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EXPERIMENTAL STUDY OF THE NEW CRITERION OF LIGHTING QUALITY BASED ON ANALYSIS OF LUMINANCE DISTRIBUTION AT MOSCOW METRO STATIONS

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ABSTRACT

The article presents the experiment in studying a new criterion of lighting quality based on spatial and angular distribution of luminance proposed by the Lighting Engineering sub-department of NIU MPEI. The experiment studies correlation between expert evaluations of lighting quality at 21 stations of the Moscow Metro with analysis based on the criterion of quality of *RAW*-format luminance photographs of the stations made by means of a camera and adjusted according to luminance measured by a luminance meter. The obtained photos were processed using the proposed criterion. The article presents design of station models and calculations made by means of *DIALux* software and the programme developed (as part of the work) on the basis of local evaluations. It is demonstrated that the proposed criterion allows us to take account of extended veiling reflections and may be considered as enhancement of the unified glare rating *UGR*.

Keywords: lighting quality criterion, luminance distribution, local evaluations, metro system, glare

1. INTRODUCTION

Light is one of the main artistic methods of creation of metro station architecture. It forms an illusion of air-filled, light and luminous space under ground. However, lighting is the most important factor of passenger safety at the same time.

Architects have always considered the Moscow Metro as a system of underground palaces for people who fulfil the order on creating the most democratic mode of transport. And there is no other metro system in the world where valuable types of stone as well as sculptures, murals, mosaics and relief sculptures are used in interiors of stations in such amounts.

The factor of light is especially important in any metro system in the world, but in the Moscow Metro, apart from safeguarding passengers, it is also important to emphasise unique style of every station by means of lighting. Here, architectural and functional components of lighting are inseparable and lighting quality plays a special role.

Based on the conducted experiment, this work formulates lighting quality criterion (LQC) with one of its key targets being to take account of the factors which are poorly considered in the *UGR* method, namely veiling reflections. The newly-opened stations of the Moscow Metro turned out to be specifically appropriate for such experiment. Prevalence of glaring finishing materials (marble, granite, metal, glass) and availability of a large number of different light sources (LS) cause numerous veiling reflections at the stations, which eminently suites for evaluation of the new LQC.

2. LIGHTING QUALITY CRITERION

The new LQC based on analysis of spatial and angular distribution of luminance was proposed in

[1]. It has been corrected during subsequent evaluations by means of an experimental unit in the Light Engineering sub-department of NIU MPEI, and as part of the present work. So, according to this LQC, lighting quality may be evaluated from a set point in a scene space and in a set direction using one number:

$$Q = \frac{1}{K_{thr}} \int K(x,y) h(x,y) dxdy, \qquad (1)$$

where K_{thr} is the threshold value of contrast, h is the weight function allowing to consider a light engineering problem, $K(x, y)$ is the generalised contrast in a point of the scene determined as

$$K(x,y) = \frac{\left|\text{grad}\left(L(x,y)p(x,y)\right)\right|}{\bar{L}}, \qquad (2)$$

and mean luminance is determined as

$$\bar{L} = \frac{1}{A} \int_{(A)} L(x,y) p(x,y) dxdy, \quad A = \int_{(A)} dxdy.$$

Variables x and y are determined in analysis plane of an image seen from the studies point in the set direction, $p(x, y)$ is the function associated with non-uniformity of density of rods and cones distribution over eye retina. Any other function affecting the result may be taken into account in a similar way.

