Proceedings

EXPERIENCING LIGHT 2009

International Conference on the Effects of Light on Wellbeing

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Keynotes and selected full papers
Eindhoven University of Technology,
Eindhoven, the Netherlands, 26-27 October 2009

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ISBN: 978-90-386-2053-4

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Reference specification:
Name Author(s), "Title of the Article", In: Proceedings of EXPERIENCING LIGHT 2009 International Conference on the Effects of Light on Wellbeing (Eds. Y.A.W. de Kort, W.A. IJsselsteijn, I.M.L.C. Vogels, M.P.J. Aarts, A.D. Tenner, and K.C.H.J. Smolders), 2009, pp. X (startpage) – Y (endpage).

Effect of Glazing Types on Daylight Quality in Interiors: Conclusions from Three Scale Model Studies

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ABSTRACT
This paper reports the results of three scale model studies about the effect of glazing types on daylight quality in interiors. This paper emphasizes on the constancy in the results of the three studies, which indicate that glazing types have a statistically significant effect on the perception of brightness, naturalness, beauty-pleasantness and precision. Glazing types with higher visual transmittance yield brighter, more natural, beautiful-pleasant and sharp views of the interior. The three studies also indicate that the glazing visual transmittance is negatively correlated with glare comfort: higher transmittance glazing types result in more glaring views of the interior. Finally, the three studies show that the glazing type has no effect on the perception of shadows.

Keywords
Daylight quality, windows, glazing, visual transmittance, glare, tinted glazing, reflective coating, low-e coating.

INTRODUCTION
Fifteen generations ago, most of our ancestors spent the majority of their waking hours outdoors and buildings primarily provided only shelter and security during the hours of darkness [1]. Today, people spend nearly 85-90% of their time indoors [2] and the interior of buildings is the main scenery supporting daily lives.

In interior environments, a contact with the exterior, natural world is of prime importance, and this contact is made possible by the window glazing material. Window glazing is the primary filter of daylight in a building and the main interface between the interior and exterior worlds. A large field study carried out in Denmark [3], indicated that "being able to see outside" was the most important benefit of windows for office workers.

Recently, the need for energy conservation in buildings has spurred innovations in window technologies. The use of coated and tinted glazing is one of the strategies that can improve energy efficiency of buildings [4]. Window coatings and tints alter the quantity and spectral quality of daylight, which may have an effect on user satisfaction, daylight utilization and even photobiological responses in humans. According to Chain et al. [5], glazing types which are thermally efficient are rarely evaluated according to their visual impact: grey or green tints can lead to the impression of being sick. Glazing types which are thermally efficient may also produce a colour distortion of the natural light spectrum which may affect pupillary reflex, alertness, mood and performance in fully daylit buildings. A recent discovery [6, 7] about circadian retinal photoreceptors (photosensitive retinal ganglion cells: ipRGCs) suggests that short-wavelength (blue) light is associated with the good functioning of neuro-endocrinal systems and circadian cycles, with evidence for the involvement of these ipRGCs cells in pupillary reflex, alertness, mood and performance [8].

This paper presents the results of three studies of the effect of glazing types on daylight quality in interiors. The three studies were achieved in scale models under artificial as well as natural skies in Denmark and Canada, using a within-subject experimental design. The objective of the artificial and natural sky studies was to examine the relationship between the optical properties and colour coordinates of different glazing types and various qualitative factors related to daylight quality: brightness, glare, naturalness, beauty and pleasantness, precision, light distribution and shadows. This paper emphasizes on the constancy in the results obtained in the three studies.

LITERATURE REVIEW
There are a large number of researches about artificial light sources in terms of spectral characterization [9] and effects on occupant satisfaction, performance, mood [e.g. 10, 11]. Previous research on electric lighting strongly suggests that both brightness *and* spectral distribution are contributing to the visual experience, to perception and performance in a space. One study [12] indicated a relationship between desktop daylight illuminance and the preferred colour

temperature: low daylight levels (500 lux) cause preferred CCT around 3300 °K, while higher daylight levels (1500 lux) result in increased CCT to 4300 °K. This is in agreement with the Curve of Amenity for artificial lighting (Kruithof Diagram [13]), which shows that the higher the overall lighting level, the higher its colour temperature should be. Conversely, high colour temperatures under low luminance tend to make the space look cold and dark, while low colour temperatures under high lighting level tend to make the space look artificial [14]. In relation with this research on electric lighting, older research on glazing types [15, 16] indicated that solar bronze glass (warm shift) had been found to give an enhanced perception of the same transmittance while solextra glass had been found to give a reduced perception of brightness relative to a spectrally neutral glass of the same transmittance.

Overall, research specifically focused on the effect of window glazing type on daylight quality is scarce, dated or confounding:

In a recent doctoral thesis [17], computer simulations with *Lightscape* were used to assess the effect of two tinted glazing (bronze and green) on indoor correlated colour temperature (CCT). The study showed that tinted glazing greatly affected the interior average CCT but the author concluded that this effect would not be important since the occupant would be chromatically adapted to the scene. One research [18], which examined the attitudes towards the use of heat rejecting or low-light-transmission glasses in high-rise office buildings, supports this statement. This research concluded that tinted glass had little or no effect on the visual environment.

On the contrary, another study [19] indicated that people were clearly able to distinguish between a standard three-pane clear glass window and a super insulated four-pane window (green shift) in a full-scale laboratory experiment where two identical rooms furnished alternately as office and bedroom were evaluated by 95 subjects using a between-subject, random order experimental design. The room with the four-pane window felt more enclosed, and the daylight felt less strong and clear. The four-pane window also affected colour perception, making the colours of the room and of the view look drabber.

