Toward colour rendering method of window glass

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Abstract: The aim of this study was to expand the understanding of modern glazing materials' effects on the colour distortion in interiors and to develop a rather simple colour rendering method useful for any type of glazing and based on colorimetry measurements and mathematical calculations. The qualitative and quantitative aspects of different light sources on colour rendering are frequently discussed topics among the researchers, but one of the issues touched only sporadically is the impact of tinted glazing on colour rendering of daylight. The study started from the following question: Is the colour rendering method proposed by Joe Lynes reliable also for present-day high-tech glazing types?

The experiment was carried out in the Norwegian University of Science and Technology's (NTNU) with the artificial sky, which enables mimicking of skylight of the following correlated colour temperatures: 2700K, 6500K and 8000K. Three high-tech glazing types were used in five different transmittance scenarios. Colorimetric measurements were taken with the SpectraScan PR655 spectroradiometer. The findings indicated that the Lynes method is reliable to predict which glazing have the biggest impact on all aspects of colour but only in 6500K.

New set of measures have been proposed: average colour shift distance for Hue, gamut area for Chroma and median transmittance for Value. However, for higher precision regarding the direction of shift and the overall perception of the respective colours in building context, experiments with subjects are needed.

Key words: advanced glazing, colour rendering, Electrochromic glass, Electrotopic glass, Photochromic glass, gamut area, colour shift, transmittance ratio, Hue conservation index

Introduction

This study is a part of a bigger experiment examining shift of surface colours caused by advanced glazing, which was done in 2016-17 under an Artificial Sky at the Daylight laboratory of the Norwegian University of Science and Technology (NTNU) [1].

Inspired by previous research, we have developed and tested measures that in combination can be used as a colour rendering method of window glass. This could enable evaluation of a visual effects of filtering daylight by means of mathematical calculations. The measures has been developed starting from the Lynes colour rendering method and contains Lynes approach for Chroma [2].

Previous research

The quantity of the light transmitted by glazing defines the daylight level in interiors. Its spectral composition has impact on the perception of colours in interiors, something that is important for the impression of the room's atmosphere, visual clarity and light quality that we experienced inside the room.

Despite numerous research on colour rendering of different lamps e.g. LED lamps, there seems to be little investigation on the effects of filtered daylight through window glasses on illumination of spaces and objects [3,4].

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Colour Rendering Index (CRI) is the colour rendering metric recognized internationally, and it is universally used by the lighting industry. Nevertheless, many other methods for quantifying the colour rendering properties of electric light sources have been proposed [5]. All of these methods, including CRI, have limitations in characterizing the various aspects of colour perception associated with colour rendering (e.g., vividness, discriminability, naturalness) [5-9]. Every method utilizes the SPD of the light source. It has to be stressed that glazing is not a light source and it functions as an optical filter with a specific spectral transmittance.

An interesting new "colour rendering method" for window glass was proposed by Joe Lynes on 14th of October 2015 at the CIBSE conference 2. It is based exclusively on the usage of the colorimetric data of window glazing and 8 standard CIE colour samples.

In the research done by Davis and Ohno [10], 15 new Munsell samples were used instead of 8 CIE samples to improve colour rendering index. They argued that the old set of 8 samples does not adequately span the range of normal object colours. This change was proposed mainly for colour rendering index of LEDs, which in general are characterized by stronger chromaticity than traditional light sources. Since this is not the case for daylight, we decide to work with the 8 CIE samples.

There are three main perceptual attributes used to describe colour sensation, which can be found in many colour system, as Munsell or NCS; Hue, Chroma and Value.

Hue is the subjectively dominant part of the spectrum. Chroma is the colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white. Value corresponds to lightness and reflectance. Lightness describes the brightness of an area judged relatively to the brightness of a similarly illuminated area that appears to be white [11]. To estimate the effect of window glass on these three attributes is the main target in this research study.

A light source may affect all three dimensions of surface colour. Glazing can be thought of as a light filter. As such, it is especially noticeable if its transmittance is not equal for all wavelengths. Filtering daylight by window glasses may affect hue, chroma and value of surface colours.

As Joe Lynes indicated, a form of colour rendering index of window glasses is of a high importance as:

-It helps to compare the performance of alternative glasses.

- It clarifies the choice of electric lamps for interiors with daylight in different conditions, i.e. when tinted glasses are used [2]. In his presentation, he tried to answer if it is safe to use green tinted solar glazing in a hospital or not? To answer this question, he proposed three measures: gamut area for chroma, transmittance ratio for value and a conservation ratio for the hue.

Gamut area

It is defined as a two dimensional area, limited by lines connecting points representing coordinates of colour samples at xy or u'v' colour space (see Fig. 1) [5].

In our study, the gamut area is the area of the octagon defined by the 8 CIE test colours.

According to Lynes research, within reasonable limits and up to a certain point, people like to see surface colours strengthened. So a large gamut area is preferred to small gamut area [2].

Gamut area is one of potential criterions for chroma rendering of window glasses. However, following Lynes, some points need to be taken into account:

-Gamut area is a property of light sources, and window glass is not a light source, but a filter of a daylight source.

-Gamut area for window glass depends partly on the spectrum of the daylight source.

It can be said that the chroma rendering potential of window glass is the gamut area of its transmittance. Thus, calculating the gamut area for window glasses is applicable only if we assume the presence of a standard neutral (light) source. On the other side it is interesting to discover how strong is the impact of the spectrum of the light source. Consequently, the study was repeated for three correlated colour temperatures CCT: 2700, 6500 and 8000K.

