The impact of advanced glazing on colour perception

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The aim of this study was to expand the understanding of modern glazing materials' effects on the perception of colours. To this end, the appearance of eight standard CIE test colour samples were evaluated in a sequence of experimental conditions. The experiment was carried out in the Norwegian University of Science and Technology's (NTNU) artificial sky, which mimicked skylight using correlated colour temperatures: 2700K, 6500K and 8000K. Three high-tech glazing types were used in five different transmittance scenarios. The experiment involved 21 participants, who were exposed to a simultaneous matching procedure whereby the test colour samples, arranged in a Mondrian-like pattern, were positioned on the inside and outside of a scale model, representing real rooms scaled 1:5. Colorimetric measurements were taken with a spectroradiometer. ANOVAN was used for statistical analysis. The findings indicated that all of the glazing types studied had a statistically significant impact on the perception of colours. The strongest impact registered was for reddish colours observed through Electrochromic glass in the low-transmittance state (fully coloured).

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Introduction

Developments in building technology, especially regarding building glass, is dictated nowadays by the building sector's need for sustainability, as well as by the user's desire for more daylight, perfect outside views and visual comfort. Glazing technologies and materials are under development as viable replacements for walls to support the fashion of covering the whole building with glass. Electrochromic (EC) glass, electrotopic (ET) glass and photochromic (PC) glass are examples of advanced technologies to achieve a maximal transparency effect, reduce glare and contribute to energy efficiency of the building.

Glazing can be thought of as a light filter. As such, it is especially noticeable if its transmittance is not equal for all wavelengths. In this case, the spectral distribution of the light after passing through it is changed, causing a significant difference in colour perception and thereby affecting the quality of the space. The effects of coated glazing on colour perception have been studied [1-9] for only a few glazing types; more investigation is needed.

For most people, the correct perception of colours of objects and room surfaces is an important part of the quality of life. We may realise how important this is when this possibility is missing, e.g. when familiar objects seen through coloured glasses appear unacquainted. How colours are perceived is determined by numerous factors, including the individual's vision and perception, surroundings, light source, light direction and colour of light. The colour of light produced by a light source determines not only the apparent colour of objects, but also the atmosphere of the space and the perceived quality of the interior.

Previous research

The research conducted by Ne'eman *et al.* [10] shows that acoustics, heating, lighting, ventilation and air conditioning systems, as well as outside views and work space design, are among the most important physical environmental factors affecting worker satisfaction. Daylighting and outside view are the topmost important factors. This may partly explain why highly glazed façades have gained an enormous popularity, particularly façades with shading systems that are difficult to operate and maintain [2, 11]. Their application in office buildings especially increases simultaneous requirements for daylight, outside views, visual comfort, thermal comfort and low-energy consumption, as well as allowing some control of indoor conditions. Window glass is becoming a high-tech product.

New glass-based solutions are being developed to meet the material with advanced coatings which has dynamic transmittance. The spectral distribution of the daylight passing through such glazings can be changed, and our colour perception may be affected accordingly [7]. This could especially be important since, according to Pineault and Dubois [8], 85-90% of a person's time is normally spent inside.

A major challenge connected with the application of all kinds of window coatings is their serious effect on the intensity, spectral distribution and colour of daylight. The light intensity reduction leads to an increase in the usage of artificial lighting, while the change in its spectral power distribution may result in a different perception of the place and its quality (Chain, Dumortier & Fontoynont, 1999, cited in [5]). The colour of light sources can affect how people perceive brightness. The colour of a room's surfaces can change how the ratio of luminance is perceived. Colours make it possible for objects to be highlighted in a situation in which luminance contrasts are too small [9].

The colour of light is different from the colour of the light source. According to Arnkil *et al.* [12], the first one refers to the tone that is generally experienced in a particular space, and by this we can describe how we experience a space. In contrast, the colour of the light source is what you can measure as spectral radiation at a specific point on the light source.

Window industry executives have identified a new generation of dynamic, responsive glazing called 'smart windows'. One example of smart window technology is the Electrochromic (EC) glazing system, which can be reversibly switched from a clear to a transparent, coloured state by means of a small applied voltage, resulting in thermal and optical properties that can be dynamically controlled [13]. Its functional features were first described in 1969 [14]. As typically 30-50% of the total energy consumption in commercial office buildings is used for lighting, such a switchable glazing can help control the daylight admission and, as a result, the heat gain from the sun can be adjusted accordingly.

A recent study [1, 7] concluded that one layer of clear 4mm window glass does not cause a colour shift, and only a very small shift was observed for two layers of clear glass, i.e. glass without any coating. A considerable colour shift was found for three coated glass layers. The study confirmed that such low-energy glazing clearly changes the perception of colours compared to an open window.

Reviewing the literature, a considerable amount of research examining the effects of switchable glazing on visual and thermal comfort was found [6, 13, 15-17], but since it is a new technology, very few researchers have studied its effects on colour perception [18].

There is often confusion as to the differences between natural sciences and technology outcomes and the experiences gained directly through our visual system, and therefore studies involving both methods are needed. Additionally, there has been very little research on the spatial interaction between light and colour so far. More work is especially needed because research has proven that light and colour affect the human organism on both a visual and non-visual basis [19].

In this regard, the different spectral compositions of light are interesting issues, since they have an impact on colour shift and colour perception. Of course, glazing is one of the elements that changes the spectral composition of light.

Aim and scope

The current study was motivated by the following research question:

How is the perception of colour influenced by glazing in combination with light of various correlated colour temperatures (CCT)?

In other words, this study explores how different glazing types can influence the perception of outdoor surface colours that we may see through the glazing. It is an important question since the distortion of colour perception has an impact on the quality of the view through the window.

Since international research suggests that window coatings are likely to affect visual performance, fatigue and discomfort [20-22], this current study of visual perception and coated glass was initiated as part of a larger research project on advanced glazing. The study presented in this article investigates the impact of five coated glazing states on the visual perception of colours using scale models.

Method

The developed method was based partly on Matusiak *et al.* [7] and Arbab and Matusiak [23]. Studies on colour shifts in different situations have also been carried out by Billger [24] for rooms lit with different types of artificial light, by Fridell Anter [25] for façades in different natural viewing situations and by Hårleman [26-27] regarding rooms with daylight from different directions.

Participants

A total of 21 subjects consisting of 6 males and 15 females, between the ages of 22 and 54 years old participated in the study, of which 8 had no expertise or training regarding buildings, glazing and/or lighting. Participants were recruited from administrative staff, students and researchers at the NTNU (through the faculties of architecture and electrical engineering) by e-mail. They represented different nationalities and cultural backgrounds. To ensure that they did not have colour vision impairments, all participants were asked to pass colour vision tests prior to the experiment or right after the experiment.

The conducted tests used the Farnsworth Munsell D15 Colour Vision Test and the Ishihara Test for Colour-Blindness.

Experimental setting

Since it is extremely expensive and time-consuming to change the glazing in a full-scale room, scale-model study has been chosen as a research method. The experimental setting consisted of two equal room models, 60cm × 60cm × 60cm each, representing, for example, a large office room, 3m × 3m × 3m, in the scale 1:5. The relatively large dimensions of the model were chosen to create comfortable observation conditions.

