Lighting quality and work performance based on glazing types and dynamic LED Lighting

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***Abstract*— The combination of daylight characteristics and LED lighting quantities determines offices' visual environment. Lighting conditions can influence office workers' health and work performance. This study is an experimental one containing lighting measurements in two offices, subjective performance tests, and questionnaires to find out how work performance, lighting preferences, and satisfaction with lighting quality modify in terms of various glass types and dynamic LED lighting quantities. Glass types have strong impacts on contrast tests on paper and luminance which are corresponding to work performance. Regarding lighting quality, it strongly relates to the homogeneity of light, the impression of artificial light and the perception of objects' textures and color, contrast balance between paper and the surrounding. When the glass was modified in offices, we observed that participants preferred to change the CCT setting of LED by remote control, and in relation to that the eye-level illuminance and SPDs showed significant changes. So, the findings depicted the importance of the choice of glass types concerning LED lighting settings in terms of the above variables.**

Keywords*— *glazing type, dynamic lighting, work performance, lighting quality

I. Introduction

Lighting affects the well-being, motivation, and mood of individuals as well as the successful execution of visual tasks [1]. Since it is a component of energy use and economy in buildings, the majority of research has focused on office lighting. Specifically, daylighting has priority in terms of energy saving and human health. Daylight performance is related to location, orientation, day and time, sky cover, window size as well as glass type. The number of buildings covered with fully glazed façades is increasing through the potential of advanced window systems to balance solar heat gain and loss and save energy. This allows better daylight utilization without compromising indoor thermal and visual comfort [2,3]. However, recent studies have indicated that the amount and color quality of light entering through such windows may affect work performance and lighting quality in workplaces [4]. A study showed that individuals' alertness/attention level was reduced when blue glazing was used and that daylight transmitted through bronze glass caused a general trend of appreciation [5]. Another study using a similar method focused on the light transmission of spectrally neutral, brightness-reducing solextra, and brightness-enhancing solar bronze glasses and stated that the minimum acceptable light transmission of window glasses should be in the range of 25-38% [6]. Dangol, Kruisselbrink and Rosemann [7] report that the spectral transmittance values of glass affect the color rendering index values of indoor daylight.

Although the use of daylight has increased, artificial lighting systems are still needed because the illuminance may drop below the desired level due to sky conditions or large volumes. LED lighting systems offer economical solutions, especially when targeting energy efficiency. However, issues such as glare, optical damage, LED flicker, nocturnal exposure to LED light, and the toxic chemical content of LEDs provide insight into the adverse effects of LED light on human health [8]. The energy distribution of LED light is higher in the blue wavelength. Recent studies have discussed that this may disrupt the circadian rhythm of people by affecting the release of the melatonin hormone [9,10]. The correlated color temperature (CCT), illuminance, and spectrum of the light source were associated with circadian rhythm and people's work performance [11].

This paper is based on a field study that aims to examine the effect of glazing types on indoor lighting quality and, accordingly, the change in artificial lighting preferences (CCT, illuminance), work performance, and satisfaction of office workers.

II. Methodology

A. Materials

The study was carried out in two offices facing north (3.20mx6.10m) and south (4.30mx6.70m) (Fig.1). It involves an adjustable dynamic LED lighting system which is dimmable (indoor illuminance level can be changed), and CCT values can be changed from 2700K to 6500K. A total of five window glasses often recommended to provide solar/heat control and energy efficiency in office buildings were determined to be tested in this study. Double glazed, electrochromic/smart, film-coated solar low-e and reflective glasses are installed on windows, respectively (Table I).

