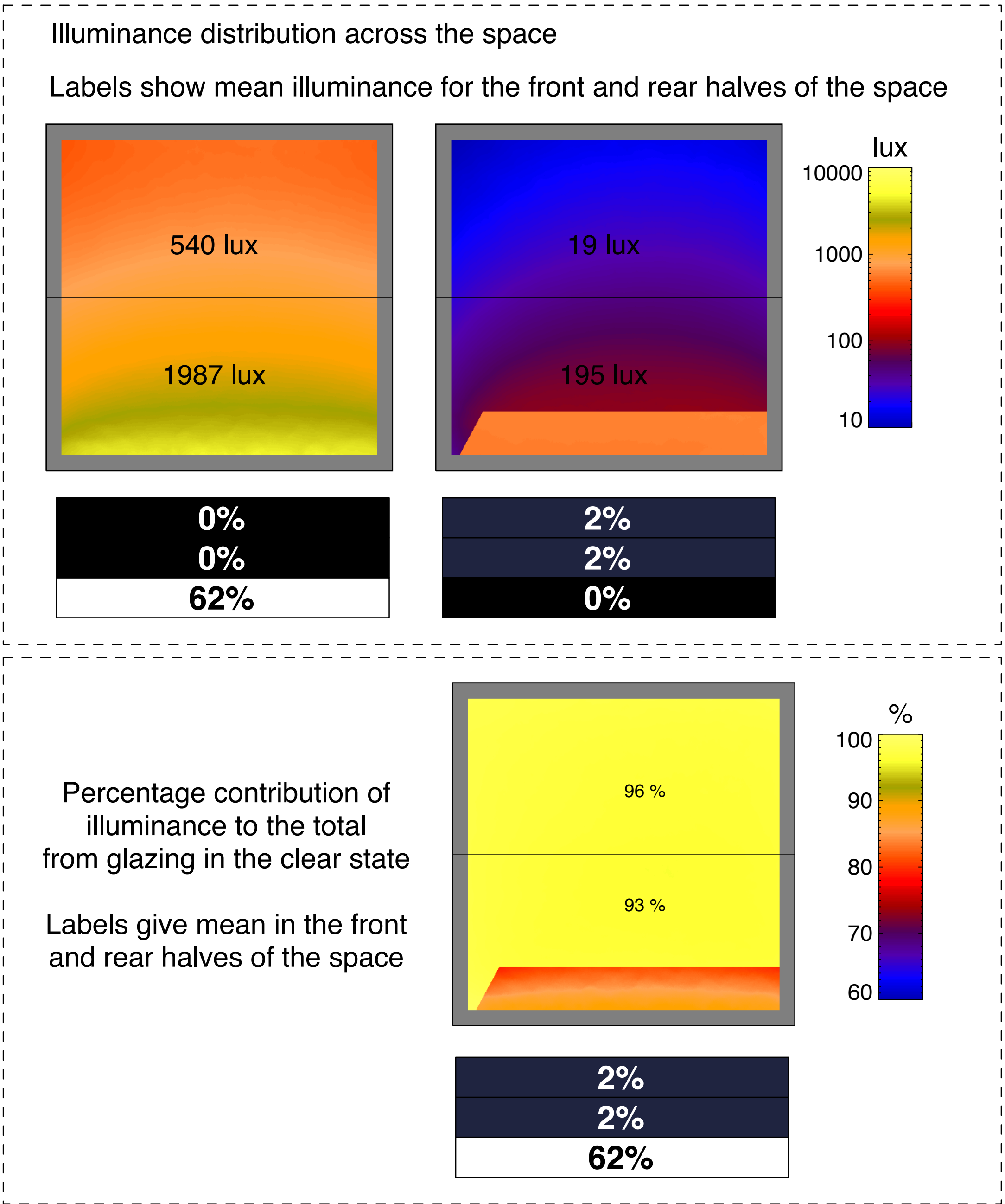

Figure 9 – Simulation of the illuminance contribution from clear and full-tint strips of EC glass in a 1:2 ratio