In a series of experimental model studies [20], where room and window size, room décor, illuminance (total incident light) level and light colour were manipulated, the responses of office staff to the appearances of windows with variable glazing transmission characteristics were analysed. The study showed that the acceptability of an office can be increased by the use of reduced transmittance glazing, and that generally, there is a preference for a colour effect that gives a warm shift, but the author concluded that these preferences can be influenced by room and window sizes and by room décor.

In another experimental study [21] about the minimum acceptable transmittance of glazing where three types of glass (spectrally neutral, brightness enhancing solar bronze and brightness reducing solextra) were tested under a range of conditions by subjects viewing a real sky and scenery through the window of a model office, the authors concluded that the minimum acceptable glazing visual transmittance lied in the range 25-38%. The study also pointed no statistically significant difference between the spectrally neutral glass and the brightness reducing solextra glass regarding the minimum acceptable transmittance.

In summary, this literature review yields the following conclusions:

- Two studies [17, 18] suggest that tinted glazing has no effect on the visual environment due to adaptation of the visual system.
- In contradiction, another study [19] indicates that the glazing type has a significant effect on the perception of the visual environment: a four-pane window with two coatings (green shift) makes the room feel more enclosed and gives an appearance of weaker daylight and drabber colours.
- On the other hand, Cuttle [20] found that the acceptability of an office can be increased by the use of reduced transmittance glazing. Studies by Boyce et al. [21] even concluded that quite low glazing visual transmittance is acceptable.
- Cuttle [20] found a preference for a warm shift, a result which seems to agree with the results of Boyce et al. [15, 16] who found that a brightness enhancing solar bronze glazing is perceived to result in a brighter room environment than the spectrally neutral glazing. This result does not necessarily disagree with Bülow-Hübe's experiment [19] where a window with a green shift, (which is opposite to a warm shift) was studied.

METHOD

This paper presents the results of three separate scale model studies where the effect of window glazing types on daylight quality in interiors was investigated. The first study [22] was carried out at the Danish Building Research Institute in Hørsholm, Denmark (lat. 55,4° N) and the second [23] and third [24] studies were achieved at the École d'Architecture of Université Laval, Quebec City, Canada (lat. 46,5° N).

Scale models

The three studies were achieved using scale models of a regular rectangular room. The scales used were 1: 7,5 in the first study and 1:6 in the second and third studies.

Previous research [25, 26] has shown that scale model studies are a quick and reliable method provided that the scale is not too small and that great care is taken to represent the details and décor of the real environment.

Room geometries and furniture

In all three studies, a regular rectangular room with a single window was simulated. In the first study, no specific décor was represented; the room only contained a scaled table and some objects that research participants could observe (Fig. 1). In the second and third studies, the room was fully furnished as a typical residential living room with sofa, table, book shelf, curtains, etc. (Fig. 2).

In the first (Danish) study, paired comparisons were used. Athough all efforts were made to make the two rooms look exactly the same, some unintentional differences between the Test and Reference rooms did appear, which may have introduced some bias in this first study. The two identical scale models with interior dimensions of 3,5 * 6,0 * 3,0 m^3 (width * depth * height, full-scale) were built and placed next to one another. The scale models thus measured 0,47 * 0,8 * 0,4 m^3 (w * d * h). Each scale model had a unique opening for the window measuring 0,17 * 0,24 m^2 (height * width) placed 0,18 m above the floor (window full-scale dimensions were 1,2 * 1,8 m^2, located 1,35 m above the floor). Opposite the window, a small horizontal hole allowed the research participants to make their observations. The research participants thus looked straight ahead towards the window when making their assessments. The interior of both scale models was painted a diffuse white colour (refl. > 85%) and furnished with a brown, scaled table, a silver key (on the table), a piece of broccoli, a baby tomato, a pine cone, a staple remover and a yellow tennis ball (Fig. 1). There was no electric lighting in the scaled rooms.

In the second and third studies, paired comparisons were abandoned and thus a single scale model (1:6) was built of a typical living room measuring 0,92 m by 0,66 m (width x depth, full scale: 5,5 m x 3,9 m) with a single, centrally placed window measuring 0,41 m by 0,22 m (width x height, full scale: 2,4 m x 1,3 m), with window sill height at 0,14 m (full scale: 0,8 m) from the floor (Fig. 2). The scale selected for the study allowed a detailed and faithful representation of furniture, interior finishes of various colours and textures. The walls were painted a light beige (70% reflectance), the ceiling was white (74% reflectance) and the floor was covered with a veneer similar to a wooden floor (52% reflectance). There was no electric lighting in the scaled room. The research participants observed the room through an opened door on the lateral wall of the model.

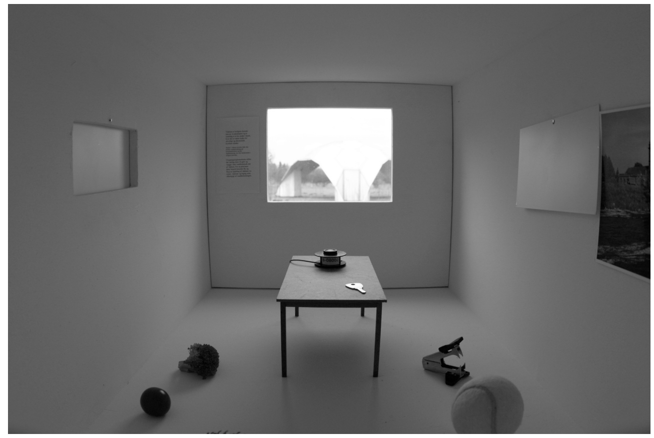

Fig. 1 Photograph showing the interior of the scaled room in the first (Danish) study.