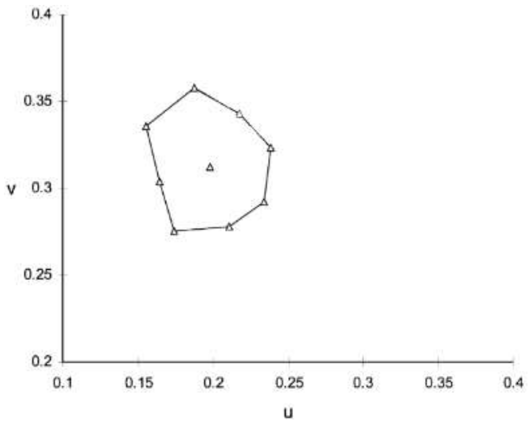

Fig. 1. Gamut area of D65.

Transmittance ratio

According to Lynes [2], the ability of window glass to preserve surface reflectance is given by the transmittance ratio that is defined as minimum/maximum wavelength transmittance.

Hue conservation index

As Lynes mentioned, one of the possible causes that the window glass cause hue shift is a roller-coaster transmittance/reflectance curve. "The nightmare scenario can occur when both the glass and surface have a roller coaster between 525 and 760 nm" [2]. The roller coaster effect is a situation in which there are many big and sudden changes.

The Hue Conservation Index (HCI) formula was proposed by Lynes is presented in equation (1):

$$\text{Hue Conservation Index} = 1- \frac{Tc-Td}{Ta+Tb} \qquad (1)$$

Where:

Ta = Transmittance at 525 nm

Tb = Transmittance at 700 nm

Tc = Transmittance at peak

Td = Transmittance at trough

Aim and Scope

The current study was motivated by the following research question:

How reliable is the colour rendering method proposed by Lynes for high-tech glazing types with unusual spectral transmittance? And does the correlated colour temperatures (CCT) of the light source (artificial daylight) have an impact?

In other words, this study was aimed to explore how well the three colour rendering measures describe the colour differences. Lynes proposed them for a glazing with a green tint, is this a useable method also for modern high-tech glazings?

Method

To calculate the impact of window glasses on colour perception i.e. hue, value and chroma, a grey box representing a room was placed in Daylight laboratory more specifically under artificial sky. We used the method to evaluate the following attributes:

Hue ➔ The subjectively dominant part of the spectrum

Chroma ➔ Saturation, Vividness, Purity of colours.

Value ➔ Lightness, Reflectance

All the measurements were done in the test room that is a grey scale model, representing a large office room 3m x 3m x 3m in the scale 1:5. The room had identical openings to let in light and for observer to look in (Fig. 2). The study was carried out under an artificial sky at NTNU [12,13]. The following CCTs were used in the study: 2700K, 6500K and 8000K. To enable both stable and comfortable illumination, the illuminance level under artificial sky was adjusted to 50% of the maximum power giving the illuminance in the range 129– 700 lx on the floor of the model. The spectral distribution of three used artificial conditions is presented in Fig.3. From the outside, the model was painted in black to reduce undesired light reflections in the artificial sky. The wall with the opening (eye position) was also covered externally by black textile during the measurements to avoid the light penetration from the artificial sky.

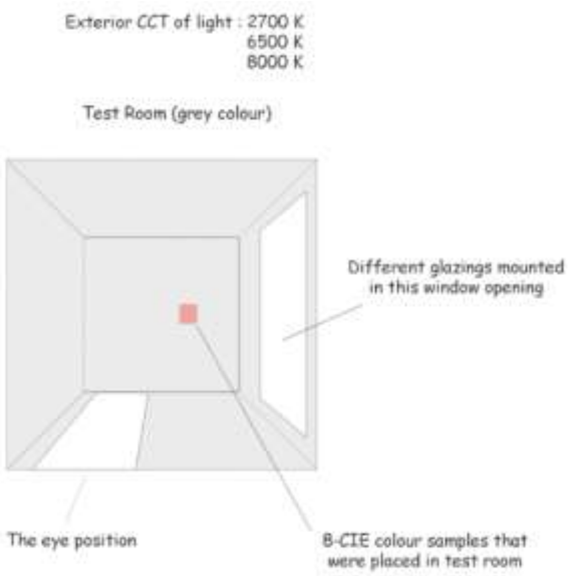

Fig. 2. Top view of experimental set-up.

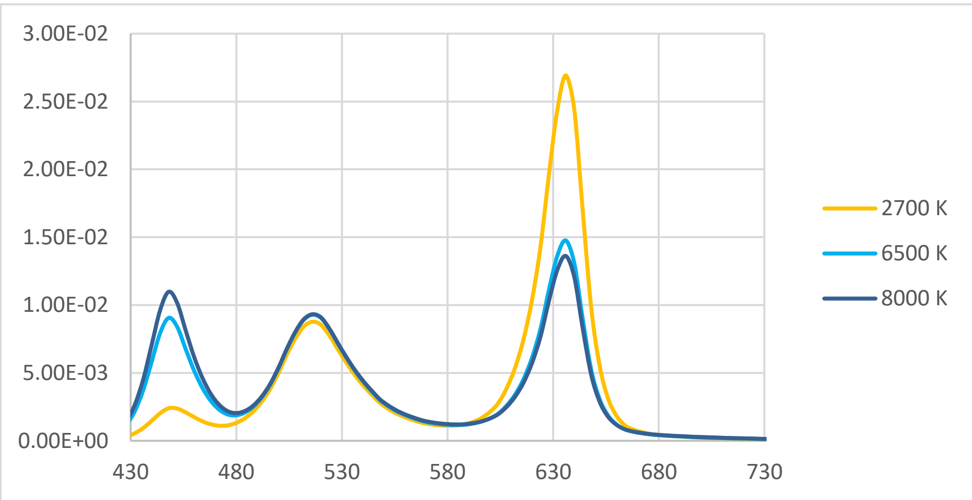

Fig. 3. Spectral power distribution of three used CCTs.