Each model had an opening imitating a window that was 30cm high by 30cm wide and placed 20cm above the floor. In each room, a symbolic door was made in a form of a vertical hole in the side wall, i.e. the wall adjacent to the window wall. Subjects used door openings to look into the model during the experiment (Figure 1). The doors of both models were set side-by-side. This setting enabled subjects to compare rooms easily.

The first model, the one on the right hand side in Figure 1, functioned as a test room with the glass samples successively attached to the window opening and the second one as a reference room, i.e., without any glass in the window opening. The model, including walls, ceiling and floor, was constructed using 5mm medium-density fibreboard (MDF) plates. On the outside, both models were painted black to avoid any impact of the colour of the model on the colour of light in the artificial sky. On the inside, both models were painted with neutral grey S 2500-N. This colour corresponds to the luminous reflection factor of 50%-60%, which is typical for walls in modern interiors, according to European standards [28].

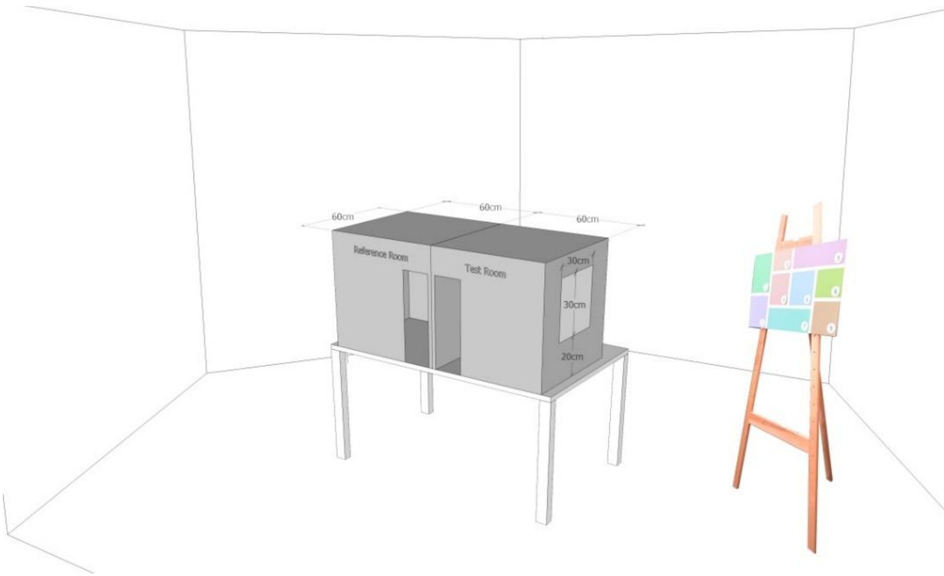


Figure 1: The boxes used in the study.

During experimental sessions, both models, as well as the subject's head, were covered by a black curtain to minimise any unwanted lateral penetration of light from the surroundings.

Independent variables

Two of the glazing samples included in the experiment, electrochromic glass (EC) and electrotopic glass (ET glass), were provided by a GESIMAT manufacture [29] (see Table 1 and Figure 2), and one sample was provided by the Institute for Energy Technology (IFE) – namely photochromic glass (PC) based on photochromic oxygen containing yttrium hydride. The specification of glazing from GESIMAT is presented in Table 1.

Type	Description	U value (W/m²K)	LT (%)		TST (%)	
EC - 2 panes	Electrochromic	5.6	77% fully bleached	8% fully coloured	56% fully bleached	6% fully coloured
ET - 2 panes	Electrotopic	5.6	74% milky	84.7% clear	72% milky	80.8% clear

Table 1: Specification of the glazing types from GESIMAT, collected from GESIMAT.

The photochromic glazing is under development, thus the precise Light Transmittance (LT) and Total Solar Transmittance (TST) data are not available.

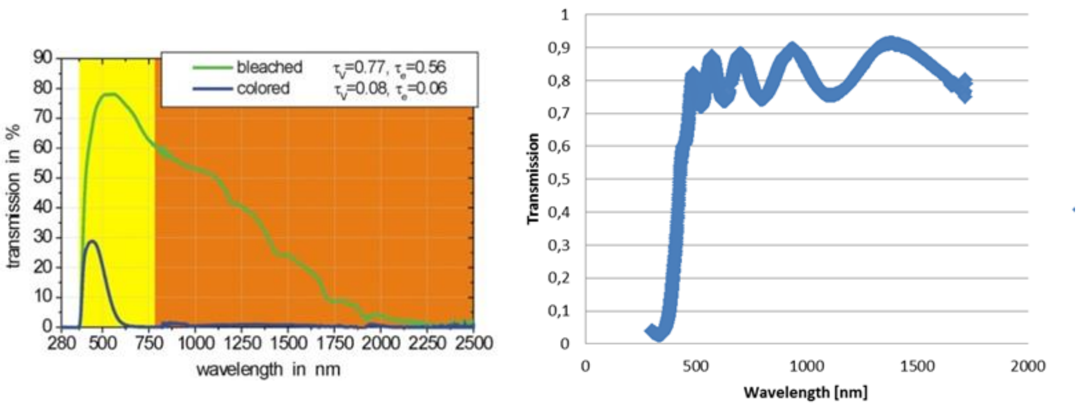


Figure 2: Light transmission data for EC glazing from GESIMAT (left) and for PC glazing from IFE (right).

Since the experiment was carried out to examine the impact of different modern glazing types in combination with different correlated colour temperature (CCT) of exterior light on the visual perception of colours, two stimuli were involved.

Stimuli 1: Correlated Colour temperature of exterior light.

The values chosen for the experiment were 2700K, representing sunrise/sunset sunlight; 6500K, representing a white, overcast sky; and 8000K, representing a clear, blue sky (Figure 3). They were simulated in the artificial sky [30].

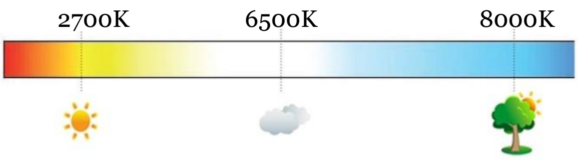


Figure 3: CCT of exterior light.

Stimuli 2: Glazing types.

Three different glazing types were chosen. The EC glazing enabled three options: transparent, coloured and the midpoint of these two states. For the other two glazing types, ET and PC, only the fully transparent states were considered. Five different glazing stimuli were created:

ET Electrotopic (clear)
PC Photochromic
EC-coloured Electrochromic fully coloured
EC-midpoint Electrochromic middle-point
EC-uncoloured Electrochromic fully bleached (transparent)

Dependent variables

Nine colours were chosen for the experiment (see Figure 4 and Table 2). The first eight colours in Table 2 are the original test colour samples taken from the early edition of Munsell (1929). They represent good coverage for hues and were used internationally to evaluate the colour-rendering index of light sources. The evaluation method was proposed by Nickerson in 1960 [31] and was specified later on for CIE 1995.