Any change of luminance will make a contribution to the result in the formulated LQC (1). It is obvious that luminance fluctuations below some threshold luminance level do not cause discomfort of perception. Let us limit their effect with the threshold L_{thr}:

$$K(x,y) = \begin{cases} L(x,y) \le L_{\text{ïîð}} & \rightarrow \quad 0 \\ L(x,y) > L_{\text{ïîð}} & \rightarrow \quad K(x,y) \end{cases}. \qquad (3)$$

3. EXPERIMENT IN THE MOSCOW METRO

21 stations were selected for the study: Rasskazovka, Borovskoe Shosse, Solntsevo, Govorovo, Lomonosovsky Prospekt, Minskaya, Pyatnitskoe Shosse, Volokolamskaya, Myakinino, Slavyansky Bulvar, Shelepikha, Khoroshevskaya, CSKA, Petrovsky Park, Sretensky Bulvar, Trubnaya, Dostoevskaya, Maryina Roscha, Butyrskaya, Fonvizinskaya, Okruzhnaya. The main criterion of selection was availability of large amounts of glaring finishing materials, and before conducting the experiment, the stations being selected were (deliberately) categorised as "good" and "bad".

One of actual visual problems being solved in metro systems is reading of signs. It is this problem that formed the basis of the experiment. In the meantime, expert comparison of different lighting installations (LI) providing the same type of functional lighting is often conducted in light engineering practice. For instance, lighting of one station may be compared to lighting of another one using the "better-worse" scale or another one. Therefore, our experiment was conducted according to the scheme below.

- An observer gets off a train at a station and adapts to the new level of luminance at the station as compared to that inside a car for 1 minute. An observer has 1 minute to examine the entire station, to identify an exit sign and to estimate the quality of station lighting during observation of the sign on a scale from 0 to 10, where 0 corresponds to "high-quality" lighting and 10 corresponds to "low-quality" lighting. Feeling of high-quality lighting is interpreted as visual comfort while reading the sign and being at the station. The normal value is in the middle of the scale and an observer's estimation should be given from one view of the scene, namely, according to regulations, near the end wall, along the centre line of the premises, at eye level, at an angle of 0° to the horizontal – for further comparison with a standard value of the *UGR* parameter for a LI simulated in *DIALux*.

Fig. 1. The process of the experiment

Table 1. Average Luminance and the Observers' Average Estimations for Each Station

Station	Luminance, cd/m²	Estimation	Station	Luminance, cd/m²	Estimation
CSKA	38	4	Lomonosovsky Prospekt	108	5
Trubnaya	45	2.66	Okruzhnaya	111	7
Khoroshevskaya	49	5	Myakinino	128	3.33
Rasskazovka	53	3.66	Sretensky Bulvar	146	3
Shelepikha	57	4	Minskaya	149	6
Slavyansky Bulvar	61	1.66	Butyrskaya	180	7
Volokolamskaya	62	3.33	Dostoevskaya	188	5
Pyatnitskoe Shosse	73	3	Solntsevo	223	6
Maryina Roscha	75	1.66	Fonvizinskaya	225	7
Petrovsky Park	76	5	Govorovo	239	9
Borovskoe Shosse	90	7.66			

Table 2. Chaddock Scale

c(x, y)	0.1–0.3	0.3–0.5	0.5–0.7	0.7–0.9	0.9–1.0
Correlation	very low	low	average	high	very high

• Then a wide-range *RAW* photograph is made by means of a *Nikon D3100* digital camera from several angles, and simultaneously, from the same angles, luminance is measured by means of a *Konika Minolta LS-100* luminance meter to make it possible to normalise the photograph (Fig. 1). At stations illuminated only by means of open LSs, luminance at the point of maximum luminance of the scene and luminance of an LS itself are measured, and at stations with indirect ceiling lighting, luminance of the brightest glare of the scene is measured.

• Average luminance of a station is determined during processing of the photographs in the course of their normalisation by means of *Matlab*.

Three persons took part in the experiment and the averaged data summarised in Table 1 were obtained for each station.

During processing of the results on the basis of the proposed LQC, average luminance at a station was taken as threshold luminance at the first stage. It should be noted that low values of luminance were similarly removed in [2], where an attempt of analysis of lighting quality on the basis of spatial and angular distribution of luminance was taken as well. Fig. 2 presents the original photographs of two metro stations and the contrast obtained on the basis of them as well as the "photographs" and contrasts after correction by means of formula (3).