In this experiment, three different glazing were mounted as a window glass in the test room: Electrotopic glass (ET), Electrochromic glass (EC) and photochromic glass (PC). Under standard daylight conditions, real sky that has 6500K, the EC-uncoloured (transparent) glass appears as standard clear glazing. Samples of coloured and midpoint states of EC glass have a bluish tint, and their chromaticity is inversely proportional to their Light Transmittance (LT) and is dependent on the voltage adjustment. The ET glass has a milky appearance, and the PC glass has a pale yellowish tint (Fig. 4).

Eight original CIE Test Samples (Table I) were placed inside the grey box close to the window opening where the light level is even over a large area. The colorimetric measurements of these samples were done with different glazing types in combination with different CCTs. The measurements were carried out with spectroradiometer SpectraScan PR-655 from the exact eye position (Fig. 2) [1]. The measurement method was developed based on the one proposed by Joe Lynes [2].

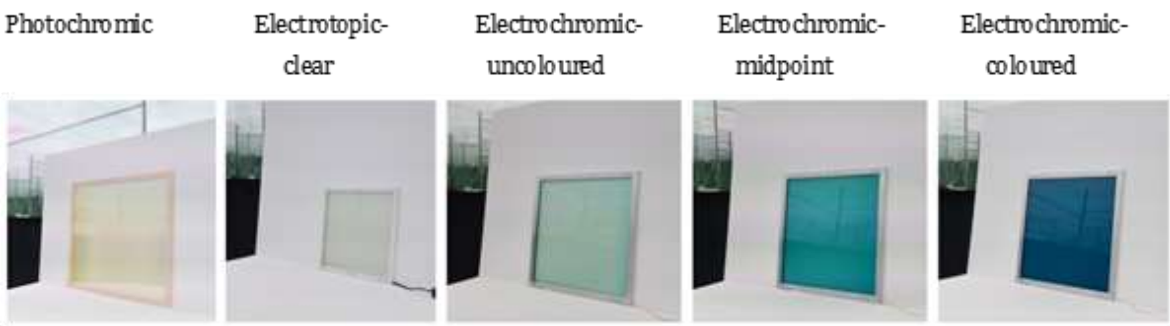

Fig. 4. Glazing types used for the measurements, except ET-off.

Name	**Munsell Notation**
TCS01	7,5 R 6/4
TCS02	5 Y 6/4
TCS03	5 GY 6/8
TCS04	2,5 G 6/6
TCS05	10 BG 6/4
TCS06	5 PB 6/8
TCS07	2,5 P 6/8
TCS08	10 P 6/8

TABLE I. Eight original CIE test samples

In order to assess colour rendering of glazings, the following items are needed:

-An ideal light source reference (artificial sky)

-A limited number of representative "test colour" samples; here we used 8 samples from Munsell system which is commonly used by CIE and have the medium lightness and saturation, and are approximately equally spaced when plotted on CIE 1960 u v chromaticity diagram [5].

-A uniform "Chromaticity Scale" to score colour differences. In this paper we used u' and v' chromaticity chart which is believed to be uniform for all colours.

Results

Gamut area, for Chroma

The measured chromaticity coordinates are shown in Figures 5-7 for different CCTs. The gamut area calculations were performed in the CIE 1976 (u', v'). But to better understand the changes for respective hues, the gamut is also presented in a, b values which can be found in appendix 1. The numbers for gamut area can be found in Table II.

The CCT of the light source has significant impact, both on the position of the gamut and on the gamut area. The gamut area with CCT 2700K is to be found in the upper part of the graph (large v') and is nearly ½ of that of CCT 8000K both, for "no-glazing" and for all the glazings (Fig. 5 and Table II). However, the difference between 6500K and 8000K was very small.

Based on the results for 6500K we can order glazings from the lowest to the highest gamut area (chroma): EC-coloured, EC-midpoint, PC, EC-uncoloured and, at the end, both ETs scored equally.

In normal daylight conditions, the ET glazings appears whitish, something that gives an expectation for a slight colour change toward white. Interestingly, the ET-on and ET-off showed the largest gamut area in all CCTs.

The PC glass had a little lower score than ETs and EC-uncoloured. This result is interesting, since the PC glazing has a yellowish tint and was liked more than ETs by subjects in the previous study [1].

As expected, EC-coloured showed lowest gamut area. EC glazing has a bluish tint, both in the fully coloured state and in the midpoint state. As the fully coloured state is most bluish, it does not transmit yellow-red part of the spectrum well, so the gamut area is positioned in the bluish part of the graph and is much smaller than all others. In 6500K and 8000K, EC-midpoint had lowest score of all glazing types after EC-coloured.