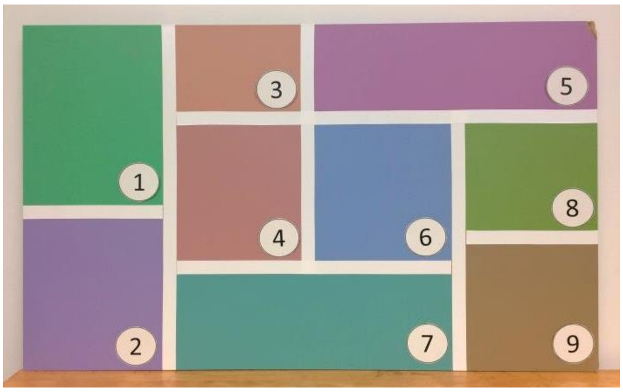


Figure 4: Nine selected colours.

Number (Figure 3)	Munsell Notation	NCS Notation	Appearance Under Daylight
Sample 1	2.5 G 6/6	NCS S 2050-G10Y	Moderate yellowish green
Sample 2	2.5 P 6/8	NCS S 2040-R60B	Light violet
Sample 3*		NCS S 3020-Y50R	Light yellowish red (orange)
Sample 4	7.5 R 6/4	NCS S 3020-Y90R	Light greyish red
Sample 5	10 P 6/8	NCS S 2040-R40B	Light reddish purple
Sample 6	5 PB 6/8	NCS S 2040-R80B	Light blue
Sample 7	10 BG 6/4	NCS S 3030-B50G	Light bluish green
Sample 8	5 GY 6/8	NCS S 2060-G40Y	Strong yellow green
Sample 9	5 Y 6/4	NCS S 4020-Y	Dark greyish yellow

** This colour was added by the authors.*

Table 2: Specification of the glazing types from GESIMAT, collected from GESIMAT.

The early edition was used, since the test colour samples are paler than those presently recommended by International Commission on Illumination (CIE) and are therefore more similar to colours commonly used in interiors. Another reason was that, based on a previous study [7], dark and/or strongly chromatic colours were not affected by changes in the colour of light, so it was wiser to choose lighter colours, as they are easily affected. The last reason for this selection was that it was easier to find Natural Colour System (NCS) notations for the colours in the Munsell atlas. This is essential as we needed to buy paint of each colour to prepare two similar plates, the small one for the reference room and the large one for the exterior of the test room.

Sample 3, was added by the authors. According to the present colour registration in Trondheim [32], this colour is included in the range of typical exterior façade colours of Trondheim, but there was no similar orange-like colour among the eight test colour samples. Even more importantly, this colour is similar to, and therefore may represent the colour of human skin.

Experimental procedure

The experiment was performed at the NTNU's Daylight Laboratory, Department of Architectural Design, Form and Colour; Light & Colour Group. More specifically, it was conducted under an artificial sky (Figure 5), which simulates overcast sky and creates even and diffused illumination in entire room [30, 33]. The artificial sky provides stable experimental conditions independent of the weather and time of day. The ceiling of the artificial sky is made of regularly distributed RGBW LED-chips positioned above two layers of translucent canvas. This enables the generation of light of different correlated colour temperatures (CCTs). 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 around 900 lux at the middle of the reference room floor.

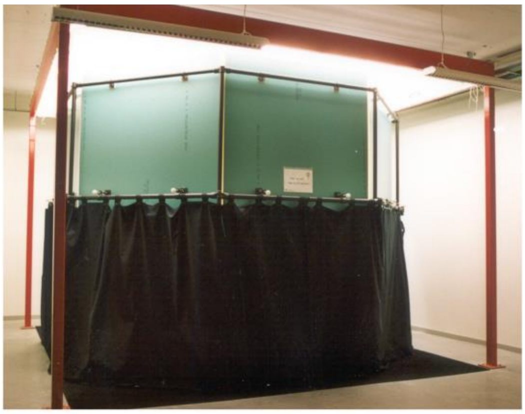


Figure 5: Artificial sky.

The participants were asked to sit on a stool and look into the two scale models through the door openings. The models represented equally illuminated rooms in the scale 1:5 with the same colour temperature of the exterior light. This scale allowed comfortable observation of the interiors and a comparatively large view through the window into the test room.

A previously prepared picture (see Figure 4), made of nine test colour samples assembled in a Mondrian-like design, was placed outside the test room and was visible through the glazing in the test room (Figure 6); a much smaller version of it was placed in the reference room hanging on the wall.

The participants were exposed to a simultaneous matching procedure, i.e. they were asked to shift their focus between both Mondrian-like pictures and observe if, and to what degree, the colour perception of a colour sample selected from the outdoor Mondrian picture matches the corresponding colour sample in the reference room. During the experiment, the glazing samples covering the opening in the test room were successively shifted by the research assistant.

The participants were asked to note their evaluation during the observation time in a questionnaire on a 5-step scale, whereby 1 refers to no difference (perfect match) and 5 to the largest difference experienced in the study.

To avoid possible misunderstandings, the experiment was preceded by a short tutorial where the researchers specified the meaning and provided the definition of the terms used in the questionnaire and explained how to use the scale. The matching procedure, including the tutorial, lasted almost 45 minutes for each subject.

Figure 6: Experimental design used in the study.

During the experiment, three different glazing types were used for the window opening of the test room: EC, ET and PC. Under standard daylight conditions, the sample of 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 LT and is dependent on the voltage adjustment (Figure 7). The ET glass has a milky appearance, and the PC glass has a pale yellowish tint (Figure 8).

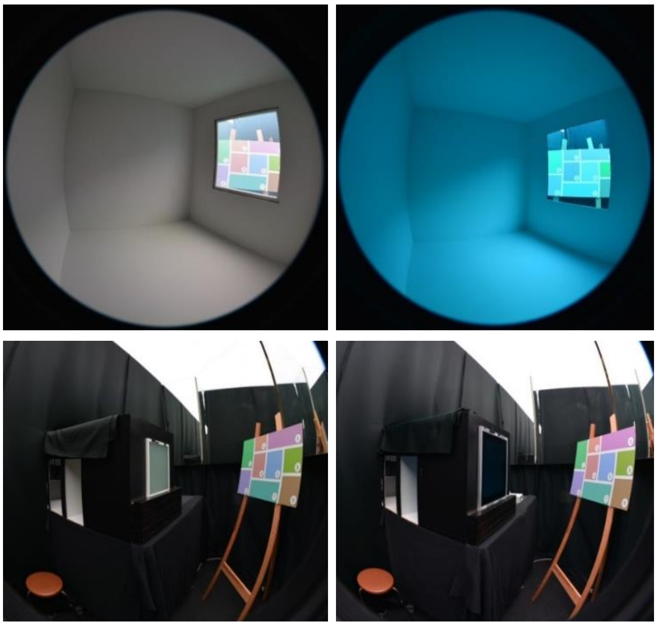


*Figure 7: **Above:** Fish-eye photographs of scale models with ET glass (left) and EC-coloured glass (right). **Below:** Exterior view of scale models with ET glass (left) and EC-coloured glass (right).*

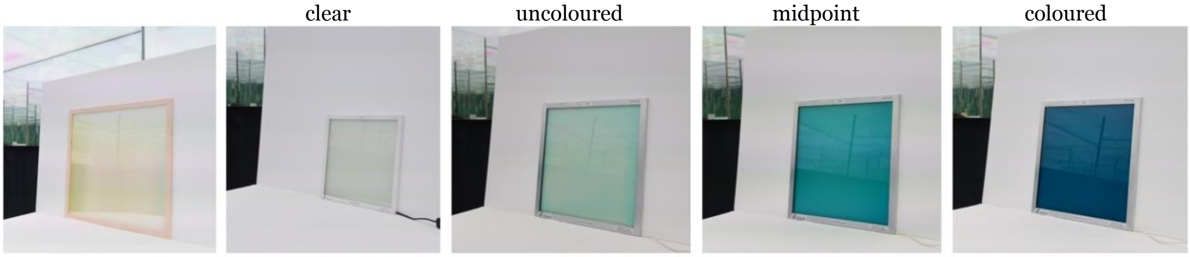


Figure 8: All glazing types used in the study.