Fig. 1. Photo of the room facing South (left) and facing North (right)

TABLE I. TECHNICAL PROPERTIES OF WINDOW GLASSES

No	Glazing type	Layers	Transmittance(%)
1	Clear, double glazed	4mm+9mm air+4mm	90
2	Smart glass	4mm+12mm air+8mm	82 (transparent), 2 (opaque)
3	Solar low-e glazing	4mm+9mm air+6mm	50
4	Low-e glazing	4mm+9mm air+6mm	72
5	Reflective glazing	4mm+9mm air+6mm	21

B. Participants

A minimum of 32 people for each glass type were included in the experiment to evaluate the lighting conditions generated in both rooms. A total of 350 experiment executed with 51 males (mean age=24.3, STD=5.4) and 124 females (mean age=24.4, STD=7.2). Architecture faculty students and staff who do not have any mental or physical disorders to perform experimental tasks participated in the experiments. Performance tests and questionnaires were carried out each day at 9:00, 11:00, 13:00, and 15:00. Since it is a long-term study, the effect of glazing on the visual environment in different weather conditions was also examined. The date and time of the experiment for each participant were scheduled in advance. They are learned about the aim of the experiment, procedure, performance tests and questionnaire at the beginning of the experiment. Each participant signed a consent form stating that they participated voluntarily. The application diagram of the glazing types is shown in Figure 2.

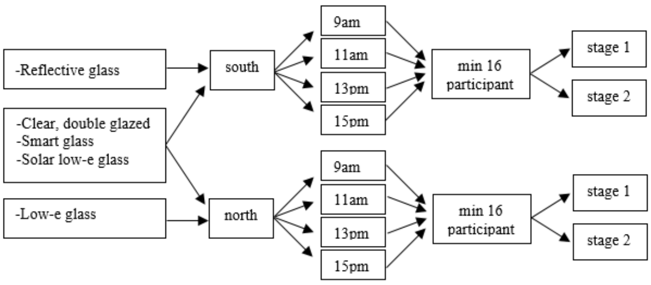

Fig. 2. Experiment scheme according to glass types.

C. Settings

The study/experiment included lighting measurements, work performance tests and a questionnaire. Horizontal illuminance, CCT and spectral power distribution (SPD) at the outside and inside the window, illuminance and CCT on the desk, luminance at specific points within the field of view, vertical illuminance, CCT and SPD at the eye-level of the user in a sitting position are the measured lighting values before the tests and questionnaire. Figure 3 shows the measurement points on the schematic representation of the rooms.

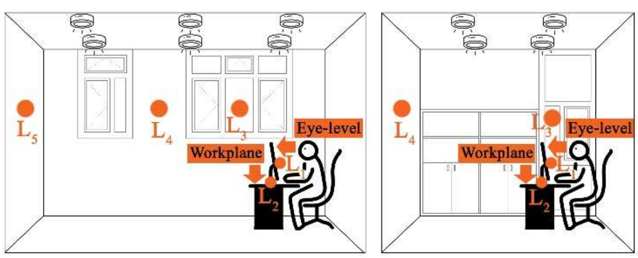

Fig. 3. Schematic representation of measurement points

The work performance tests are composed of Landolt Rings on paper [12], Stroop (on a computer screen), Short term memory/N-back (on the computer screen) [13, 14]. The performance tests and questionnaire were repeated for each glazing type, first with the default lighting setting (stage 1) and then with the LED setting adjusted by the participant's preferences (stage 2). The default setting for the south-facing room refers to the condition where the blinds are semi-open (to avoid excessive/direct sunlight) and only daylight is present. Since there was insufficient daylight for the north-facing room, the LED lighting system was adjusted to various illuminance and CCTs in the beginning to evaluate their impact on task performances and subjective judgments. The flow of the experiment is given in Fig. 4.

The non-visual (circadian) influences of light on human health were calculated using two prominent prediction models in the literature. One of the circadian indicators is the Equivalent Melanopic Lux (EML) suggested by the International Well Building Institute [15], and the other is the Circadian Stimulus (CS) developed by the Lighting Research Centre [16]. Both developers offer a computational tool that simplifies the measurements of these effects, using the spectral characteristics of the light entering the eye and the vertical illuminance.