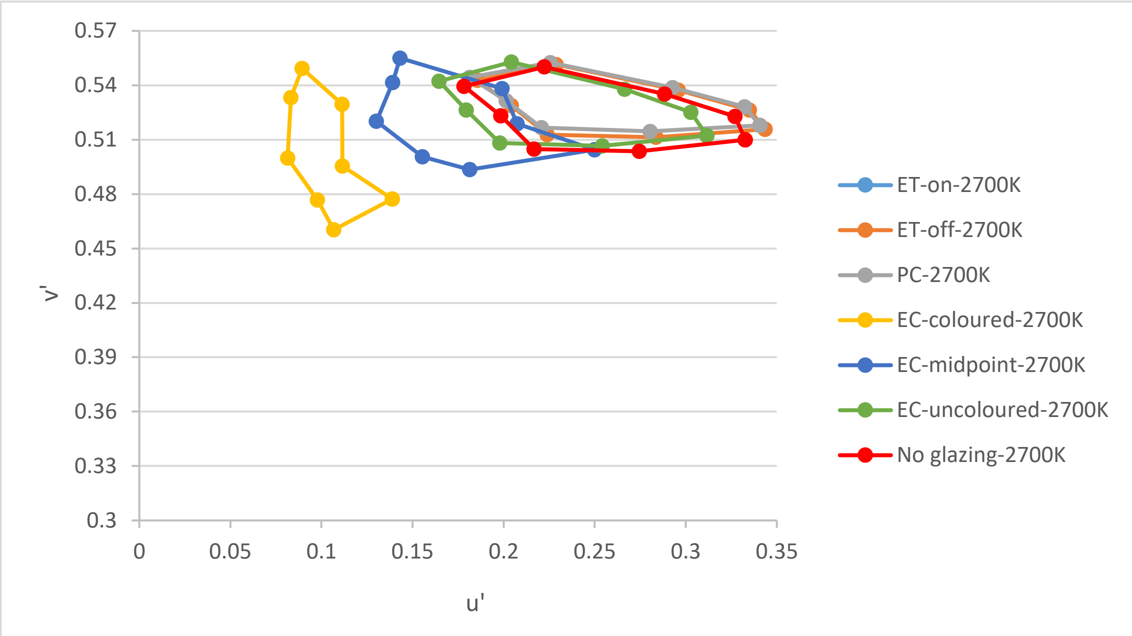

Fig. 5. Gamut area of different glazings in 2700K based on u' and v' values.

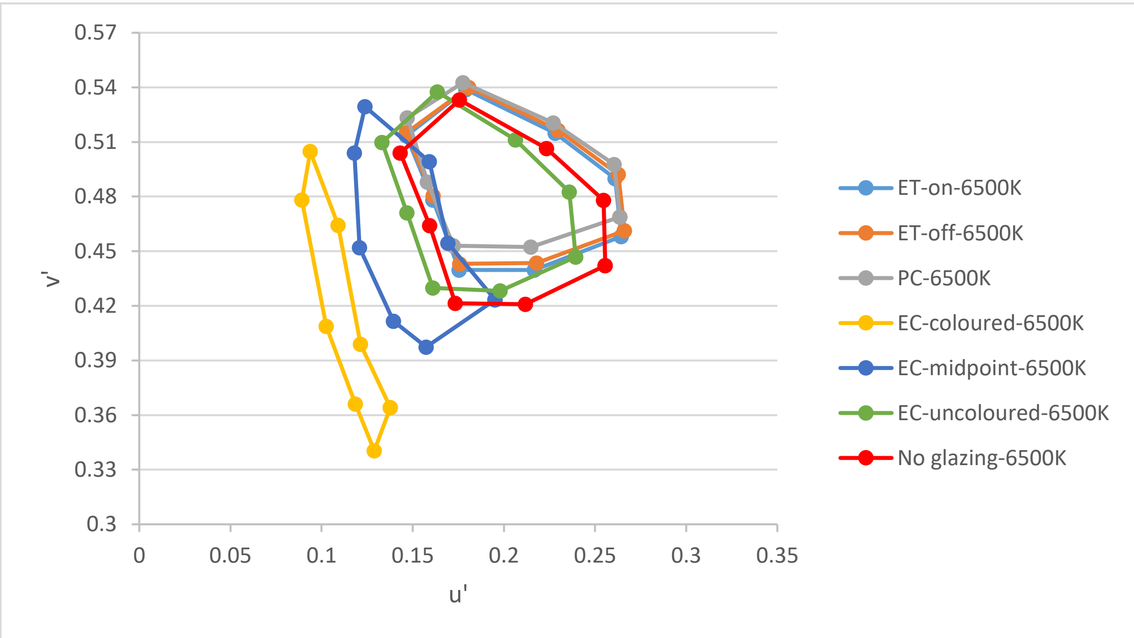

Fig. 6. Gamut area of different glazings in 6500K based on u' and v' values.

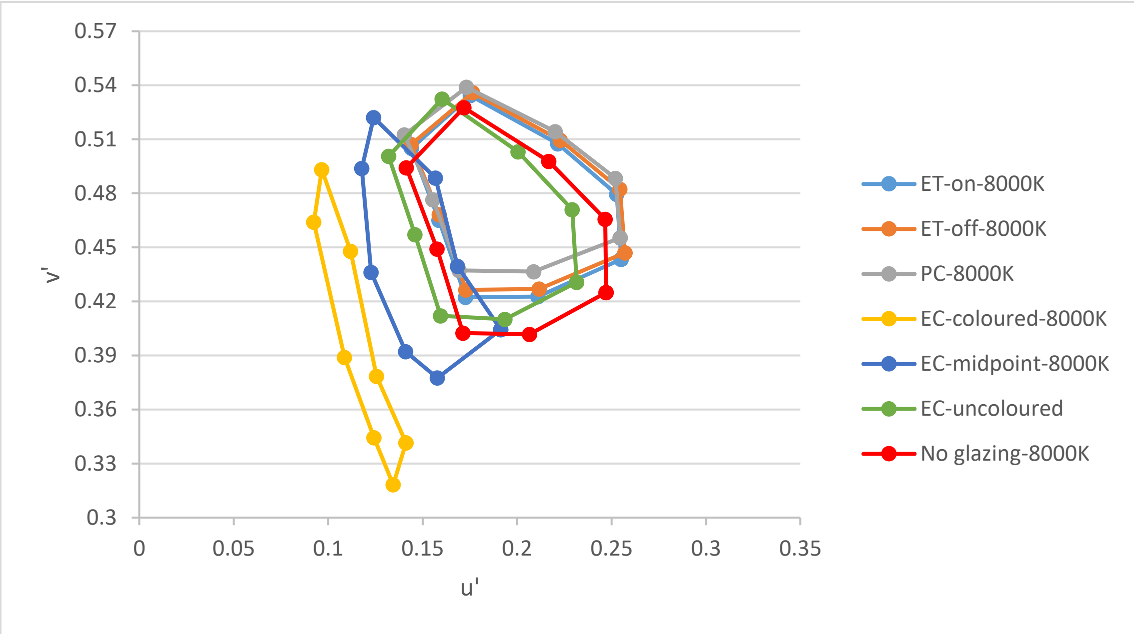

Fig. 7. Gamut area of different glazings in 8000K based on u' and v' values.