Since all the subjects received all stimuli, this experiment had within-subject design. It was a full factorial approach and all possible combinations of independent variables were distributed in a completely randomised order to avoid any influence of succession on the subjective rating.

Light technical measurements

The following measurements were taken prior to the experiment:

- CIE coordinates of all nine colours included in the large Mondrian picture through all glazing alternatives were taken. The values were measured with spectroradiometer SpectraScan PR-655 from the exact eye position of the observing subjects.
- CIE coordinates of all nine colours included in the small picture in the reference room were taken with the same spectroradiometer from the eye position of the observing subjects.
- Interior illuminance in both rooms at the point on the floor at a distance of 18.2cm from the window wall and 28cm from the side wall.

Results and discussion

The changes in colour perception observed by subjects and noted in the questionnaire are shown in Figure 9, which presents the average scores obtained for each glazing in the three CCTs of light. As expected, EC-uncoloured glass showed minimal impact on colour perception for each CCT; the average score was between 1 and 2 (where 1 indicates a perfect match). Interestingly, the PC glass had a similarly low effect, with scores between 1 and 2. This result was unexpected, since the PC glazing has a yellowish tint in daylight. Both glazings had the highest score, indicating the strongest impact, on the pinkish colour (sample 5). This colour was perceived differently from all other glazing samples except for ET glazing.

ET glazing had scores around 2, which was a surprisingly high score. In normal daylight conditions, this glazing appears whitish, something that gives an expectation for a minimal colour change. The green (sample 1), had the highest score, i.e. it was perceived most differently while seen through this glazing.

As expected, the EC-coloured glazing had the highest scores of all. EC glazing has a bluish tint, both in the fully coloured state and in the midpoint state. It had the lowest impact on the bluish and green-bluish hues (samples 6, 7 and 8) and the highest impact on the reddish hues (samples 3, 4 and 5).

In order to understand the effects of CCT on colour perception, the graphs in Figure 10 summarise the results by showing the average score for lights of different CCT. We can observe that EC-coloured glazing and EC-midpoint glazing have the highest scores for most colours, besides samples 6 and 7, in all three CCTs of light. The milky ET glazing scores are nearly as high as the EC-midpoint glazing, but the scores of the EC-midpoint glazing vary much more between colours.

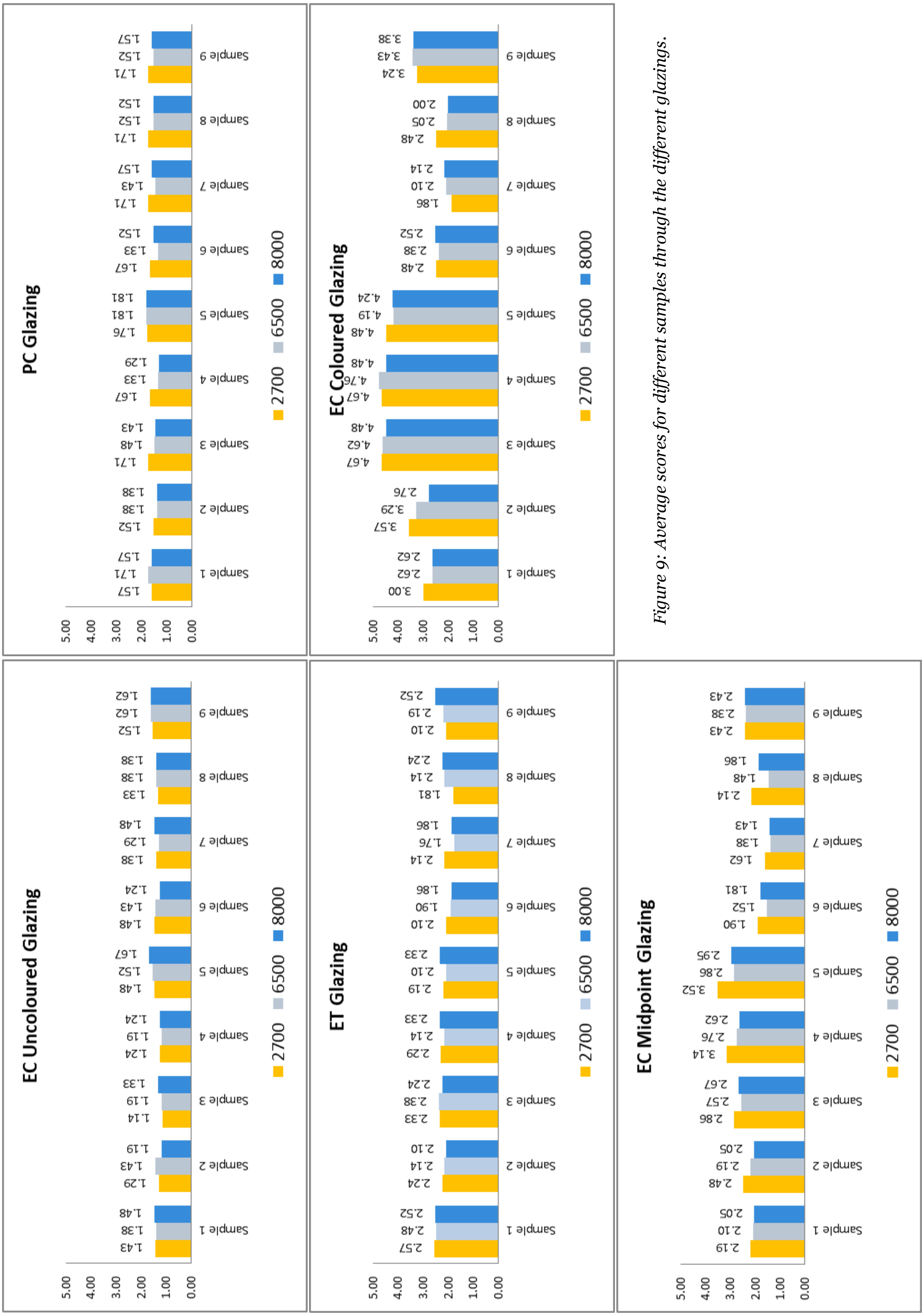


Figure 9: Average scores for different samples through the different glazings.