It is convenient to use scatter diagrams of two variables allowing us to estimate availability of correlation visually in the course of data processing. Fig. 3 presents the scatter diagram of LQC and observers' answers. It is not difficult to see that the points are generally located along the diagonal line with a rather wide scatter. The check of the relation between the two considered variables is performed using the linear correlation coefficient (CC) determined as

$$c(x,y)=\frac{\dfrac{\sum_{i=0}^{N-1}(x_i-\overline{x})(y_i-\overline{y})}{N-1}}{\sqrt{\dfrac{\sum_{i=0}^{N-1}(x_i-\overline{x})^2}{N-1}}\sqrt{\dfrac{\sum_{i=0}^{N-1}(y_i-\overline{y})^2}{N-1}}},$$

where

$$\overline{x}=\frac{1}{N}\sum_{i=0}^{N-1}x_i\,.$$

CC for the obtained results was equal to 0.57.

CC is conventionally estimated using the Chaddock scale (Table 2).

It should be noted that CC may also be negative, which corresponds to scattering of data along the second diagonal line. In this case, inverse correlation is seen.

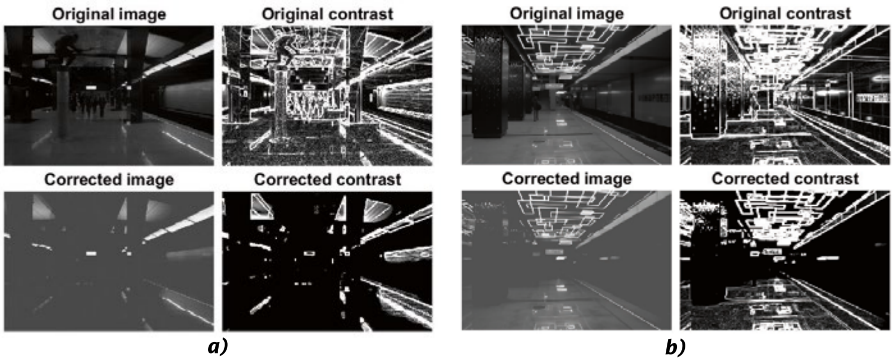

Fig. 2. Processing of photographs of the CSKA (*a*) and Govorovo (*b*) stations. (Original image, original contrast, corrected image, corrected contrast.)

The issue of threshold luminance for each station is debatable. It should be taken into account that conducting of the experiment in the metro system was fraught with organisational difficulties and time constraints, as a result of which, the observers visited each stations for 5 to 15 minutes. They moved between the stations in metro cars where luminance varied very significantly. Luminance was measured in cars and its mean value was equal to 183 cd/m^2. However, in general, mean luminance at stations and inside metro cars lies within two orders of values: from 38 cd/m^2 at the CSKA station to 239 cd/m^2 at the Govorovo station.

Let us assume that threshold luminance should be partially formed by average station luminance and average luminance inside metro cars.

$$L_{thr} = cL_{av.car} + (1-c)L_{av.station},$$

where $L_{av.car}$ = 183cd/m^2 in our experiment, as already mentioned above.

Fig. 4 presents the scatter diagram with c = 0.5, CC was equal to 0.76 in this case, which is high correlation according to the Chaddock scale.

Dependence of CC and the c factor was also calculated within the range of 0 to 1 (Fig. 5). More than 80 % of the graph chart lies within the region of high correlation according to the Chaddock scale, which allows us to make a conservative assumption that it is necessary to take account of luminance inside metro cars during processing of results.

4. STUDYING OF THE QUALITY CRITERION ON THE BASIS OF EXPERIMENTAL DATA

The well-known formula of unified glare rating *UGR*

$$UGR = 8\lg\left[\frac{0,25}{L_{\mathrm{a}}}\sum_{\mathrm{i}=1}^{N}\frac{L_{\mathrm{i}}^{2}\omega_{\mathrm{i}}}{p_{\mathrm{i}}^{2}}\right],$$

was obtained empirically (by summarising the experimental data), but it has also physical patterns. For instance, there is an opinion [3] that addition