In Table II, we assume open (no glass) in each CCT as a reference target 100% and calculate the percentage of gamut area based on that, which you can see in blue colour.

TABLE II. Gamut area for all types of glazing in combination with different CCT based on u' v' values.

CCT	open	ET-on	ET-off	EC-coloured	EC-midpoint	EC-uncoloured	PC
2700	0.0045 100%	0.0039 87%	0.0038 84%	0.0023 51%	0.0037 82%	0.0042 93%	0.0036 80%
6500	0.0084 100%	0.0077 92%	0.0077 92%	0.0023 27%	0.0052 62%	0.0076 90%	0.0071 85%
8000	0.0088 100%	0.0082 93%	0.0082 93%	0.0022 25%	0.0054 61%	0.0079 90%	0.0077 88%

Spectral transmittance and Transmittance Ratio for Value

The spectral transmittance, which is the ratio of transmitted incident light behind the glazing and in front of the glazing, of all types of glass was measured with SpectraScan PR-655 (Fig. 8). To avoid measurement errors that typically appear at both ends of the spectrum interval, we limited the wavelength interval to 430nm-730nm. We could observe that the transmittance graphs for the respective glazings have almost the same shape in all three CCTs. Nevertheless, differences can be found when we look at numbers, see Table III.

Fig. 8. Spectral transmittance of glazings.

The graphs show also that even though there are some small differences in the numbers, the effect of CCTs 6500K and 8000K had almost the same flow and distribution.

As expected, the EC glazing transmitted short wavelengths (blueish part) much better than long waves. ET glazing, which has whitish tint, transmitted all wavelengths almost equally. The PC glazing that has yellowish tint shows low transmittance in the blue part of spectrum, as expected. Interestingly, PC had significantly different transmittance behaviour in yellowish exterior light 2700K than in bluish light 8000K.

We calculated the transmittance ratio (TR) based on the Lynes's formula that was presented in the introduction (see results in Table III).

The spectral transmittance of glazing is needed to predict how a given kind of glazing would have impact on the value (lightness) of interior colours. The question is if the proposed Transmittance Ratio is a good measure for high-tech glazings.

Figure 8 shows distinct difference between transmittance of ET-on and ET-off over the whole wavelength interval, we could expect transmittance of ET-on being significantly (40%?) higher than ET-off, but the TRs for those glazings in 6500K are nearly equal; 0.56 and 0.54 respectively (Table III).

Table III. Calculation of the Transmittance Ratio and the Hue Conservation Index for all glazing types.

	ET-on 2700k	ET-off 2700k	EC coloured-2700k	EC midpoint-2700k	EC uncoloured-2700k	PC 2700k
Ta at 525nm	0.45	0.26	0.24	0.48	0.68	0.70
Tb at 700nm	0.5	0.32	1.32	0.08	0.53	0.85
Tc at peak	0.5	0.33	0.34	0.51	0.69	1.04
Td at min	0.32	0.18	0.00	0.04	0.42	0.42
Transmittance Ratio	0.65	0.55	0.00	0.07	0.62	0.40
HCI	0.82	0.75	-0.43	0.15	0.78	0.60

	ET-on 6500k	ET-off 6500k	EC coloured-6500k	EC midpoint-6500k	EC uncoloured-6500k	PC 6500k
Ta at 525nm	0.45	0.26	0.23	0.48	0.69	0.70
Tb at 700nm	0.51	0.29	0.00	0.09	0.45	0.63
Tc at peak	0.59	0.32	0.33	0.51	0.69	0.75
Td at min	0.33	0.18	0.00	0.07	0.33	0.43
Transmittance Ratio	0.56	0.54	0.00	0.14	0.48	0.57
HCI	0.73	0.73	-0.46	0.22	0.69	0.76

	ET-on 8000k	ET-off 8000k	EC coloured-8000k	EC midpoint-8000k	EC uncoloured-8000k	PC 8000k
Ta at 525nm	0.45	0.26	0.23	0.48	0.69	0.70
Tb at 700nm	0.49	0.28	0.00	0.02	0.41	0.67
Tc at peak	0.50	0.30	0.33	0.51	0.69	0.75
Td at min	0.33	0.17	0.00	0.00	0.35	0.43
Transmittance Ratio	0.66	0.59	0.00	0.00	0.50	0.57
HCI	0.82	0.77	-0.46	-0.03	0.69	0.76

The Transmittance Ratios of EC-coloured and EC-midpoint are 0.0 or very close to 0.0 something that contradicts with observations of *Value* of surface colours in the room with those glazings [1,14] (Fig. 3); such rooms are not completely dark as the 0.0 suggests. Conclusion is that some of the TR results contradict with observations and therefore the TR is not a reliable measure of *Value*.

The Hue Conservation Index for Hue

The Hue Conservation Index was calculated to evaluate impact of glazings on the hue for all glazing types in a grey box (Table III). Calculations are based on the equation (1), Lynes's formula, given in introduction at Hue conservation index section.

As expected, the EC-coloured had the lowest HCI, followed by EC-midpoint; the highest values are for PC (6500) or ET-on (2700 and 8000), which is not fully consistent. Even more strange are the results for EC-midpoint across the CCTs, which vary surprisingly much, from 0,15 to -0.03. The most serious weakness of HCI-formula is that, contrary to the Lynes intension of keeping the index between 0.0 and 1.0, all of the HCI for EC-coloured and EC-mid 8000k have negative values.

Discussion

This experiment is a part of a bigger experiment heading to evaluate colour shift in spaces equipped with different glazing types and illuminated by light of different CCT, which gave us possibility to harvest experience of the colour shift as perceived by subjects.