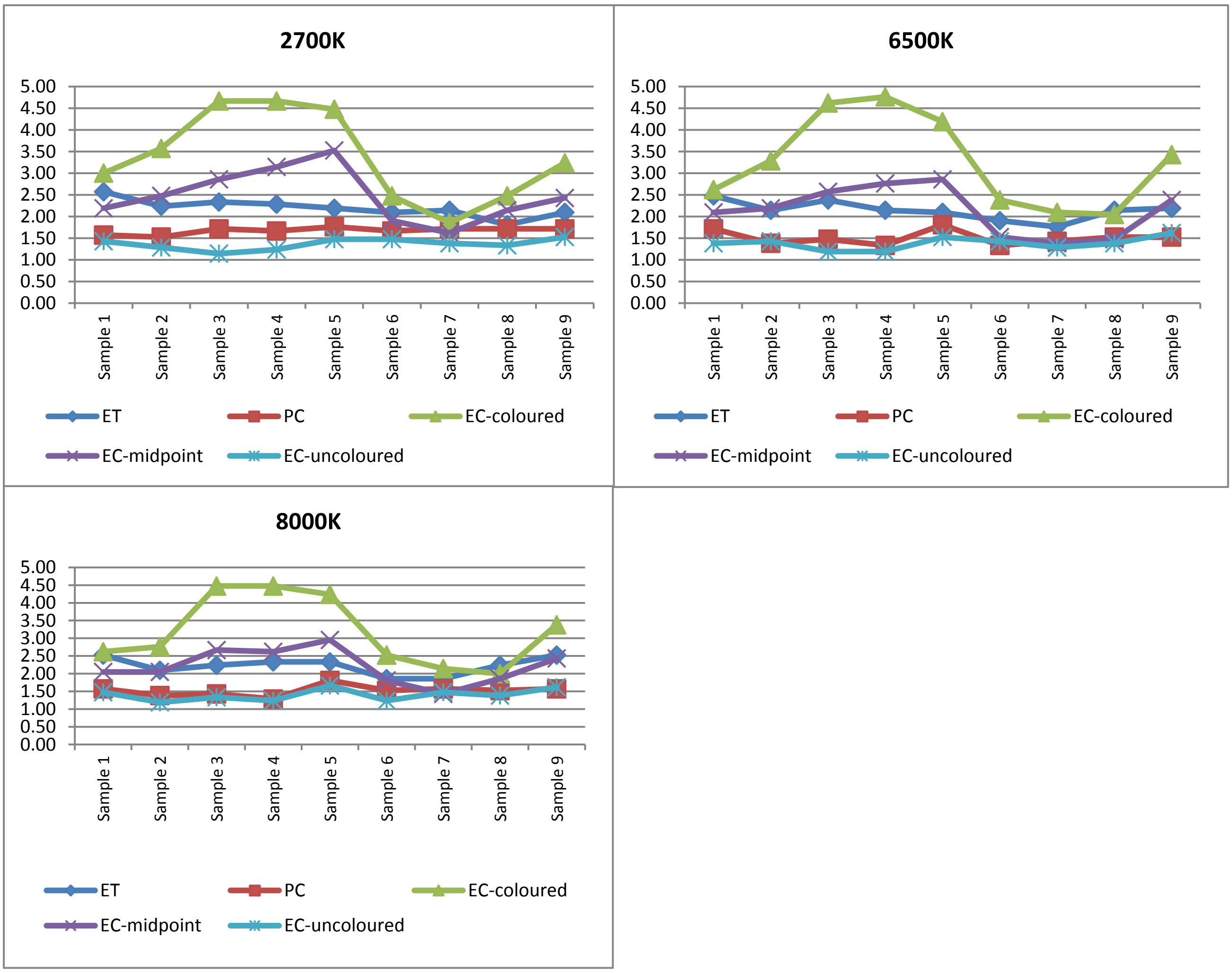


Figure 10: Comparison of glazing with different lights of CCT for all nine samples (the vertical axis represents the average score of all research subjects.

The EC-uncoloured and PC glazings show the same trend in colour perception. In general, this figure shows that even though there are some small differences in the scores, the effect of all CCTs of light on colour perception had almost the same flow and distribution. To test the impact of dependent variables even more precisely, the n-way ANOVA was used.

N-way analysis of variance - ANOVA

In this experiment, two stimuli worked as independent variables: CCT of light (three levels) and the glazing (five levels). To test the effects of multiple factors on colour perception, n-way ANOVA was used for a factorial design. Each observation generated data on all factors. Table 3 shows the result of the analysis of variance for each of the independent variables and their interaction (values of $p<0.05$ indicate statistically significant difference between the perception of colours). The results suggest that all glazing types separately had significant impact on colour perception and CCT of light had impact only on sample 2 (light violet). The interaction of CCT and glazing type was statistically significant for only test colour sample 8, which is a strong yellow green.

Stimuli	Colour samples	df	F	P-value
Glazing	Sample 1-NCS S 2050-G10Y	4	39.88	**0**
	Sample 2-NCS S 2040-R60B	4	68.5	**0**
	Sample 3-NCS S 3020-Y50R	4	191.98	**0**
	Sample 4-NCS S 3020-Y90R	4	202.79	**0**
	Sample 5-NCS S 2040-R40B	4	126.85	**0**
	Sample 6-NCS S 2040-R80B	4	22.08	**0**
	Sample 7-NCS S 3030-B50G	4	10.5	**0**
	Sample 8-NCS S 2060-G40Y	4	13.87	**0**
	Sample 9-NCS S 4020-Y	4	42.39	**0**
CCT	Sample 1-NCS S 2050-G10Y	2	0.7	0.4983
	Sample 2-NCS S 2040-R60B	2	5.19	**0.0061**
	Sample 3-NCS S 3020-Y50R	2	0.69	0.5037
	Sample 4-NCS S 3020-Y90R	2	2.17	0.1159
	Sample 5-NCS S 2040-R40B	2	1.52	0.2197
	Sample 6-NCS S 2040-R80B	2	2.29	0.103
	Sample 7-NCS S 3030-B50G	2	1.31	0.271
	Sample 8-NCS S 2060-G40Y	2	1.7	0.1838
	Sample 9-NCS S 4020-Y	2	0.4	0.6733
CCT*Glazing	Sample 1-NCS S 2050-G10Y	8	0.5	0.8548
	Sample 2-NCS S 2040-R60B	8	1.08	0.3767
	Sample 3-NCS S 3020-Y50R	8	0.47	0.8799
	Sample 4-NCS S 3020-Y90R	8	0.79	0.6116
	Sample 5-NCS S 2040-R40B	8	1.11	0.3547
	Sample 6-NCS S 2040-R80B	8	0.49	0.8634
	Sample 7-NCS S 3030-B50G	8	0.84	0.5695
	Sample 8-NCS S 2060-G40Y	8	2.11	**0.0346**
	Sample 9-NCS S 4020-Y	8	0.4	0.9195

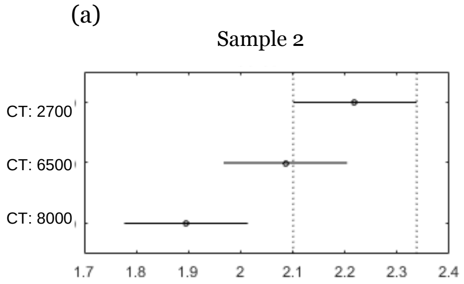
Table 3: Effect of each stimuli and their interaction on the nine colour perceptions.