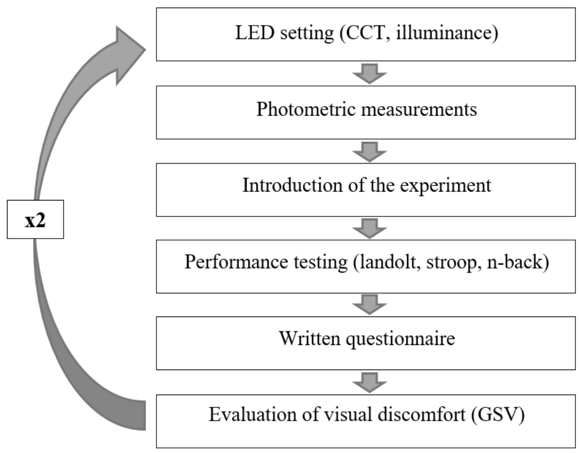

Fig. 4. Flow chart of the experiment

The written questionnaire consists of twenty questions regarding visual comfort, precision, naturalness, and lighting quality in the room. Participants rated each question containing opposite adjectives from the least (1) to the most (5) on a five-degree Likert scale. Thus, the answers were analyzed to determine whether there was a change in the participants' subjective evaluations according to the physical parameters.

III. GENERAL FINDINGS

This section presents the results of the influence of glazing types on indoor photometric measurements, participants' task performance, and lighting assessments through linear regression models and graphical representations. Figure 5 shows the variation of SPD trends according to the glazing type based on measurements taken outside and inside the window at 13:00. The characteristics of daylight differ according to the room orientation. Sky SPDs on the south facade show greater emission at all wavelengths, while sky SPDs measured on the north facade show a rapid decline from short wavelengths to longer wavelengths. The measurements through the window indicate that clear, double glazing shows the closest trend to the sky SPDs in the south, meaning that glass has more neutral behavior than others. However, all glazing types show similar behavior in the north, and the radiations in the interior are decreased at short wavelengths.

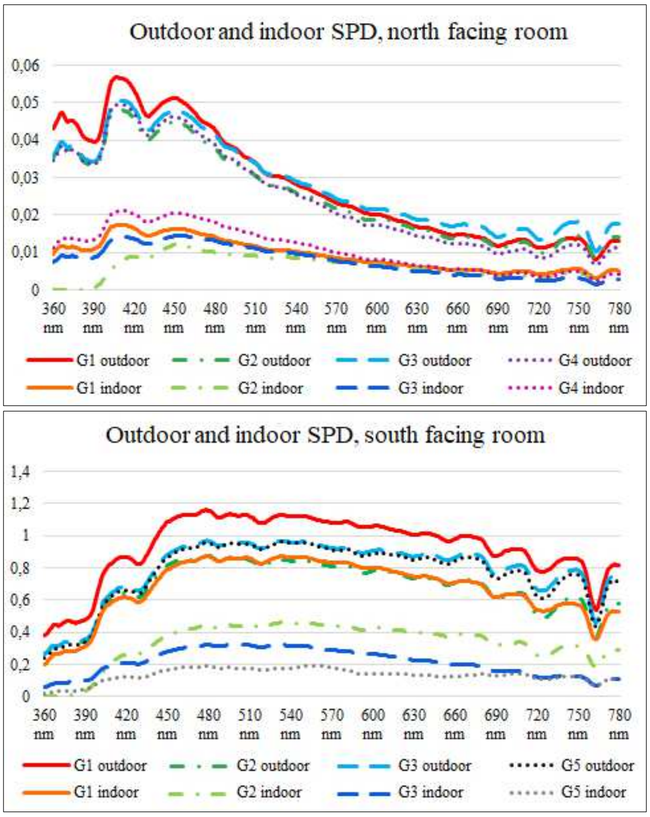

Fig. 5. Outdoor and indoor SPDs on a clear sky day at 13 pm.