We were aware that it is not so informative to compare the gamut area of different glazings with each other as different glasses have different tint and target and it is best to compare each one with the reference, which is no glazing. However, in this study, the comparison between glasses were done to have general overview about the impact of different glazings on the chroma.

In general, the gamut area is helpful to evaluate the amount of colours that can be reproduced. A window glass with a smaller gamut area, EC-coloured and EC-midpoint, tends to have bigger chroma distortions, i.e. smaller number of colours can be perceived. On the other hand, large gamut area contributes to large number of colours and it is easier to discriminate the surface colours. It helps also for visual clarity. It makes sense that larger gamut area would be preferred by users because surface colours will look more vivid. It is exactly what we found in previous experiments with participants.

The strongest hue shift HCI was registered for the EC-coloured (lowest and negative HCI). The Transmittance Ratio of EC-coloured was also the lowest of all glazings, namely 0.0. Still the 0.0 is not consistent with the observation.

In Table III there is a clear difference between ET-on glazing and PC glazing, especially in 8000K. As PC glazing has yellowish tin, we expect it to have higher impact on hue and value in all colour temperatures. The milky glass ET-on had slightly lower colour rendering numbers regarding hue and value than the PC-glass in 6500K opposite to what we see in 2700K and 8000K.

The experiment and measurements reported in this article (Table IV) have shown that the method can be useful for normal glazing for 6500K, but in the case of glazing with extreme spectral transmittance (EC) the evaluations of the value and hue were not reliable.

The conclusion is that we can use the gamut area to evaluate the Chroma, exactly as Lynes proposed, but a new effort is needed to improve the method for hue and value.

Development of new measures

Hue: Average Colour Shift Distance

It may be useful to look at the gamut again. As the u' v' graph is characterized by uniformity, the distance between two points at this graph should be a good measure of the hue difference, e.g. a measure of colour shift caused by the glazing.

A new measure of colour rendering method for hue could be based on the calculation of the distance between the point at the u' v' representing a sample illuminated directly by a given light source (CCT) and the point representing the same colour sample illuminated by the same light source after passing through the glazing under consideration (Table IV).

The results in Table IV represent the distance for each colour sample separately compared to "no glazing" and the last row is the average distance for shift of all colour samples for the respective combination of glazing and CCT.

We can observe that the results are very consistent with the gamut area drawings in Figures 5-7. For example, we may expect the largest colour shift for EC-coloured, the numbers confirms this, or that the colour shift will be a bit larger for EC-mid than for both ETs and PC and it is also exactly what we find in the Table IV.

TABLE IV. Distance for each colour sample separately compare to no glazing.

	ET-on 2700k	ET-off 2700k	EC coloured-2700k	EC midpoint-2700k	EC uncoloured-2700k	PC 2700k
Sample 1	0.01	0.01	0.22	0.12	0.02	0.01
Sample 2	0.01	0.01	0.18	0.09	0.02	0.01
Sample 3	0.01	0.01	0.13	0.08	0.02	0.00
Sample 4	0.01	0.01	0.10	0.04	0.01	0.01
Sample 5	0.01	0.01	0.12	0.07	0.02	0.01
Sample 6	0.01	0.01	0.12	0.06	0.02	0.01
Sample 7	0.01	0.01	0.17	0.09	0.02	0.01
Sample 8	0.01	0.01	0.20	0.08	0.02	0.01
Average shift distance	0.01	0.01	0.15	0.08	0.02	0.01

	ET-on 6500k	ET-off 6500k	EC coloured-6500k	EC midpoint-6500k	EC uncoloured-6500k	PC 6500k
Sample 1	0.01	0.02	0.15	0.09	0.02	0.02
Sample 2	0.01	0.01	0.12	0.06	0.02	0.01

Sample 3	0.01	0.01	0.09	0.05	0.01	0.01
Sample 4	0.01	0.01	0.06	0.03	0.01	0.02
Sample 5	0.01	0.02	0.08	0.04	0.01	0.02
Sample 6	0.02	0.02	0.08	0.04	0.01	0.03
Sample 7	0.02	0.02	0.12	0.06	0.02	0.03
Sample 8	0.02	0.02	0.14	0.06	0.02	0.03
Average shift distance	0.01	0.02	0.10	0.05	0.02	0.02

	ET-on 8000k	ET-off 8000k	EC coloured-8000k	EC midpoint-8000k	EC uncoloured-8000k	PC 8000k
Sample 1	0.02	0.02	0.15	0.08	0.02	0.02
Sample 2	0.01	0.01	0.12	0.06	0.02	0.02
Sample 3	0.01	0.01	0.08	0.05	0.01	0.01
Sample 4	0.01	0.01	0.06	0.02	0.01	0.02
Sample 5	0.02	0.02	0.08	0.04	0.01	0.03
Sample 6	0.02	0.02	0.07	0.03	0.02	0.03
Sample 7	0.02	0.03	0.11	0.05	0.02	0.03
Sample 8	0.02	0.02	0.13	0.06	0.02	0.03
Average shift distance	0.02	0.02	0.10	0.05	0.02	0.02

Value: Mean, Average or Median Transmittance

The transmittance of high-tech glazings in a part of the spectrum can be close to zero. Instead of the Transmittance Ratio that may also be close or equal zero for such glazings (TR is minimum/ maximum wavelength transmittance), we may consider the mean or the average transmittance. We measured the mean transmittance at 580nm, which is the midpoint on the wavelength axis. The average transmittance was calculated as the sum of transmittances for all wavelengths divided by the number of the wavelengths. A good way of prediction of the average is to look at the area below the transmittance curves. On the graphs for 2700, we could expect the lowest average for EC-coloured, then ET-off, EC-midpoint, ET-on, EC-uncoloured and PC. The numbers in the Table V confirm this.