Fig. 2 Photograph showing the interior of the scaled room in the second and third (Canadian) studies.

Orientation, sky conditions and view out

In the first (Danish) study, both scale models (Reference and Test rooms) were placed behind the window of an empty office room at the Danish Building Research Institute (SBI), Hørsholm, Denmark. This window, which had a north orientation, was replaced by a single, iron free window pane (daylight transmittance = 91%). This study was entirely achieved during January and February 2002, between 09.30 and 15.00 hours, under overcast sky conditions, in order to make sure that exterior daylight conditions were as constant as possible. The window allowed a view of a white sculpture placed on a grass lawn and surrounded by trees and shrubs (Fig. 1).

In the second study, the experiments took place during May 2007, between 10.00 and 19.00 hours. The scale model was placed next to the artificial sky of the École d'Architecture of Université Laval, Québec, Canada. The light coming from the artificial sky penetrated through the window opening of the scale model. This artificial sky consists of a mirror box measuring 1,22 m x 1,22 m x 1,22 m, which has the distribution of a typical CIE overcast sky. The illumination is achieved with "daylight" fluorescent tubes placed above a diffuser (acrylic white sheet). In this second experiment, the visible part of the artificial sky was simulated as a typical landscape of a suburb using small plants and shrubs (Fig. 3).

Fig. 3 Photograph showing the view of the interior of the room towards the window in the second study.

Fig. 4 Photograph showing the view of the interior of the room towards the window in the third study.

In the third study, the same scale model (as in the second study) was moved so as to expose the window to the natural climate. The window of the scale model was oriented facing the south-east direction. The experiments took place during October 2007 between 12.00 and 16.00 hours to avoid the presence of any direct sunlight penetration due to the south-east orientation of the window. The position of the observation hole was the same as in the second study (i.e. via a lateral door). The exterior scene viewed through the window of the scale model consisted of one of Quebec City's most beautiful views of a park overlooking St-Lawrence River (Fig. 4).

Glazing samples tested

In the first (Danish) study, paired comparisons were used with one Reference and one Test room. The glazing samples tested (Table 1) were selected because they are widely used in Denmark according to the glazing manufacturer who provided the samples and thermal-optical data. The Reference glazing (Ref_{77}) was selected because it was the most neutral in colour and had a high transmittance.

In the second and third studies, paired comparisons were abandoned and thus a single scale model was used throughout. The window opening of the scale model was alternately covered by different glazing samples presented in random order during the experiments. A set of glazing samples commonly used in residential buildings was chosen from a stock of samples provided by local glazing manufacturers. A total of seven glazing types were selected based on their optical properties (Table 1). Glazing type A_{83} was selected because it was an iron-free combination. The other glazing types were selected because of the availability of measured optical data.

In the third study, only five glazing samples were selected from the second study (Table 1, see *). Glazing B_{82} was selected because it is one of the most common glazing assemblies in older buildings. Apart from glazing G_{38}, all glazing samples looked almost the same in all three studies; the differences between the samples were subtle and the research assistant needed to look at the code written on the side of each sample to be able to identify it.

In the second and third studies, the effect of glazing type on the transmitted light colour was determined using a digital photographic image technique [see 24], which consisted of subtracting colours from two digital images: a reference- and a test-photo. Since colour temperature of daylight varies according to sky type and time of day, four series of photos were taken, each one corresponding to a sky type: (1) clear sky, (2) partly sunny, (3) partly cloudy and (4) overcast. The colour subtractions were then performed using *Photoshop CS2* according to the three channels (red, green and blue) of the RGB model. The RGB data were then converted to CIE-L*a*b coordinates using a colour calculator (see Fig. 5). The more salient points of this analysis are summarized below:

- Glazing A_{83} yields a negligible green shift and small yellow shift;
- Glazing B_{82} is significantly greener and slightly yellower than A_{83};
- Glazing types C_{74} and F_{65} exhibit colour shifts in two directions (similar values for both axes);
- Glazing G_{38} yields the strongest green shift but the weakest yellow shift amongst all glazing types studied. A blue shift appears under clear sky conditions.

Table 1 Glazing samples tested in the three studies with their thermal and optical properties.

	Name	Description	U-value cog	Daylight					Solar
				Tr	CIE*Lab		Rext	Rint	Tr
			(W/m^2°C)	(%)	a	b	(%)	(%)	(%)
Study 1 (Denmark)	A_{79}	1 cl. + 1cl. low-e (s)	1.12	79	-2.8	2.3	11	12	63
	B_{76}	1 cl. + 1 cl. low-e (h)	1.45	76	-2.7	3.2	17	16	72
	C_{70}	1cl. low-e (s) + 1 cl. + 1cl. low-e (s)	0.46	70	-4.3	4.1	14	14	46
	D_{66}	1 solar low-e + 1 cl.	1.12	66	-7.0	8.8	20	18	42
	E_{50}	1 solar low-e + 1 cl.	1.04	50	-8.9	3.2	18	15	26
	Ref_{77}	1 ironfree + 1 cl. low-e (h)	1.45	77	-1.8	2.2	17	16	79
Study 2 and 3* (Canada)	A_{83}*	1 iron-free + 1 iron-free	n/a	83	n/a	n/a	7	7	79
	B_{82}*	1 cl. + 1 cl.	n/a	82	n/a	n/a	n/a	n/a	n/a
	C_{74}*	1 cl. + 1 low-e (Ti-PS)	n/a	74	n/a	n/a	11	12	46
	D_{73}	1 cl. + 1 low-e (h)	n/a	73	n/a	n/a	16	15	54
	E_{68}	1 Ti-AC 40 + 1 cl.	n/a	68	n/a	n/a	9	11	34
	F_{65}*	1 Ti-AC 36 + 1 cl.	n/a	65	n/a	n/a	10	10	31
	G_{38}*	1 Ti-AC 23 + 1 cl.	n/a	38	n/a	n/a	13	11	18

n/a= data not available

Research participants

In all three studies, the research participants were recruited by email. In the first study, the participants were mainly from the administrative staff of the Danish Building Research Institute while in the second and third studies, the participants were mainly students from the school of architecture. The participants were not paid to take part in the experiments and they were not aware of the real goal of the research. The participants over 45 years old or with important visual problems, as well as those with knowledge about windows or glazing were excluded from the study. A total of 18 participants (9 males) took part in the first study, 15 (7 males) in the second study and 30 (16 males) in the third study.