Figure 11 presents the comparison interval for all colours, which already had significant differences. If there is no overlap between intervals, it means that there are significant differences in colour perception, and the amount of overlap shows how similar their behaviour is and how they impact perception. For example, in Figure 11a, it appears that the impact of CCT of 2700K and 8000K on the perception of sample 2 are significantly different. In Figure 11b, for sample 1, three glazings have population marginal, meaning they are significantly different from ET glazing. These three groups are PC glazing, EC2 (EC-midpoint) glazing and EC3 (EC-uncoloured) glazing.

The same logic is valid for Figure 11c, which shows the effects of interaction of different stimuli on sample 8. In Table 3, we can find that the interaction between CCT and glazing was statistically significant for sample 8. In graph 11c, no group has population marginal means significantly different from CCT of 2700K and ET glazing.

Subsequently, the mean value of scores was calculated for each glazing in combination with different CCT of light and is shown in Table 4, together with calculated standard deviations (SD).

(a)



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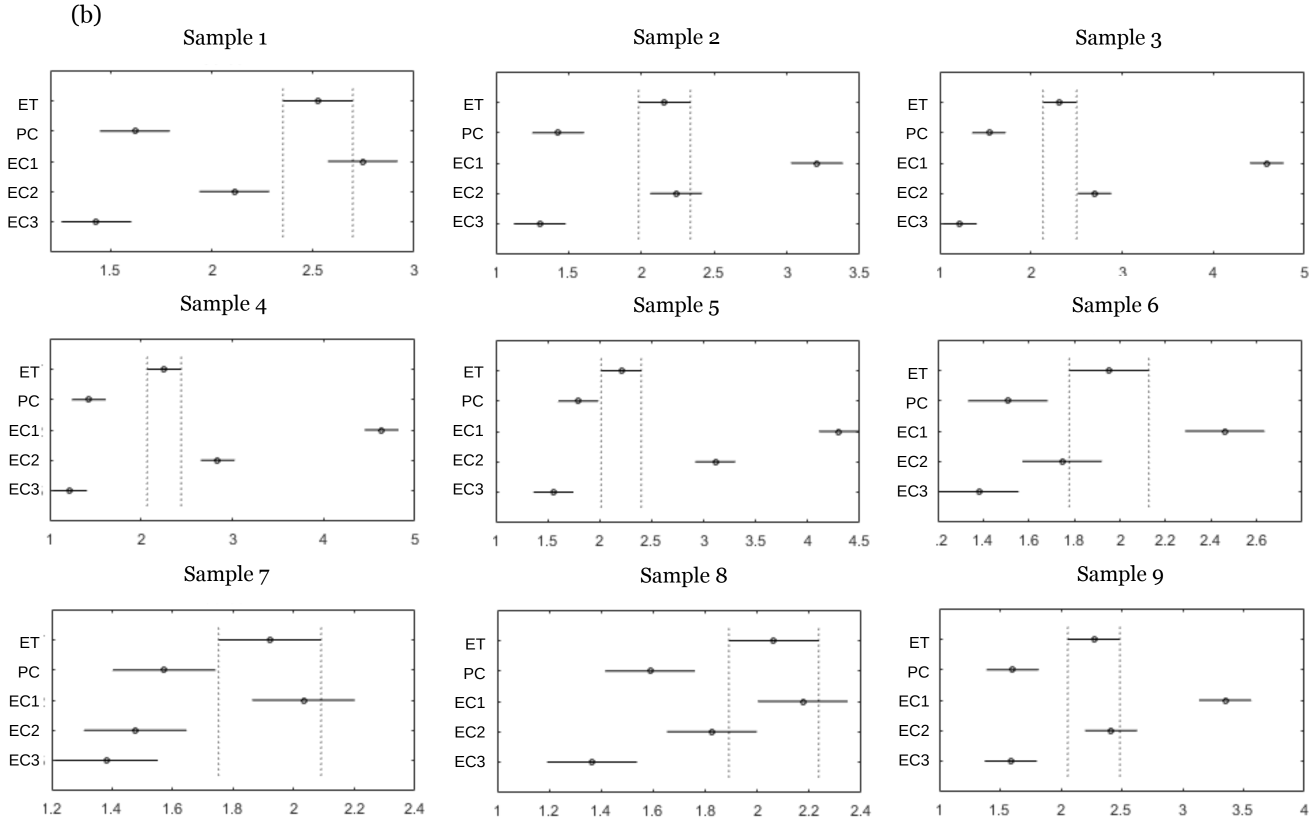

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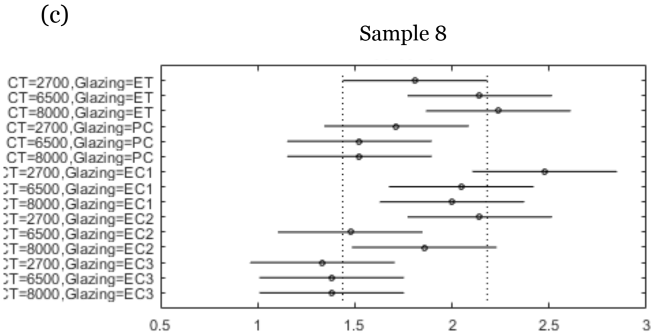

Figure 11: Multi-comparison graphs for colours with p-value<0.05 – (a) effect of CCT on sample 2, (b) effect of glazing on all nine samples and (c) effect of interaction between CT and glazing on sample 8.