Another interesting measure could be the median transmittance of glazing because it shows the value for the member of the group that is at the middle.

As it was mentioned before, we limit the wavelength interval to 430nm-730nm to avoid measurement errors at both ends of the spectrum interval. In Table V two median transmittances are presented one for the limited range and one for the whole range of the spectrum. In this way a strong impact of the extreme low or high values is avoided, they are never at the middle. The median is remarkable for this purpose, as the errors in readings at the ends will not have any impact.

TABLE V. Mean and average transmittance of glazings in different CCTs.

	ET-on 2700k	ET-off 2700k	EC coloured-2700k	EC midpoint-2700k	EC uncoloured-2700k	PC 2700k
Mean Transmittance	0.47	0.28	0.09	0.35	0.65	0.71
Average Transmittance	0.44	0.27	0.14	0.32	0.60	0.70
Median Transmittance Limited range	0.46	0.27	0.05	0.29	0.59	0.70
Median Transmittance	0.47	0.28	0.11	0.34	0.56	0.71

	ET-on 6500k	ET-off 6500k	EC coloured-6500k	EC midpoint-6500k	EC uncoloured-6500k	PC 6500k
Mean Transmittance	0.47	0.28	0.08	0.35	0.65	0.71
Average Transmittance	0.46	0.27	0.13	0.32	0.59	0.67
Median Transmittance Limited range	0.46	0.27	0.05	0.29	0.59	0.68
Median Transmittance	0.47	0.27	0.08	0.37	0.57	0.69

	ET-on 8000k	ET-off 8000k	EC coloured-8000k	EC midpoint-8000k	EC uncoloured-8000k	PC 8000k
Mean Transmittance	0.47	0.28	0.08	0.35	0.65	0.71
Average Transmittance	0.45	0.26	0.13	0.31	0.58	0.68
Median Transmittance Limited range	0.46	0.27	0.05	0.29	0.59	0.69
Median Transmittance	0.45	0.27	0.05	0.31	0.56	0.68

Looking at the numbers in Table V, we can see quite consistent results suggesting possibility of using any of the three Transmittances. The glazings can be ordered from lowest to highest transmittance; EC-coloured, ET-off, EC-mid, ET-on, EC-uncoloured and PC. The result is valid for each of the transmittances.

A closer examination shows that the largest differences between the three types of transmittance can be found for ECs.

Conclusion

The study pointed at the weaknesses of the colour rendering method for window glazing proposed by Lynes and, after testing different alternative measures, propose to use the following three.

1. Chroma: Gamut area for 8 CIE colour samples on the u' v' graph (as proposed by Lynes)
2. Hue: Average Colour Shift, the distance for the same 8 CIE colour samples represented at the u' v' graph by points "no glazing" and "glazing".

3. Median Transmittance of the glazing

The method comprises usage of spectro-radiometer which enables measurements of spectral colour distribution and u' v' coordinates. A sample of the glazing under consideration and the 8 standard CIE colour samples are needed as well.

In general, practitioners who are responsible for choice of glazings can look at the Chroma, Hue and Value numbers collected with this new method to preliminary evaluate which glazing may have biggest impact on colour distortion. To find out exactly in which direction is the shift for each colour and to know how people will perceive the glazing in the building context, the participation of subjects are still needed. For example, with EC-coloured we could expect that all the colours will change toward blueish but to know precisely how strongly the impact of glazing will be perceived is a question that we cannot answer with this method.

To further investigate the reliability of this method, the results of measurements and calculations should be compared to visual assessments of the same combinations of light, glass and coloured materials.

This study also attempted to answer if the CCT has an impact on the three measures. We found the strong effect of CCT on the position and the size of gamut area, that is on the chroma and on the average colour shift distance, namely hue. However, the impact of CCT on the transmittance, that is value, is minimal.

As explained in results, there is no full consistency when the original Lynes method is used for advanced high-tech glazings. The method is most reliable for traditional glass and with 6500K, as a standard light source.

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Appendices

Appendix 1

Another way to present gamut area is to calculate the 8 Munsell colour samples based on CIE a and b values. Therefore, the gamut area in a and b graph for all glazings in three different CCTs have been presented below.