Questionnaire

In the first study, a two-page questionnaire (see [22]) which used semantic, seven-grade, bipolar scales was developed to cover most of the following dimensions of light: brightness, distribution, shadows, reflexes, glare, light colour and colours. These factors were identified in the literature as the most important for the description of light quality in interior spaces [27]. The questionnaire was adapted from Bülow-Hübe [19] and focused more specifically on daylight intensity and colour, colours in the interior and in the view out, glare, shadows and textures.

After the first study, a principal component analysis (PCA) was carried on the 27 questions of the questionnaire. Using Jolliffe's criteria [28] which consists of retaining only the factors with associated eigenvalue larger than 0,70, the PCA retained seven (F1-F7) factors explaining 79,5% of the variance in the scores. The number of factors was also confirmed by the scree plot test [29]. The results of the PCA (with a Varimax rotation) and the interpretation of each factor retained is presented in detail in the relevant paper [22].

The questionnaire for the second and third studies was developed from the first questionnaire, taking into consideration the seven factors identified previously: (F1) brightness, (F2) glare comfort, (F3) naturalness, (F4) beauty pleasantness, (F5) precision, (F6) distribution and (F7) shadows. The factor "colour temperature" (from the first study) was abandoned since the research participants did not know what it referred to and we introduced a factor called "distribution", since this parameter is often discussed in lighting design and research. The other qualitative factors were used when designing the questionnaire and throughout the statistical analysis of the results. The questionnaire, which was identical for the second and third study, contained a total of seven questions (14 sub questions) and also used seven-grade bipolar scales (see Table 2).

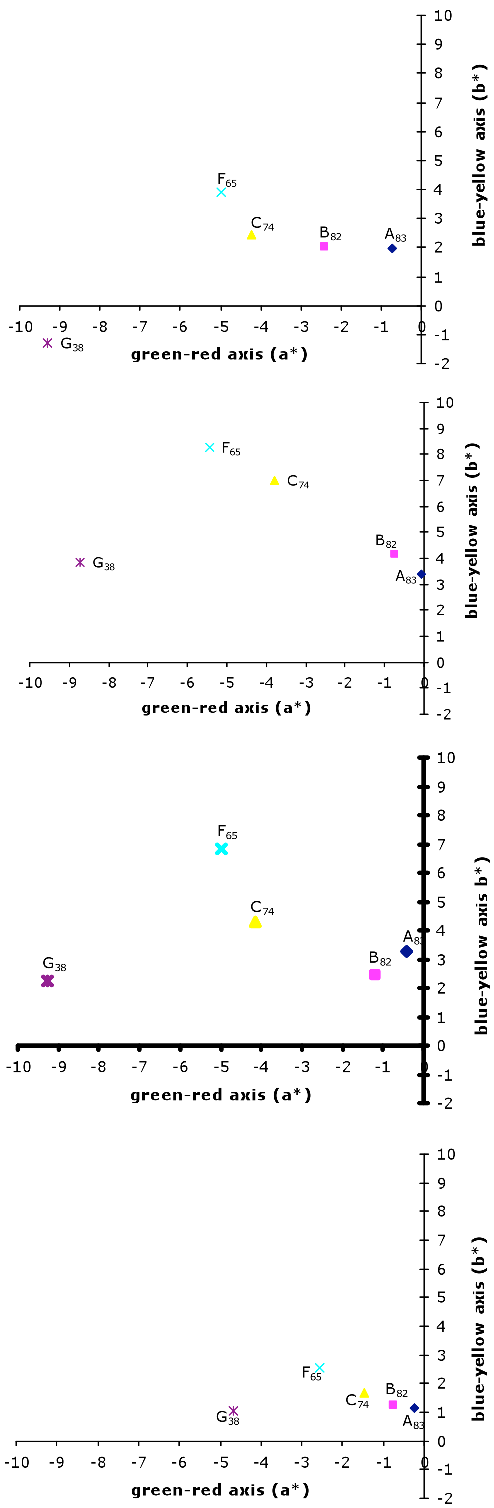

*Fig. 5 Resulting CIE-L*a*b coordinates for (1) clear, (2) partly sunny, (3) partly cloudy and (4) overcast sky.*

Experimental design and research procedure

The three studies used a within-subject experimental design so every research participant evaluated every glazing situation. Each participant had a unique and random order of presentation and no particular order of presentation prevailed. Latin Squares [30] were used to conserve the random order of presentation while narrowing the required number of participants.

In the first study, one of the scale models was used as a Reference Room and fitted with a double-pane window with an iron free and a low-emissivity coated glass (glazing "Ref_{77}", see Table 1). The other scale model, called the "Test Room", was alternately fitted with one of the other glazing types (A_{79}, B_{76}, C_{70}, D_{66} or E_{50}, see Table 1).