The glazing types produced different results in two orientations according to the illuminance and CCTs measured on the same date/time with SPDs. Low-e glass has a minor effect on the outdoor illuminance level, while the reflective glazing significantly reduces the indoor light level. The influence of glazing features on CCTs was more pronounced in the north. The smart glass distorted daylight characteristics the most; clear glazing became the most neutral. Measurement results are given in Table II.

TABLE II. PHOTOMETRIC MEASUREMENT RESULTS

Measurements in north-facing room	**Illuminance**		**CCT**	
	Outdoor	***Indoor***	***Outdoor***	***Indoor***
Clear, double glazed	1897	679	17727	12650
Smart glass	1748	571	14758	8428
Solar low-e glazing	1961	621	12845	12603
Low-e glazing	1686	814	19417	15415
Measurements in south-facing room	**Illuminance**		**CCT**	
	Outdoor	***Indoor***	***Outdoor***	***Indoor***
Clear, double glazed	79297	60546	5556	5516
Smart glass	59345	31873	5675	5256
Solar low-e glazing	67846	21194	5392	6046
Reflective glazing	67092	12207	5420	6059

Three different regression models were established to determine office users' work performance, satisfaction/preferences and circadian indicators in various lighting conditions generated by glazing types and dynamic LED lighting. The results of the regression analysis are explained separately in the following sections.

A. Regarding Photometric Measurements

The first regression model analyzed the effect of environmental variables (direction, time, glazing type, and weather conditions) on photometric measurements, individual LED settings (dimmer, CCT) of the participants and circadian indicators. The changes in experimental stages were also examined. Table III presents the correlation coefficients for lighting settings, circadian indicators and glare probability. Results show that the LED lighting preferences of the participants differed according to the orientation of the room; higher illuminance and CCT values were preferred in the south-facing room. Although there is no significant difference in the CS values, the EML value differs significantly in the two rooms. Glass types also significantly affect participants' CCT preferences and EML values.

TABLE III. CORRELATION COEFFICIENTS FOR LIGHTING PREFERENCES, CIRCADIAN INDICATORS AND GLARE PROBABILITY.

	LED Settings		**Circadian Indicators**		**Glare Indicator**
	Dimmer	***CCT***	***CS***	***EML***	L_{min}/L_{max}
Orientation	**-90.76**	**-349.41**	-29.62	**-390.98**	0.00
Stage	173.19	84.01	16.73	73.00	0.01
Time	0.91	21.45	-0.58	2.20	0.00
Glazing	17.35	**137.58**	15.88	**-37.89**	-0.01
Weather	-24.07	50.26	25.25	**-103.14**	**0.01**

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

Table IV reports significant correlations regarding eye-level illuminance, CCT, and dominant wavelength values according to the orientation of the rooms and experimental stage. Apart from workplane CCT and dominant wavelength values, measurement results support LED lighting preferences. Strong changes are observed in the illuminance at eye-level depending on the glazing type and weather conditions.

TABLE IV. CORRELATION COEFFICIENTS FOR ENVIRONMENTAL VARIABLES AND PHOTOMETRIC MEASUREMENTS.

	Eye-Level			**Workplane**		
	Illum.	***CCT***	***Dom.Wav***	***Illum.***	***CCT***	***Dom.Wav.***
Orientation	**-403.69**	**-555.08**	**103.29**	**-144.03**	-148.54	61.69
Stage	**115.81**	**-399.13**	**120.23**	**349.54**	**-231.25**	**78.68**
Time	5.87	-29.98	0.91	-15.76	9.32	-0.25
Glazing	**-45.07**	47.99	-0.71	**-50.73**	6.55	-0.54
Weather	**-110.30**	-87.13	19.86	**-100.25**	-15.90	-0.69

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

B. Regarding Work Performance

According to lighting conditions and environmental and demographic variables, the most visible change in work performance occurred in the paper-based Landolt test (Table

V). Contrary to computer-based performance tests, Landolt results show significant differences in glazing type, eye-level CCT, and dominant wavelength values. Participants performed better at counting the rings correctly in the second stage of the experiment. Higher CCTs (colder light) positively affected contrast/attention.