Colour samples	Glazing types	2700K	6500K	8000K
Sample 1-NCS S 2050-G10Y	ET	2.571(0.676)	2.476(0.680)	2.524(0.814)
	PC	1.571(0.676)	1.714(0.717)	1.571(0.598)
	EC-coloured	3.000(1.000)	2.619(0.740)	2.619(0.669)
	EC-midpoint	2.190(0.814)	2.095(0.768)	2.048(0.805)
	EC-uncoloured	1.429(0.507)	1.381(0.498)	1.476(0.512)
Sample 2-NCS S 2040-R60B	ET	2.238(0.768)	2.143(0.655)	2.095(0.625)
	PC	1.524(0.680)	1.381(0.590)	1.381(0.498)
	EC-coloured	3.571(1.165)	3.286(0.902)	2.762(0.889)
	EC-midpoint	2.476(0.928)	2.190(0.680)	2.048(0.805)
	EC-uncoloured	1.286(0.463)	1.429(0.507)	1.190(0.402)
Sample 3-NCS S 3020-Y50R	ET	2.333(0.577)	2.381(0.865)	2.238(0.889)
	PC	1.714(0.956)	1.476(0.750)	1.429(0.507)
	EC-coloured	4.667(0.577)	4.619(0.498)	4.476(0.750)
	EC-midpoint	2.857(1.014)	2.571(0.978)	2.667(1.111)
	EC-uncoloured	1.143(0.359)	1.190(0.402)	1.333(0.577)
Sample 4-NCS S 3020-Y90R	ET	2.286(0.644)	2.143(0.854)	2.333(0.966)
	PC	1.667(0.796)	1.333(0.577)	1.286(0.463)
	EC-coloured	4.667(0.658)	4.762(0.436)	4.476(0.680)
	EC-midpoint	3.143(1.062)	2.762(1.136)	2.619(1.203)
	EC-uncoloured	1.238(0.436)	1.190(0.402)	1.238(0.436)
Sample 5-NCS S 2040-R40B	ET	2.190(0.750)	2.095(0.700)	2.333(0.966)
	PC	1.762(0.700)	1.810(0.814)	1.810(0.512)
	EC-coloured	4.476(0.512)	4.190(0.750)	4.238(0.889)
	EC-midpoint	3.524(0.981)	2.857(0.964)	2.952(1.071)
	EC-uncoloured	1.476(0.750)	1.524(0.680)	1.667(0.577)
Sample 6-NCS S 2040-R80B	ET	2.095(0.700)	1.905(0.768)	1.857(0.478)
	PC	1.667(0.483)	1.333(0.577)	1.524(0.680)
	EC-coloured	2.476(0.814)	2.381(0.921)	2.524(1.123)
	EC-midpoint	1.905(0.625)	1.524(0.680)	1.810(0.814)
	EC-uncoloured	1.476(0.680)	1.429(0.676)	1.238(0.436)
Sample 7-NCS S 3030-B50G	ET	2.143(0.727)	1.762(0.700)	1.857(0.478)
	PC	1.714(0.717)	1.429(0.598)	1.571(0.746)
	EC-coloured	1.857(0.655)	2.095(0.889)	2.143(1.153)
	EC-midpoint	1.619(0.590)	1.381(0.498)	1.429(0.676)
	EC-uncoloured	1.381(0.590)	1.286(0.463)	1.476(0.680)
Sample 8-NCS S 2060-G40Y	ET	1.810(0.680)	2.143(1.014)	2.238(0.831)
	PC	1.714(0.644)	1.524(0.680)	1.524(0.602)
	EC-coloured	2.476(0.814)	2.048(0.669)	2.000(0.548)
	EC-midpoint	2.143(0.964)	1.476(0.512)	1.857(0.793)
	EC-uncoloured	1.333(0.577)	1.381(0.498)	1.381(0.590)
Sample 9-NCS S 4020-Y	ET	2.095(0.768)	2.190(1.030)	2.524(0.981)
	PC	1.714(0.644)	1.524(0.680)	1.571(0.746)
	EC-coloured	3.238(1.044)	3.429(1.121)	3.381(1.071)
	EC-midpoint	2.429(0.811)	2.381(0.973)	2.429(0.978)
	EC-uncoloured	1.524(0.750)	1.619(0.740)	1.619(0.669)

Table 4: Mean value and SD (in parentheses) for each factor. Values highlighted in grey are of mean values >3 and in blue are of SD values >1.

On the rating scale, 5 corresponds to a very large difference, 1 to a perfect match and 3 to a middle score; all colours with mean values higher than 3 thus had a very different appearance. See values marked with grey in Table 4.

Besides the mean value, the distribution of responses (SD) is important to consider as a descriptive statistic to find out how differently people answered. The SD values higher than 1.0 are marked with blue; they mostly occurred for EC-coloured or EC-midpoint glazings.

The way in which the perception of colours was changed by the respective glazing was investigated with the help of colorimetric measurements. The colorimetric values of each colour sample (CIE coordinates) were measured for all variants. As an example, we present the results for samples 2, 4 and 8 combined with 2700K (see Figures 12 to 15). In Figure 12, we can observe that the spectral distribution in the reference room (2700K-R box) in comparison to the test room without any glazing (2700K-open) had the same pattern, but the power for the reference room was proportionally smaller. The reason is that the samples in the reference room received indirect light, while the painting outside the model received more intense light from the artificial sky. It may also be observed that the spectral power distribution of EC-coloured glazing (EC1) and of EC-midpoint glazing (EC2) is significantly different from all others, i.e. the levels in the red part of the spectrum are much smaller.

Additionally, it was interesting to find out that the spectral distribution for ET glazing and the test room without glazing followed more or less the same pattern, and their power was even higher than for PC glazing.

Figures 13-15 show that coordinates of EC-coloured and EC-midpoint glazings, in combination with CCT of 2700K, are positioned a large distance to the left (blue and/or green) of all other results. (Note, in Figures13-15, R box refers to the reference room, open refers to the test room without any glazing filter, EC1 refers to EC-coloured glazing, EC2 refers to EC-midpoint glazing and EC3 refers to EC-uncoloured glazing.) This may be explained by the fact that light transmission of EC-coloured glazing is much higher for short wavelengths (see Figure 2). It is worth noting that in Figure 15, sample 8, which is the strong yellow green colour, most of the points are in the orange area of CIE, while the perceived colour is green. This may be explained by the effect of the exterior light, which is yellowish, or 2700K.

Colorimetric measurements are presented only for three colours, as examples; similar measurements were done for all alternatives and are available from the authors upon request.

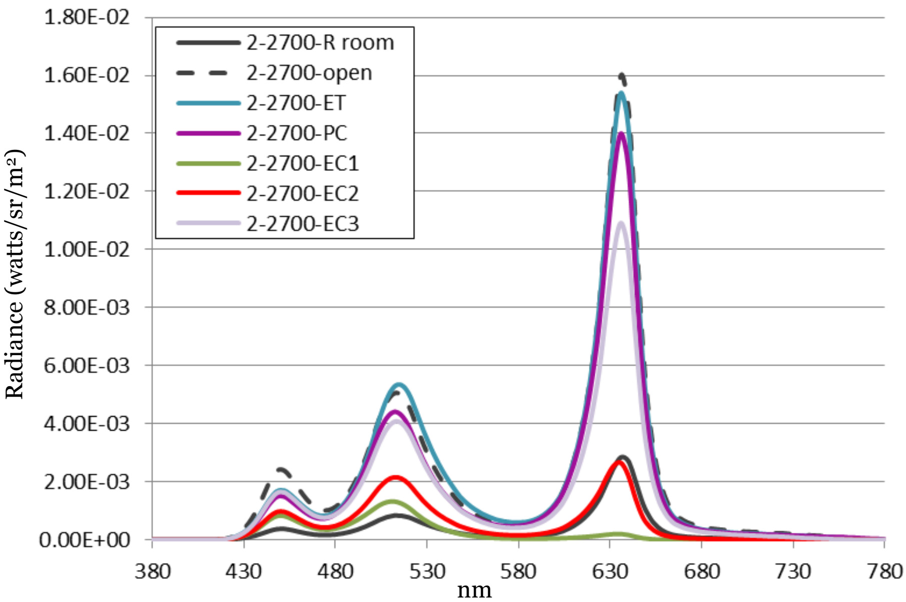

Figure 12: Comparison of spectral power distribution for sample 2 for different glazings in 2700K.