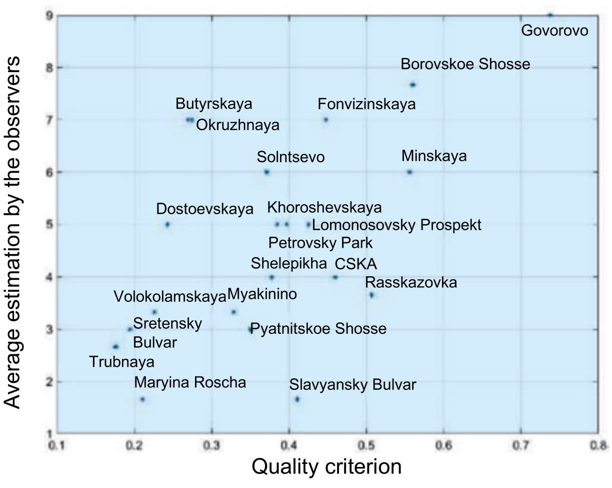

Fig. 3. Scatter of the observers' estimations and the criterion at threshold luminance equal to average station luminance

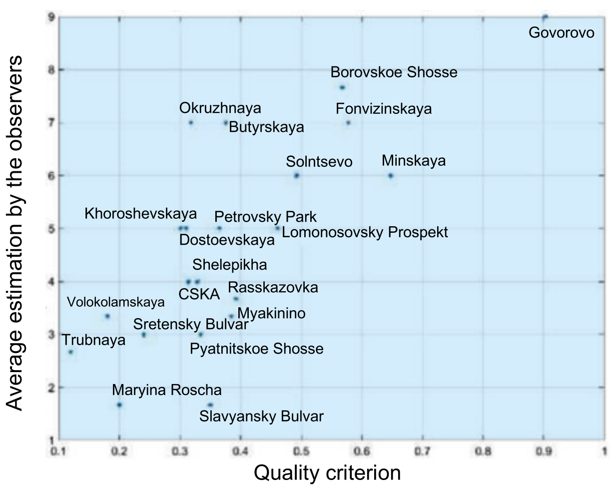

Fig. 4. Scatter at threshold luminance equal to ½ of average station luminance and ½ of average luminance in a car

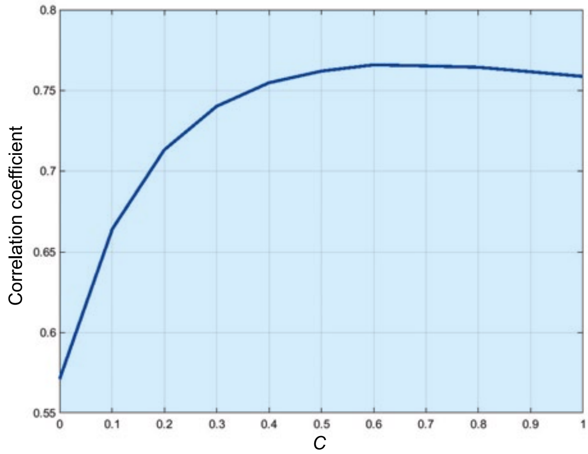

Fig. 5 Dependence of the correlation coefficient and *c*

of squares of luminance and division by adaptation luminance L_a in the discomfort formula well corresponds with the well-known signal/noise ratio

$$SNR = \left(\frac{A_s}{A_n}\right)^2, \qquad (3)$$

where A_s is signal amplitude and A_n is noise amplitude.

Let us amend the formula of LQC (1) with consideration of the expression (3) by replacing the formula (2) with the formula

$$K(x,y) = \frac{\left|\text{grad}(L^2(x,y)p(x,y))\right|}{\overline{L}^2}$$

Fig. 6 presents dependence of CC and coefficient *c*. It is not difficult to see that it is similar to that presented in Fig. 5.

The phenomenon of discomfort is studied within the region of the Weber-Fechner law [*D. Mackay*, 1963] according to which human perception *p* is proportional to the logarithm of the level of stimuli intensity *S*:

$$p = k\log\frac{S}{S_0},$$

where S_0 is lower threshold of stimuli intensity, *k* is a constant.