Stroop and n-back scores, which refers to constant attention and executive function, report no relation with lighting conditions. However, there is an improvement in favor of the second phase of the experiment. Age and gender were the performance determining factors for the Stroop and n-back tests, respectively. Younger individuals performed better in the Stroop test, while males achieved greater scores in the n-back test.

According to the regression analysis results obtained from the GSV scores, it can be inferred that the participants' visual sensation of discomfort decreases significantly in their own lighting settings. The results revealed that glass types were also quite influential on visual comfort.

TABLE V. CORRELATION COEFFICIENTS FOR WORK PERFORMANCE INDICATORS AND GSV RATINGS

	Landolt	Stroop	N-back	GSV
Stage	**-7.04E+03**	**-1.37E+05**	**8.97E+03**	**-4.19E+02**
Time	**1.44E+03**	1.87E+03	**1.61E+02**	2.71E+00
Glass	**7.97E+03**	6.49E+03	2.28E+03	**6.30E+01**
Lmin/Lmax	2.59E+04	2.56E+04	1.28E+05	-1.02E+05
E_V	3.33E+00	-5.78E+01	-3.67E+01	2.84E-01
CCT	**-1.24E+01**	1.39E+01	-3.15E+01	1.72E-01
SPD	**-3.79E+02**	6.28E+02	-6.56E+01	3.65E-01
Age	-2.45E+02	**7.00E+03**	1.06E+03	-6.10E+00
Gender	**-6.37E+03**	2.94E+04	**-4.16E+03**	-1.01E+02

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

Note: E_V, CCT and SPD indicates vertical measurements of eye-level illuminance, correlated color temperature and dominant wavelength, respectively.

C. *Regarding Lighting Quality*

One linear regression model determined the relations between room conditions, measurements, personal issues, and the responses obtained from the questionnaire about the lighting quality/satisfaction. Table VI presents the strong effectiveness of stage on visual comfort assessment questions significantly (Q2-visually comfortable, Q3-homogeneity of amount of the light, Q4-the quality of light being attractive). Glass type has a slightly significant impact on the impression of homogenously distributed light (Q3). Unlike the CCTs at eye-level, the illuminance value can significantly change the brightness and visual comfort assessments. CCT can modify whether the visual environment is attractive or not; however, spectral distribution strongly determines this.

TABLE VI. VISUAL COMFORT ASSESSMENT

	Q1	Q2	Q3	Q4
Orientation	-1.31E+02	6.43E+00	2.17E+02	-8.75E+01
Stage	-2.89E+01	**9.47E+02**	**4.01E+02**	**1.11E+03**
Glass	1.15E+01	-2.15E+01	**-1.28E+02**	-2.40E+01
Lmin/Lmax	1.16E+03	-3.34E+02	-7.53E+02	1.22E+03
E_V	**-7.26E-01**	**-1.10E+00**	-4.60E-01	**-6.58E-01**
CCT	9.29E-02	-2.97E-01	2.46E-02	**-3.54E-01**
SPD	-5.24E-01	-6.83E+00	-1.93E+00	**-1.69E+01**
Age	2.81E+00	-1.06E+01	-3.24E+00	1.74E+01
Gender	1.33E+02	1.06E+02	3.51E-01	6.15E+00

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

Note: E_V, CCT and SPD indicates vertical measurements of eye-level illuminance, correlated color temperature and dominant wavelength, respectively.