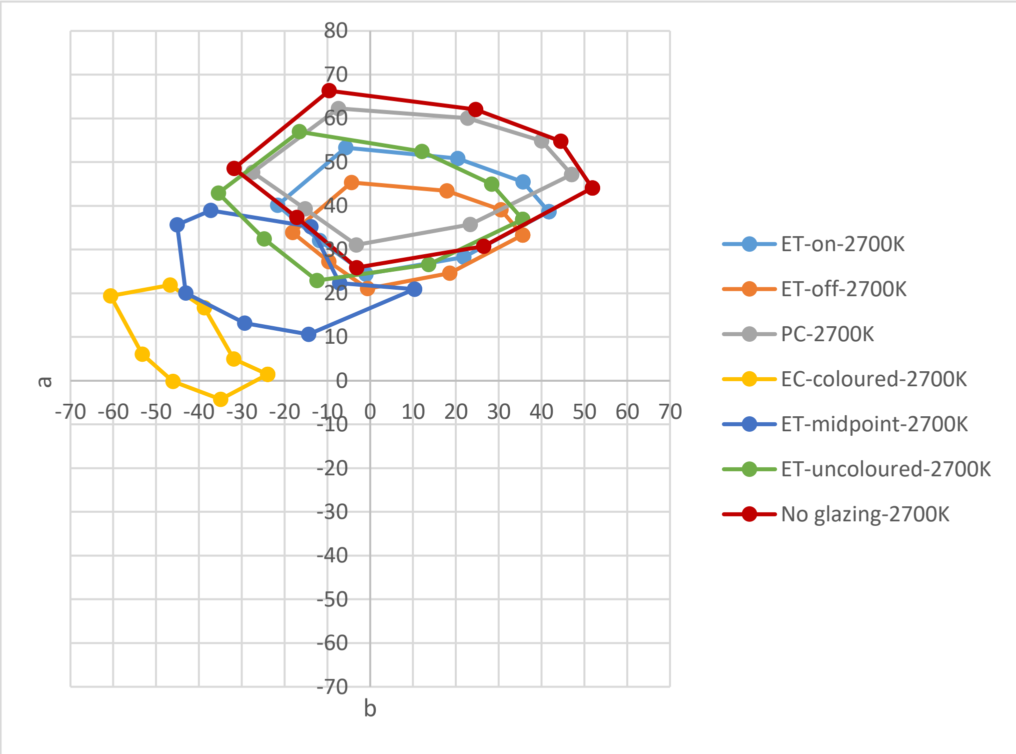

Fig. 9. Gamut area of different glazings in 2700K based on a and b values.

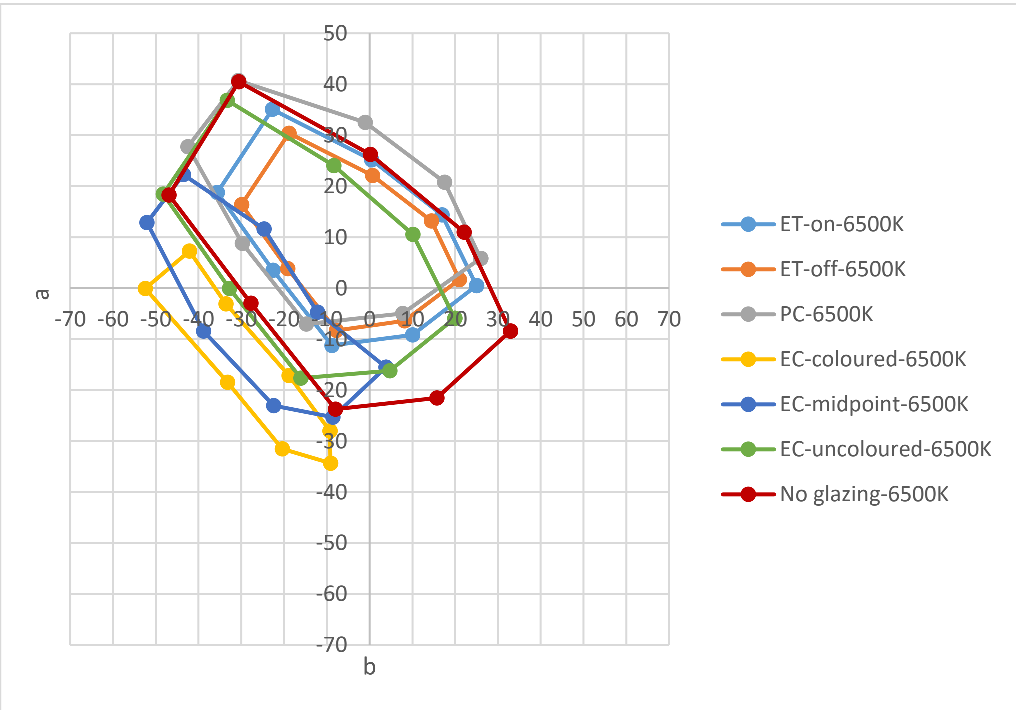

Fig. 10. Gamut area of different glazings in 6500K based on a and b values.

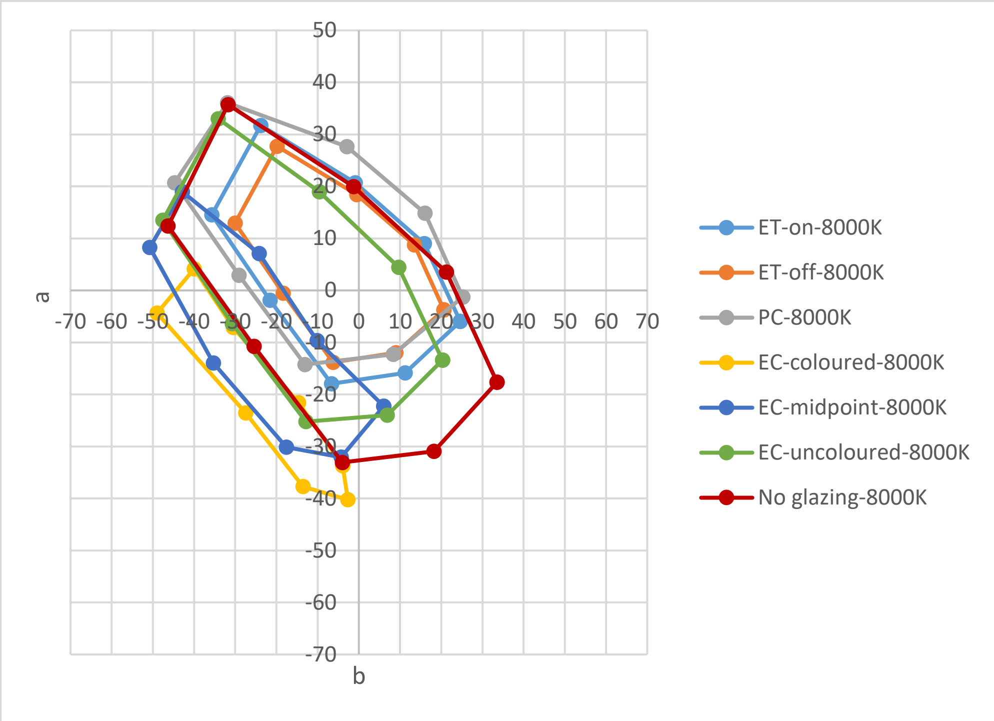

Fig. 11. Gamut area of different glazings in 8000K based on a and b values.

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