The first study relied on paired comparisons such that during each visit to the lab, the research participant was first asked to look into the Reference Room and fill in the questionnaire concerning the visual conditions in this room. The participant was then asked to look into the Test Room and fill in an identical questionnaire. S/he was allowed to look back into the Reference Room and at the first questionnaire to make sure that the evaluation of the Test room was consistent with the previous one. Once this second questionnaire was completed, the subject was asked to leave the room. The researcher then went into the laboratory, changed the glazing of the Test Room, and told the subject to come back into the laboratory and evaluate the conditions in the Test Room again, filling in a third questionnaire, identical to the two previous ones. The participant was never told that the glazing of the Test Room had been changed and s/he could not see the researcher change the glazing. The exact same procedure was repeated each time the subject had to evaluate a new glazing type.

The evaluation of all glazing types was completed using two sessions per subject, each session lasting about 40-45 minutes and covering only three glazing types (apart from the Ref_{77} glazing). The subjects used three minutes to adapt and the remaining time to fill the questionnaire. Prior to these two sessions (sessions 2 and 3), each subject was also invited to perform one whole session (session 1) to get some training and make sure that there was no misunderstanding in the questionnaire and procedure.

The glazing types were divided into two groups corresponding to each session:

Session 2: glazing types A_{79}, C_{70}, E_{50}

Session 3: glazing types B_{76}, D_{66}, E_{50}

Glazing E_{50} was evaluated during each session, to check that the ratings were consistent from one session to the next. Moreover, each session included glazing types with a high light transmittance (A_{79} and B_{76}), an intermediate light transmittance (C_{70} and D_{66}) and a low light transmittance (E_{50}). A multivariate Wilk's lambda statistic analysis was carried out on the evaluation of glazing Ref_{77} and E_{50}, which showed no difference between sessions 2 and 3 for both glazing types (Ref_{77}: Wilk's lambda = 0.426, F(9.9) = 1.345, p = 0.333 / Glazing E_{50} : Wilk's lambda = 0.441, F(9.9) = 1.270, p = 0.364). For two glazing types, the average value of the factor scores for sessions 2 and 3 was thus used for the rest of the analysis.

Table 2: Questionnaire filled by the research subjects (translated from French) in the second and third studies and associated factor.

Based on the following adjectives, how would you describe:

1. the room, as a whole:										
	dark	☐	☐	☐	☐	☐	☐	☐	bright	*(f1)*
2. the daylight:										
	artificial	☐	☐	☐	☐	☐	☐	☐	natural	*(f3)*
	unpleasant	☐	☐	☐	☐	☐	☐	☐	pleasant	*(f4)*
	uniform	☐	☐	☐	☐	☐	☐	☐	uneven	*(f6)*
3. the shadows of the furniture and of the objects:										
	blurry	☐	☐	☐	☐	☐	☐	☐	sharp	*(f7)*
4. the textures of the objects:										
	sharp	☐	☐	☐	☐	☐	☐	☐	blurry	*(f5)*
5. the colours of the objects:										
	artificial	☐	☐	☐	☐	☐	☐	☐	natural	*(f3)*
	blurry	☐	☐	☐	☐	☐	☐	☐	clear	*(f5)*
	drab	☐	☐	☐	☐	☐	☐	☐	lively	*(f4)*
6. the coulours outside:										
	artificial	☐	☐	☐	☐	☐	☐	☐	natural	*(f3)*
	lively	☐	☐	☐	☐	☐	☐	☐	drab	*(f4)*
7. the light outside:										
	dark	☐	☐	☐	☐	☐	☐	☐	light	*(f1)*
	glary	☐	☐	☐	☐	☐	☐	☐	comfortable	*(f2)*
	blurry	☐	☐	☐	☐	☐	☐	☐	sharp	*(f5)*

In the second study, the large amount of glazing types studied also required that the experimentation be conducted in two sessions to avoid visual fatigue of the participants. The validation of the results between session 1 and 2 required that glazing type B_{82} was evaluated each time. Subsequently, the scores of the first session were used for the analysis since a univariate repeated measure ANOVA showed that the scores were statistically equivalent between sessions 1 and 2 ($F(1,6) = 0,415$ and $p = 0,867$).

In the second study, the artificial sky was lit at least 30 minutes before the beginning of each experiment to stabilize the light output from the fluorescent tubes. At the beginning of each session, the participant entered the laboratory and was instructed to sit in front of the observation point from which s/he looked inside the scale model and filled a questionnaire. Once the first questionnaire was completed, the participant gave it to the researcher and left the laboratory. In the meantime, the researcher changed the glazing type. Once the second glazing was in place, the participant was asked to come back in the laboratory to repeat the exact same procedure. These steps were repeated for each glazing type and each laboratory session.

In the third study, a similar procedure was used as in the second study except that once a first questionnaire was completed, the participant gave it to the researcher and simply closed the door giving access to the observation hole. The time laps for the glazing switch was fairly rapid since the participant could remain seated without being aware of the change. The evaluation of the five glazing types took around 15 to 20 minutes to complete in the third study. The subjects used three minutes to adapt and one to two minutes to fill the questionnaire.

Measurements

In the first study, the following quantities were recorded:

- the interior horizontal illuminance,
- the exterior global illuminance,
- the exterior vertical illuminance (on the north facade),
- the vertical spectral irradiance.

Specific details regarding these measurements are carefully reported in the relevant paper [22].

In the second and third studies, the interior horizontal illuminance was the only physical quantity recorded during the experiments. Details regarding the illuminance measurements are reported in the relevant papers [23, 24].