The naturalness of the visual environment showed strong relations between lighting conditions. The satisfaction with the outside view (Q7), in this situation, is found to be significantly varying according to orientation. As the lighting preferences modified the amount of light and correlated color temperature of LEDs between stages, the variable "stage" showed a strongly significant relationship between the quality of artificial light (Q5) and how the objects' textures and form are perceived (Q6). Glass type has similar but less strongly impacts on these variables. The color perception in the room is slightly and significantly affected by stage, measured eye-level CCT, and SPDs.

TABLE VII. NATURALNESS OF THE VISUAL ENVIRONMENT

	Q5	Q6	Q7	Q8
Orientation	-3.58E+02	2.14E+02	**6.17E+02**	-2.61E+02
Stage	**9.63E+02**	**6.38E+02**	-4.25E+01	**3.81E+02**
Glass	**-2.00E+02**	**-1.40E+02**	-9.99E+00	-3.75E+01
Lmin/Lmax	1.57E+03	-1.25E+02	5.58E+01	-3.21E+02
E_V	-5.05E-01	**-7.45E-01**	-2.85E-01	-1.21E-01
CCT	**-6.08E-01**	2.20E-02	1.61E-01	**-3.97E-01**
SPD	**-1.50E+01**	-4.41E+00	-4.70E+00	-9.42E+00
Age	6.10E+00	9.57E+00	1.28E+01	1.32E+01
Gender	-1.65E+02	9.52E+01	1.94E+02	-1.70E+02

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

Note: E_V, CCT and SPD indicates vertical measurements of eye-level illuminance, correlated color temperature and dominant wavelength, respectively.

Precision assessment is about the text on paper (Q9), text on the screen(Q10), contrast balance between paper and written text on it (Q11), the perception of objects' textures (Q12), details (Q13), and colors (Q14). Glass showed similar findings as above that text readability, contrast balances, impressions of texture modify when another glass is installed. As the eye-level illuminance has similar effects, we can conclude that the transmittance of glazing has become the cause of its significant impact.

TABLE VIII. PRECISION ASSESSMENT

	Q9	Q10	Q11	Q12	Q13	Q14	Q15
Orientation	5.97E+01	5.40E+01	9.84E+01	7.48E+00	1.39E+02	1.21E+02	**5.62E+02**
Stage	1.76E+02	5.76E+01	**4.15E+02**	**3.05E+02**	**2.98E+02**	**3.81E+02**	5.76E+01
Glass	**-1.13E+02**	-7.39E+01	**-1.21E+02**	**-8.91E+01**	-6.03E+01	**-1.12E+02**	6.42E+00
Lmin/Lmax	-5.35E+01	-3.36E+02	-7.63E+02	-6.05E+02	-7.41E+02	-3.33E+02	-1.33E+03

E_V	**-7.23E-01**	**-7.38E-01**	**-6.89E-01**	**-7.03E-01**	-4.11E-01	-3.05E-01	-9.80E-02
CCT	2.80E-02	2.69E-01	2.02E-01	1.48E-01	-2.76E-02	1.03E-01	**6.62E-01**
SPD	-4.27E+00	2.96E+00	4.87E+00	-1.25E+00	-3.31E+00	1.70E+00	3.07E+00
Age	**1.60E+01**	-1.74E+00	4.16E+00	5.99E+00	7.11E+00	5.80E+00	4.73E+00
Gender	**2.56E+02**	6.36E+01	1.16E+02	1.57E+02	1.72E+02	-5.55E+01	1.90E+02

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

Note: E_V, CCT and SPD indicates vertical measurements of eye-level illuminance, correlated color temperature and dominant wavelength, respectively.

Lighting quality assessment is based on questions about saturation of colors (Q16), light ambiance (Q17), being naturally or artificially lighted (Q18), suitable light for work (Q19) and overall light quality (Q20). As the glass changed, significant variations reported in the subjective assessment of work efficiency and general satisfaction, and particularly in the perception of the ambient light as natural or artificial. The switch in the spectral characteristics and the amount of the light positively affected the evaluation of the overall lighting quality.