Let us introduce a logarithm into the formula of LQC (1) similar to the *UGR* indicator then it will be written as

$$Q = \lg\left[c_{\lg}\frac{1}{K_{thr}}\int K(x,y)dxdy\right],$$

where $c_{\lg}$ is a constant.

Relevant dependence of CC and coefficient *c* is shown in Fig. 7.

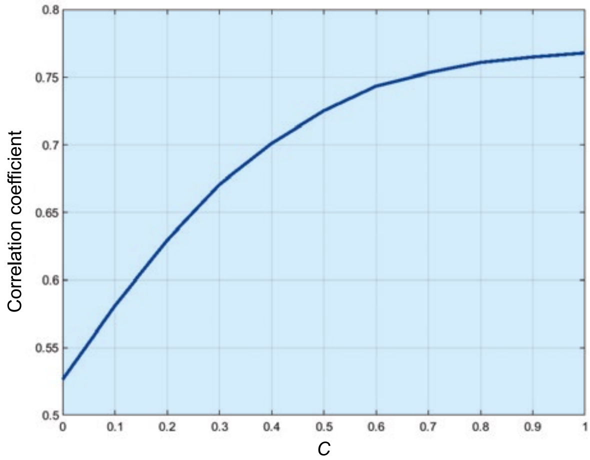

Fig. 6. Dependence of the correlation coefficient and *c* for the criterion formula changed similar to signal-to-noise ratio

5. MODELLING OF METRO STATIONS IN *DIALux*

Let us model a LS and conduct light engineering calculation by means of *DIALux 4.13* for the stations of the Solntsevskaya metro line with the highest values of LQC.

UGR should be evaluated near the end wall along the centre line of the area at height of 1.2m above the floor level, it is not limited for areas with their length exceeding two installation heights of LSs (luminaires) above the floor and, according to SP 32–105–2004, its average value in LSs of passenger areas should not exceed 20 with allowable excess of up to 20 %. Fig. 8 presents visualisations of the models in *DIALux* for four stations: Govoro-

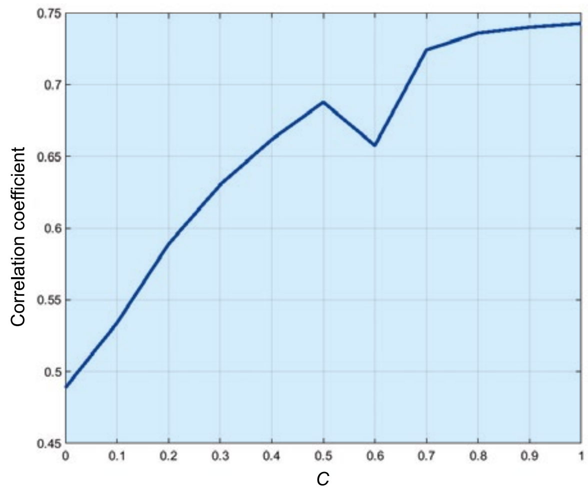

Fig. 7. Dependence of the correlation coefficient and *c* for the changed formula of the proposed lighting quality criterion (with consideration of the logarithm)

Table 3. Results of Modelling the Stations by Means of *DIALux*

Station name	Observers' estimations	UGR	LQC (NIU MEI Criterion)
Govorovo	9	17	0.94
Borovskoe Shosse	8	16	0.58
Solntsevo	6	19	0.50
Lomonosovsky Prospekt	5	12	0.48

Table 4. Results of Modelling Stations by Means of *DIALux* with Additional Sources of Light Simulating Glares

Station name	Observers' estimations	UGR	LQC (NIU MEI Criterion)
Govorovo	9	20	0.94
Borovskoe Shosse	8	23	0.58
Solntsevo	6	29	0.50
Lomonosovsky Prospekt	5	22	0.48

vo, Borovskoe Shosse, Solntsevo, Lomonosovsky Prospekt.