RESULTS

Danish study (first study)

The statistical analysis was performed using the *SPSS 12.0* software. In the first (Danish) study, a statistical analysis was carried out by identifying seven important factors to which the research questions related (also drawn from the results of a principal component analysis (PCA) and confirmed by scree plot test):

- shadows (F1);
- brightness (F2);
- naturalness and colouring (F3);
- colour temperature (F4);
- beauty and pleasantness (F5);
- comfort (glare) (F6);
- sharpness (F7);

The average of scale scores for each factor was calculated and the factors were classified with respect to their capacity to explain the variance (from F1 to F7).

Subsequently, a randomized complete block design ANOVA [31] was carried out on the average scores for each factor with the different glazing types as the within subject effect. This analysis showed that for all the factors except F1 (shadows), the glazing type had a statistically significant effect on the subjective scores (see [22] for detailed results).

Table 3 Glazing type (Daylight Tr), mean, standard error, and results for the specific orthogonal comparisons (Dunnett) and multiple comparisons (LSD method adjusted with Bonferroni), first (Danish) study.

F1 - Shadows

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	3.181	-0.209	-	
A (79%)	3.083	-0.209	p=0.997	
B (76%)	3.083	-0.209	p=0.997	
C (70%)	2.722	-0.209	p=0.396	
D (66%)	3.000	-0.209	p=0.961	
E (50%)	3.056	-0.209	p=0.992	

F2 - Light level

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	5.403	-0.189	-	
A (79%)	4.556	-0.189	p=0.010	
B (76%)	4.194	-0.189	p<0.0001	
C (70%)	3.083	-0.189	p<0.0001	
D (66%)	2.611	-0.189	p<0.0001	
E (50%)	1.861	-0.189	p<0.0001	

F3 - Naturalness. colouring

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	5.377	-0.173	-	
A (79%)	4.944	-0.173	p=0.274	
B (76%)	4.841	-0.173	p=0.119	
C (70%)	3.746	-0.173	p<0.0001	
D (66%)	3.611	-0.173	p<0.0001	
E (50%)	2.837	-0.173	p<0.0001	

F4 - Color temperature

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	3.602	-0.168	-	
A (79%)	3.796	-0.168	p=0.881	
B (76%)	4.315	-0.168	p=0.016	
C (70%)	3.889	-0.168	p=0.631	
D (66%)	4.130	-0.168	p=0.112	
E (50%)	3.509	-0.168	p=0.994	

F5 - Beauty. pleasantness

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	3.924	-0.164	-	
A (79%)	3.833	-0.164	p=0.994	
B (76%)	3.667	-0.164	p=0.701	
C (70%)	3.264	-0.164	p=0.024	
D (66%)	3.069	-0.164	p=0.002	
E (50%)	2.632	-0.164	p<0.0001	

F6 - Comfort. glare

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	4.792	-0.154	-	
A (79%)	4.806	-0.154	p=1.000	
B (76%)	5.361	-0.154	p=0.043	
C (70%)	5.639	-0.154	p=0.001	
D (66%)	5.722	-0.154	p<0.0001	
E (50%)	5.972	-0.154	p<0.0001	

F7 - Sharpness

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	5.356	-0.14	-	
A (79%)	5.167	-0.14	p=0.805	
B (76%)	4.833	-0.14	p=0.042	
C (70%)	4.511	-0.14	p<0.0001	
D (66%)	4.233	-0.14	p<0.0001	
E (50%)	3.906	-0.14	p<0.0001	

The means obtained for each factor and each glazing were also ordered with bipolar scales all presented as negative-positive (1–7) in the analysis (see Table 3). A rating of 7 corresponds to the highest (most positive) score; a rating of 1, to the lowest (most negative) score, and a rating of 4, to a neutral score. This analysis indicated that glazing types of higher transmittance generally obtained higher (more positive) scores than the glazing types with lower transmittance. However, there are two exceptions to this trend. For F1 (shadows), the means were almost constant thus indicating a weak effect of glazing type on the perception of shadows (also showed by the statistical analysis). For F6 (comfort glare), the means (Table 3) are higher for lower transmittance glazing types, indicating that lower transmittance glazing types resulted in less glare.

To improve clarity in the results, a first approach in the statistical analysis consisted of examining five planned specific orthogonal comparisons (single degree of freedom tests) so the average ratings for glazing types A_{79}– E_{50} were contrasted with the results obtained for the reference glazing, which corresponded to the way subjects arrived at their ratings. The results of this analysis are presented in Table 3 (“Dunnett”) and discussed in detail in [22]. The main conclusions from this analysis are summarised below:

- The glazing type did not have any statistically significant effect on the ratings for questions related to shadows (F1).
- In terms of brightness (F2), all glazing types resulted in a statistically significant difference compared to the reference glazing.
- In terms of naturalness and colouring (F3) and beauty and pleasantness (F5), glazing types A_{79}– B_{76} did not result in a statistically significant difference compared to the reference glazing, but glazing types C_{70}–D_{66}–E_{50} produced a statistically significant difference with respect to the reference glazing.
- In terms of colour temperature (F4), glazing B_{76} was the only one rated as statistically different compared to the reference glazing.
- In terms of comfort (glare) (F6) and sharpness (F7), all glazing types except A_{79} resulted in statistically significant differences compared to the reference glazing.

Following finding a significant effect of glazing types, a second approach in the statistical analysis was explored which consisted of performing multiple comparisons with the protected LSD method adjusted with Bonferroni correction to control the type I error rate. Detailed discussion of these results are presented in [22]. The LSD tests indicated, among other things, that for all factors studied, except brightness (F2), there was no statistically significant difference between glazing types Ref_{77}, A_{79} and B_{76} (see Table 3, last column to the right).