TABLE IX. LIGHTING QUALITY ASSESSMENT

	Q16	Q17	Q18	Q19	Q20
Orientation	-2.72E+01	-1.05E+02	-1.26E+02	4.69E+01	-5.30E+01
Stage	**6.68E+02**	**9.86E+02**	**1.01E+03**	**8.83E+02**	**6.90E+02**
Glass	**-1.11E+02**	-5.48E+01	**-1.34E+02**	**-9.73E+01**	**-8.37E+01**
Lmin/Lmax	-1.37E+03	2.52E+02	4.41E+02	-6.99E+02	-3.82E+02
E_V	-3.55E-01	**-6.18E-01**	**-9.44E-01**	**-5.96E-01**	**-1.02E+00**
CCT	-2.93E-01	**-3.54E-01**	-1.77E-01	-1.40E-01	-5.79E-02
SPD	**-1.16E+01**	**-1.52E+01**	**-1.14E+01**	**-1.22E+01**	**-8.38E+00**
Age	**2.80E+01**	1.23E+01	**2.77E+01**	9.73E+00	1.12E+01
Gender	**2.32E+02**	1.73E+02	1.31E+02	5.60E+01	1.37E+01

Statistical significance levels: (dark) when p-value<0.01, (medium) when 0.01<p-value<0.05, (light) when 0.05<p-value< 0.1

Note: E_V, CT and SPD indicates vertical measurements of eye-level illuminance, correlated color temperature and dominant wavelength, respectively.

IV. CONCLUSION

Objective and subjective measurements carried out within the scope of this study reveal significant results about the effects of glazing types on indoor artificial lighting preferences, users' health, working efficiency, and satisfaction. As a result of the measurements generated in two rooms, it was found that the different light characteristic dominates in the north and south throughout the day which affects the CCT and dimmer setting of the lighting system of the users. Even though the initial illuminance was higher in the south-facing room, people tended to increase the LED dimmer setting further to balance the lighting distribution in the room. Participants preferred an average illuminance of 680 lux and cool white light (4798K) at eye-level. In the north-facing room, the illuminance of 300 lux and neutral white light (4200K) at the same position became the participants' choice.

Although clear glass displays a relatively neutral behavior, advanced glass types have altered the structure of daylight in terms of illuminance and CCT, leading to different CCT choices indoors. The effects of these variations in lighting preferences on the health/circadian rhythm of people were examined with two calculation methods accepted in the literature, and significant differences were obtained in EML values according to the glazing type (as well as the amount of light exposed). Reflective glasses with the lowest transmittance value produced the most remarkable change in daylight character and prompted the participants to increase the LED dimmer and CCT setting more than other glass types. This resulted in a cool white light dominant environment (5057K) rather than neutral white light as with the others. The lowest eye-level illuminance, CCT, and EML were obtained with low-e glasses. However, the high error rates in the Landolt test (a paper-based contrast test) indicate that this may not be a suitable lighting environment for office users. In the case of application of other glasses (clear glass, smart glass, and solar low-e glass), the eye-level illuminance of around 500 lux, CCT of 4500K, and EML of 450 were achieved, and the participants were more successful in their task performance. Although glass type strongly influenced paper-based performance tasks, along with the CCT and spectrum of light, computer tests were associated with demographic information rather than lighting conditions. These inferences can provide a guideline for lighting designers in choosing luminaire color temperature and light intensity according to the glass type used in the building facade.

Lighting quality assessments regarding the visual environment drew a strong relationship between the homogeneity of the light, harmony of natural and artificial light, the textures and colors of the perceived objects, and the contrast balance between the paper and the surrounding. In terms of the overall assessment of visual comfort, naturalness, precision, and lighting quality in the room, clear glass became the most satisfactory glass, while reflective glass received the lowest scores in the questionnaire. The option of directing the light settings in the room according to the glass type improved the overall satisfaction. This has depicted the importance of considering the choice of glass together with dynamic LED systems in the lighting design, which is one of the essential factors in terms of the well-being, work performance, and satisfaction of the users in workplaces.