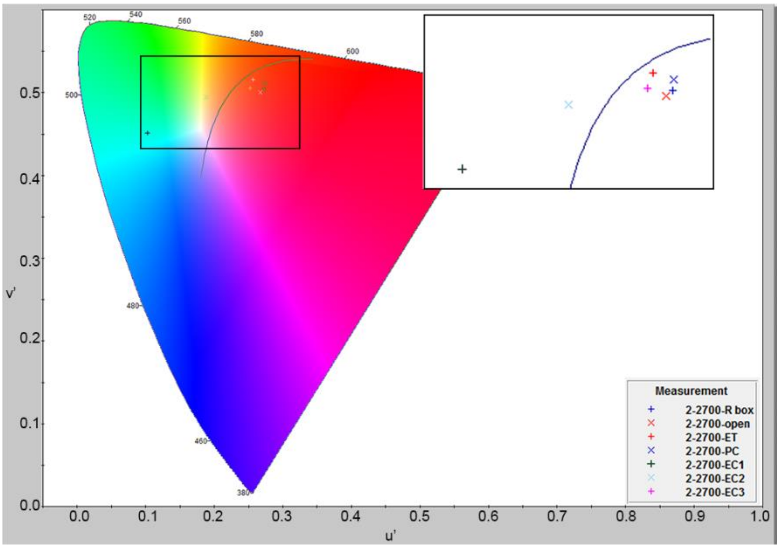

Figure 13: CIE graph for sample 2 with different glazings under 2700K.

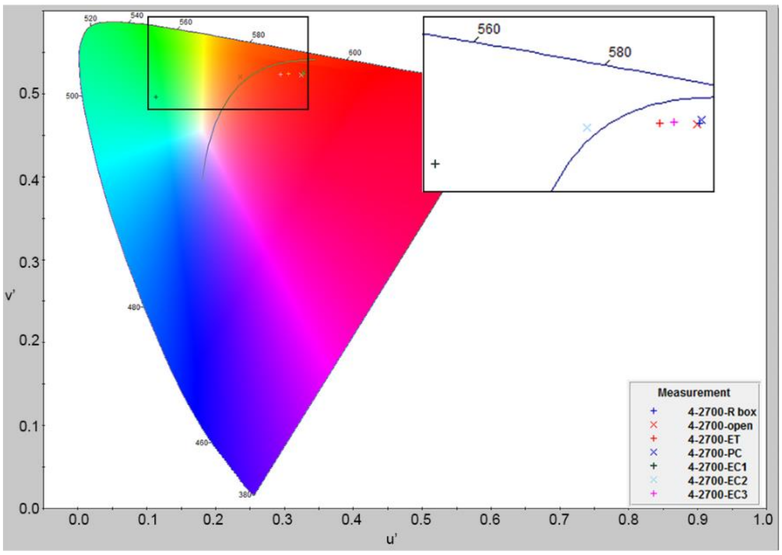

Figure 14: CIE graph for sample 4 with different glazings under 2700K.

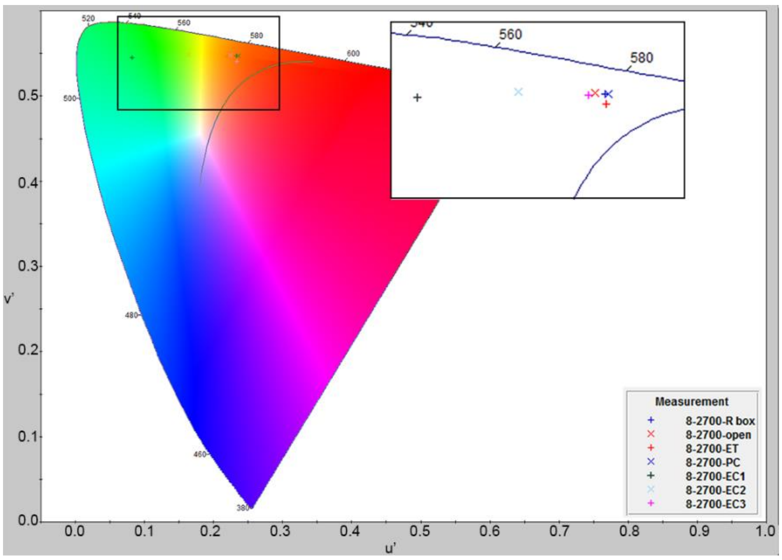

Figure 15: CIE graph for sample 8 with different glazings under 2700K.

Conclusions

As stated in the introduction, the aim of the study was to answer the question: How is the perception of colour influenced by glazing in combination with light of various CCTs? In this study, three different glazings were used to create five stimuli, which were evaluated by 21 participants in combination with light of three different CCTs. This experiment was done in specific laboratory settings; therefore, these results are fully valid for situations with diffuse daylight with similar light levels.

The results suggest that all glazing types separately had a significant impact on colour perception, while the strongest impact registered was for EC glazing. The CCT of the light had an impact on only sample 2 (light violet). The interaction between CCT and glazing types was statistically significant only for one colour sample, colour 8, which is the strong yellow green.

Based on the results presented above, we may hypothesize that the human visual system's ability to adapt to the prevailing illumination is good enough that it may explain why the CCT of exterior light has so little impact on colour perception, with the visual system adapting almost perfectly to the colour of light in the reference room.

The conditions for adaptation were very good. The relation between luminance on the small and large Mondrian picture was not higher than 1:10, and the luminance level (20–200 cd/m2) was high enough to enable high threshold sensitivity [34]. This means that the needed adaptation time was not higher than about 0.1 seconds. Additionally, the subjects were not distracted by unwanted elements in the visual field, since they looked into empty model rooms. Even the nominal colour of all surfaces in both rooms was equal. The shift of gaze from one Mondrian picture to another was done without visual distraction.

Regarding the CIE graph, the results indicate that EC-coloured glazing caused shifts towards blue for samples 2 and 4, while it shifted towards green for sample 8. In other words, CCTs of 2700K had an impact on the perception of sample 8 in combination with bluish glass. Generally, we can conclude that in the present study, the colours with a reddish tint were more sensitive to changes in their perceived colour.

Finally, it is worth mentioning that PC and EC totally transparent glazing samples produced the smallest differences in the perception of colours. In the case of PC glazing, this can be explained by the constant transmittance of this glazing for most wavelengths (see Figure 2).

Furthermore, it can be mentioned that since the EC-coloured glazing transmits the short-wavelength part of the spectrum (blue region) of visible light in much higher degree than the long-wavelength (see Figure 2), it added a blue shade to the interior of the test room.

The practice of building large glass façades with poor shadings is widespread. These façades would be more reasonable to construct with exterior shading systems, but such shading systems are very expensive, obstruct the view out of the window and need extensive maintenance. A smart glazing that can control transmittance of solar radiation could possibly solve the problem. However, for the application of advanced glazing in real buildings, it is important to consider to what extent colours perceived through the glazing may be distorted. To this end, this experimental setting of this study should be compared to the realm of a real office building where the adaptation conditions would be a little different. In any case, we believe that this study could give awareness to building owners and users and enable them to make an optimal glazing choice.

This experiment is part of a larger research project aiming to evaluate colour shift and colour rendering in differently coloured physical spaces equipped with different glazing types and illuminated by light of different CCTs.

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