Second study (artificial sky, Canada)

In the second study, the factors were slightly modified from the first questionnaire in the Danish study after we realised that questions regarding colour temperature were difficult to understand for research subjects who did not really understand the term "colour temperature" (in French "temperature de couleur" is familiar only to lighting researchers). Moreover, it appeared that this factor was already covered by the factor "naturalness". In addition, a factor called "distribution" was added since this parameter is often discussed in the literature about lighting. The factors were ordered as follows according to their capacity to explain the variance:

- brightness (F1);
- glare comfort (F2);
- naturalness (F3);
- beauty pleasantness (F4);
- precision (F5);
- distribution (F6);
- shadows (F7).

A randomized complete block design ANOVA [31] was performed using the *SPSS 12.0* software. This analysis allowed identifying the factors for which there were statistically significant differences between glazing types ($p < 0,05$). According to this analysis (outlined in Table 4), the glazing type influenced the perception of brightness (F1), beauty pleasantness (F4) and precision (F5) but had no statistically significant effect on glare comfort (F2: $p=0,280$), naturalness (F3: $p=0,920$), distribution (F6: $p=0,460$) and shadows (F7: $p=0,056$). The results are thus consistent with the previous (Danish) study concerning the perception of brightness (F1), beauty pleasantness (F4), precision (F5) and shadows (F7). Note that the absence of statistically significant effect of glazing type on F2, F3, F6 and F7 may be explained by the low participation rate.

A multiple comparison ANOVA (Tukey's test) was also performed in order to compare each pair of glazing type according to each factor for which a statistical difference was revealed. A detailed discussion of this analysis is presented in the relevant paper [23].

Of interest for the present paper is the study of the relation between the average scores for each factor and the glazing visual transmittance. Positive correlations between the glazing visual transmittance and scores were obtained for all factors except F2 (glare comfort). These results are generally consistent with results of the previous (Danish) study. The correlation with factor F1 (brightness) is very strong ($r_{F1}=0,955$). This result was expected because transmittance actually corresponds to the quantity of light transmitted. However, it is surprising to obtain that this particular correlation is weaker than the correlations for beauty pleasantness ($r_{F4}=0,972$) and precision ($r_{F5}=0,986$). Although the ANOVA did not reveal any statistically significant differences among glazing types for F7 (shadows, $p=0,056$), the correlation between F7 and the visual transmittance was fairly high ($r_{F7}=0,829$) indicating that higher transmittances result in a superior perception of shadows. We should however emphasize that the difference between both analyses (ANOVA and correlation between scores and visual transmittance) may be related to the low participation rate. The negative correlation for F2 (glare comfort) ($r_{F2}= -0,185$) suggests that a higher visual transmittance yields more glare. Although this is consistent with the previous (Danish) study, the low correlation and absence of statistically significant effect (ANOVA) reduces the overall importance of this finding in this case.

Third study (natural sky, Canada)

In the third study, a randomized complete block design ANOVA [31] was also performed using *SPSS 12.0*. This analysis allowed identifying the factors for which there were statistically significant differences between glazing types ($p < 0,05$, Table 5). According to this analysis, the glazing type influenced the perception of brightness (F1), naturalness (F3), beauty pleasantness (F4) and precision (F5) but had no statistically significant effect on glare comfort (F2: $p=0,580$), distribution (F6: $p=0,316$) and shadows (F7: $p=0,050$). Except for the factor naturalness, these results are consistent with the results of the second study [23]. The only difference between these new results and the results obtained in the artificial sky study [23] concerns the perception of naturalness (F3). In the artificial sky study, the ANOVA did not indicate that the glazing type had a statistically significant effect on the perception of naturalness. It is possible that this is attributable to the use of an artificial sky, which made the room look rather artificial. Furthermore, the present study also identified the perception of shadows as a qualitative factor not influenced by glazing type, repeating results of the two previous studies [22, 23].

To elaborate on these results, a multiple comparison ANOVA (Tukey's test) was performed in order to compare each pair of glazing type according to each factor for which a statistical difference was revealed. This analysis is presented and discussed in detail in the relevant paper [24].

Subsequently, an analysis of correlation between average scores for each factor and the glazing visual transmittance was also performed. This analysis revealed that the only negative correlation was obtained for glare comfort (F2), which means that a higher visual transmittance yields more glare. This result is consistent with the two previous studies. On the other hand, the positive correlations indicate that a higher transmittance glazing yields more positive ratings for brightness, naturalness, beauty pleasantness, precision, light distribution and shadows. Five correlations (F1, F2, F3, F4 and F5) were found to be very high ($r>|0,95|$). The only low correlation concerns the perception of distribution ($r_{F6}= 0,347$).

We should however emphasize that the difference between the ANOVA and the correlation study may be related to the low participation rate, especially in the second study. The negative correlation for F2 ($r_{F2}=-0,996$) suggests that higher visual transmittance glazing type yields more glare.

Although this is consistent with earlier research [22, 23], the absence of statistically significant effect (ANOVA) reduces the overall solidity of this finding.

Table 4 Results of the second study. The ANOVA indicates the statistical significance of a perceptible difference between glazing types for values of p < 0,05. Correlations between the glazing visual transmittance and the seven qualitative factors indicate the direction and strength of the relationship between the variables.

	F1 Brightness	F2 Glare comfort	F3 Naturalness	F4 Beauty pleasantness	F5 Precision	F6 Distribution	F7 Shadows
ANOVA	p < 0,001	p = 0,280	p = 0,920	p < 0,001	p < 0,001	p = 0,460	p = 0,056
Correlation	r = 0,955	r = – 0,185	r = 0,373	r = 0,972	r = 0,986	r = 0,586	r = 0,829

Table 5 Results of the third study. The ANOVA indicates the statistical significance of a perceptible difference between glazing types for values of p<0,05. Correlations between the glazing visual transmittance and the seven qualitative factors indicate the direction and strength of the relationship between the variables.