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References

[1] E. Ne'eman, G. Sweitzer, and E. Vine, "Office worker response to lighting and daylighting issues in workspace environments: A pilot survey," *Energy and buildings,* vol. 6, no. 2, pp. 159-171, 1984.

[2] J.-M. Dussault, L. Gosselin, and T. Galstian, "Integration of smart windows into building design for reduction of yearly overall energy consumption and peak loads," *Solar Energy,* vol. 86, no. 11, pp. 3405-3416, 2012.

[3] A. Ghosh, B. Norton, and A. Duffy, "Daylighting performance and glare calculation of a suspended particle device switchable glazing," *Solar Energy,* vol. 132, pp. 114-128, 2016.

[4] W. J. Van Bommel, "Non-visual biological effect of lighting and the practical meaning for lighting for work," *Applied ergonomics,* vol. 37, no. 4, pp. 461-466, 2006.

[5] H. Arsenault, M. Hébert, and M.-C. Dubois, "Effects of glazing colour type on perception of daylight quality, arousal, and switch-on patterns of electric light in office rooms," *Building and Environment,* vol. 56, pp. 223-231, 2012, doi: 10.1016/j.buildenv.2012.02.032.

[6] P. Boyce, N. Eklund, S. Mangum, C. Saalfield, and L. Tang, "Minimum acceptable transmittance of glazing," *International Journal of Lighting Research and Technology,* vol. 27, no. 3, pp. 145-152, 1995, doi: 10.1177/14771535950270030201.

[7] R. Dangol, T. Kruisselbrink, and A. Rosemann, "Effect of Window Glazing on Colour Quality of Transmitted Daylight," *Journal of Daylighting,* vol. 4, no. 2, pp. 37-47, 2017, doi: 10.15627/jd.2017.6.

[8] C. Ticleanu and P. Littlefair, "A summary of LED lighting impacts on health," *The International Journal of Sustainable Lighting,* vol. 1, no. 1, 2015, doi: 10.17069/ijsl.2015.12.1.1.5.

[9] N. Gentile, T. Goven, T. Laike, and K. Sjoberg, "A field study of fluorescent and LED classroom lighting," *Lighting Research & Technology,* vol. 50, no. 4, pp. 631-650, 2018.

[10] L. Bellia, F. Bisegna, and G. Spada, "Lighting in indoor environments: Visual and non-visual effects of light sources with different spectral power distributions," *Building and Environment,* vol. 46, no. 10, pp. 1984-1992, 2011, doi: 10.1016/j.buildenv.2011.04.007.

[11] Y. Zhu et al., "Effects of Illuminance and Correlated Color Temperature on Daytime Cognitive Performance, Subjective Mood, and Alertness in Healthy Adults," Environment and Behavior, vol. 51, no. 2, pp. 199-230, 2017, doi: 10.1177/0013916517738077.

[12] F. Linhart and J.-L. Scartezzini, "Evening office lighting – visual comfort vs. energy efficiency vs. performance?," *Building and Environment,* vol. 46, no. 5, pp. 981-989, 2011, doi: 10.1016/j.buildenv.2010.10.002.

[13] G. Stoet, "PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments," *Teaching of Psychology,* vol. 44, no. 1, pp. 24-31, 2017.

[14] G. Stoet, "PsyToolkit: A software package for programming psychological experiments using Linux," *Behavior research methods,* vol. 42, no. 4, pp. 1096-1104, 2010.

[15] " Well Building Institute, Human centric lighting." https://standard.wellcertified.com/light/circadian-lighting-design# (accessed January 2022).

[16] "Lighting research center." https://www.lrc.rpi.edu/cscalculator/ (accessed January 2022).