For these stations, *UGR* was calculated by means of *DIALux*, and results of this calculation are summarised in Table 3 along with the results of the experiments, and the table demonstrates that the highest level of discomfort is at the Solntsevo station, whereas, according to the observers' estimations (on scale from 0 to 10), it is the highest at the Govorovo station. The variation is caused by the fact that a larger number of low-angle LSs was considered during calculations for the Solntsevo station, whereas extended LSs at the Govorovo station cannot be "considered" by *UGR*, which distorts perception of LSs. Meanwhile the calculated level of *UGR* at these four stations is acceptable as it does not exceed 20.

Nevertheless, the veiling reflections on station floors obtained for the photorealistic image by means of ray tracing are not taken into account in the above mentioned calculation since only direct light sources (luminaires) are taken into account as per the *UGR* calculation algorithm of *DIALux*. Therefore, for detail calculation, let us model the reflected glares on the floor in the form of LSs with luminous distribution curves (LDC) of ceiling luminaires, taken the image on the floor as a direct reflection. The results of *UGR* calculation compared to observers' estimations for the scene with consideration of reflected glares are presented in Table 4.

Table 4 demonstrates that specified criteria of *UGR* are not meeting, therefore, the *UGR* calculation algorithm does not allow for such scenes to evaluate discomfort. At the same time, the pro-

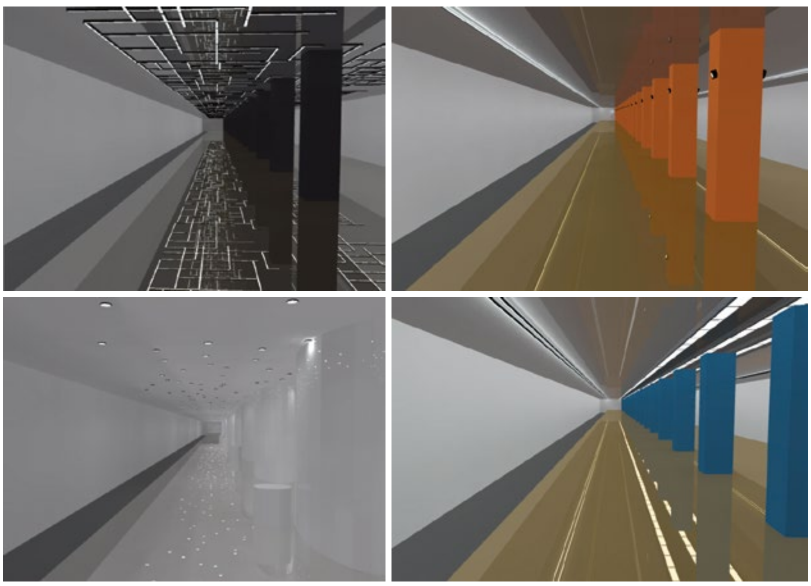

Fig. 8. Visualisation of the models of Moscow Metro stations Govorovo, Borovskoye Shosse, Solntsevo and Lomonosovsky Prospekt in *DIALux*

Table 5. Experimental and Simulated Values of the Lighting Quality Criterion

Station	Experiment	Visualisation
Govorovo	0.9396	1.0157
Okruzhnaya	0.3200	0.3991
Lomonosovsky Prospekt	0.4755	0.2558

posed LQC also shows (in accordance with the observers' estimations) that lighting at the Borovskoe Shosse station is not worse than that at the Lomonosovsky Prospekt station. Therefore, there is no contradiction between *UGR* and the proposed LQC in this case.

6. MODELLING METRO STATIONS BY MEANS OF THE MONTE CARLO METHOD LOCAL ESTIMATIONS

Within the framework of our previous work, the algorithm of local estimations was implemented to solve the global illumination equation [1]. It should be noted that, unlike *DIALux*, local estimations allow us to simulate luminance at a set point instead of illuminance. We have built and calculated the models of three metro stations in our implementation of local estimation for visualisation of three-dimensional scenes using *C++*. The visualisations and the photographs are shown in Fig. 9. LQC was also calculated for the obtained visualisations. The results of the calculations are presented in Table 5 which shows that the results for the Govorovo and Okruzhnaya stations turned out to be very close to those obtained during the experiment and variation for the Lomonosovsky Prospekt is probably caused by inaccuracy of the model.