	F1 Brightness	F2 Glare comfort	F3 Naturalness	F4 Beauty pleasantness	F5 Precision	F6 Distribution	F7 Shadows
ANOVA	p < 0,001	p = 0,580	p < 0,001	p < 0,001	p < 0,001	p = 0,316	p = 0,050
Correlation	r = 0,985	r = – 0,996	r = 0,984	r = 0,976	r = 0,985	r = 0,347	r = 0,596

DISCUSSION AND CONCLUSION

Three studies of the effect of window glazing types on daylight quality were presented in this paper. The first study was carried out at the Danish Building Research Institute in Hørsholm, Denmark. The second and third studies were achieved at the École d'architecture of Université Laval, Québec, Canada. All three studies used scale models and within-subject experimental design. The first study used a paired comparison with two identical 1:7,5 scale models of an unfurnished rectangular room with a single, north oriented window exposed to overcast skies. A total of 18 research participants evaluated daylight conditions in the two rooms, by looking straight ahead towards the window through an observation hole placed at the back of the room. The second study used a single 1:6 scale model of a rectangular room, which was fully furnished as a typical residential living room and provided with different glazing types presented in random order. This room had a single window facing an artificial, overcast sky. The third study used the same scale model as the second study but the model was exposed to the natural sky with a sunlight free, south-east oriented window. A total of 15 and 30 research participants took part in the second and third study respectively. In both studies, the participants evaluated the light conditions in the rooms (after three minutes of adaptation) from an observation hole located in one of the lateral walls of the model. Their view of the interior thus had a diagonal direction with respect to the window.

This paper focuses on the constancy in the results obtained in the three studies, which were achieved using different experimental designs. In all three studies, the results indicated the following:

The glazing visual transmittance was positively correlated with brightness, naturalness, beauty pleasantness, and precision or sharpness. Previously, Cuttle [20] found that the acceptability of an office can be increased by the use of reduced transmittance glazing, which is in contradiction with the findings of our three studies. In general we found that increasing the glazing visual transmittance produced higher scores for beauty pleasantness, naturalness, precision, brightness. However, in our three studies, all glazing types had a dominantly green or green-yellow shift in colour. We did not have any bronze glazing (with a warm shift). Cuttle [20] found that there is a preference for a colour effect that gives a warm shift and Boyce et al [15, 16] indicated that solar bronze glass (warm shift) had been found to give an enhanced perception of the same transmittance. One explanation for these confounding results may be the fact that a warm shift is preferred because it gives an impression of sunshine (sunny day) even on overcast days while dominantly greenish shifts tend to flatten out the colours in the scene, as shown by Bülow-Hübe's experiment [19]. Since the human spectral sensitivity curve (v(λ)) peaks in the green-yellow region (550 nm) in the photopic state, it may be that more stimulus is needed in the other colour bands (e.g. red) in order to produce a colourful, lively image. Also, Hårleman et al.

[32] pointed out that reddish colours are associated with human skin, facial colour, strong emotional expressions such as affection and defiance and other mental characteristics.

The glazing visual transmittance was negatively correlated with glare comfort. In other words, glazing types with higher visual transmittance created more glaring views of the interior. The difference between the glazing types was statistically significant only in the first study but the participants looked at the window directly, which may have emphasized the difference between the participants' ratings in this case. These results show that glazing with lower transmittance may contribute to reduce glare to some extent. However, the same glazing types also create interiors that are darker, less beautiful, pleasant, natural and precise. This is very interesting because it means that someone may experience an interior as more beautiful, pleasant, natural and precise, although more glaring. In the recent years, lighting research has focused on glare as the single most important parameter of lighting quality in interiors. The results of these three studies emphasize the importance of considering glare in parallel with other parameters.

Finally, the three studies indicated that the glazing type did not have a statistically significant effect on the perception of shadows. In the last studies, the perception of shadows was positively correlated with the glazing visual transmittance but the difference between the glazing types was not statistically significant according to the ANOVA. We did not obtain statistically significant differences between glazing types for a factor called distribution either. This can be explained by the fact that the glazing type do not affect contrasts between different surfaces, it reduces the luminance of both bright and dark surfaces proportionally, with no resulting effect on shadows or distribution.

Our future research in this field will investigate the effect of colour shifts, including warm shifts, for glazing types of constant visual transmittance. We also plan to include energy and photobiology related effects, and to take into consideration the use of electric lighting together with daylighting for various compass orientations and types of skies. The use of longer adaptation times and full-scale experiments are also two important aspects that should be improved in this research on window glazing types.

ACKNOWLEDGEMENTS

This paper is dedicated to Rikard Küller, who got me interested in this type of research in the first place and who was a passionate and inspiring professor. I also express my gratitude to Jens Christoffersen, from the Danish Building Research Institute and Gaétan Daigle from the Département de mathématiques et de statistique of Université Laval, who took time to read the final version of this paper. I thank the Danish Energy Agency for funding the first study and the Social Sciences and Humanities Research Council of Canada (SSHRC) for providing extra support for the statistical analyses of all three studies. I also sincerely thank architects Richard Lafontaine and Richard Langford for providing funding for the experimental setting of the second and third studies, local glazing manufacturers Multiver, Robover and Thermos de la Capital for providing free glazing samples. I thank Gaétan Daigle, who wisely supported the statistical analysis of all three studies. I thank every participant in the three studies for their time and involvement. Finally, last but not least, I thank my Master's student Nathalie Pineault for her great involvement in the second and third studies and Professor Claude MH Demers from the École d'architecture of Université Laval, who provided support for the digital photo analysis.

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