7. CONCLUSION

The experiment in the Moscow Metro has demonstrated good correlation between the proposed LQC and expert estimations of the observers. It is also shown that modelling of metro stations using *DIALux 4* software and calculation of the uni-

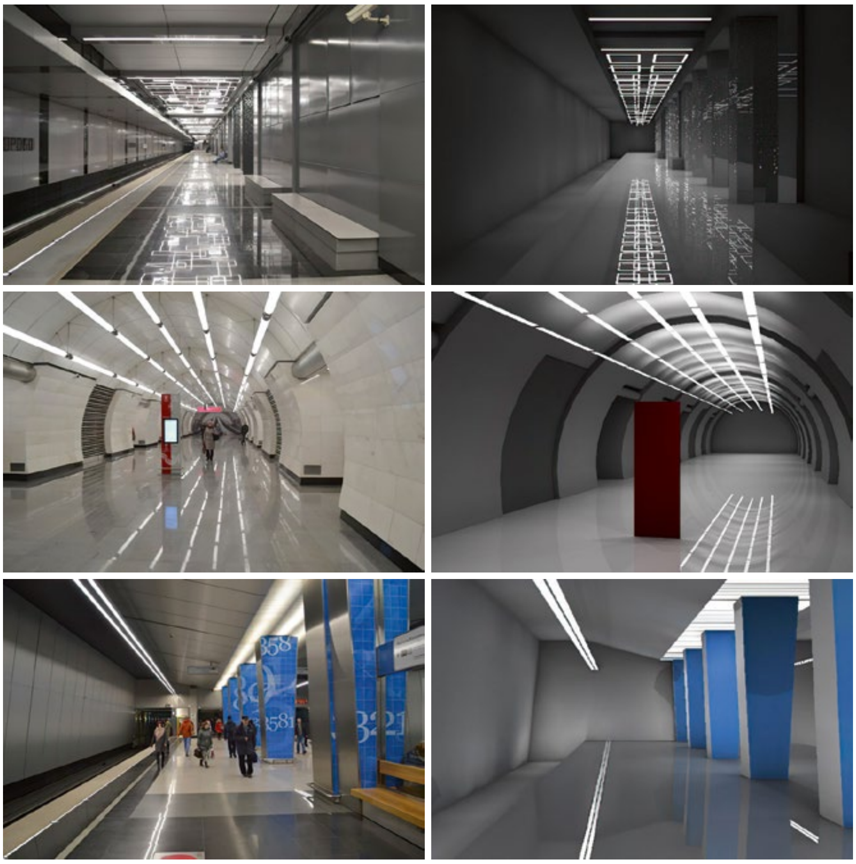

Fig. 9. Photographs and visualisations of Moscow Metro stations Govorovo, Okruzhnaya and Lomonosovsky Prospekt

fied glare rating *UGR* in it does not provide correct information on discomfort since glares appearing as a result of numerous reflections are not taken into account; the calculations conducted with simulation of glares in the form of secondary LSs have only research nature and cannot be used in everyday engineering practice.

Calculations of LQC on the basis of simulation of a number of stations by means of the programme developed as part of the work on the basis of local estimations of the Monte Carlo method demonstrate high repeatability of the experimental data. It means that (with physically adequate modelling of the global illumination equation) it is possible to obtain consistent values of LQC at the stage of design.

Obviously, the proposed LQC on the basis of the analysis of spatial and angular distribution of luminance requires additional estimations but it is already possible to state that it does not conflict with the *UGR* indicator but clarifies it. (It does not conflict with the Niels Bohr's Correspondence principle either: "a new theory shall include the older one and its results as its special case.")

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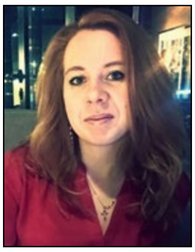

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