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Drivers' Preference for the Color of LED Street Lighting

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ABSTRACT The purpose of this paper was to initiate broad research aimed to establish the preferred color of light of LEDs from a driver's point of view. Two street lighting installations (one with 3000 K and the other with 4000 K LEDs) were evaluated both objectively and subjectively. The objective evaluation, realized using a CCD camera, included detection of small targets and pedestrians. A slight advantage was identified for the 3000 K lighting installation regarding both types of target. As for subjective evaluation (realized through a questionnaire), the task of the participants (drivers) was to choose the more appropriate between the two lighting installations regarding six lighting parameters, as well as the overall visibility. The 3000 K LED installation was evaluated as a better solution for most analyzed parameters, as well as for the overall visibility. However, only the results regarding the color of the light (in favor of the 3000 K LEDs) and the detection of small light-colored obstacles (in favor of 4000 K LEDs) were convincing, which was confirmed by the statistical analysis. Due to the obtained mild preference for the 3000 K LEDs and several limitations/challenges of the conducted surveys, it was concluded that additional research is needed in order to decide on the preferred color of light of LEDs from a driver's perspective.

INDEX TERMS Street lighting, pilot project, STV concept, drivers' impressions, questionnaire, comparison of 3000 K and 4000 K LEDs.

I. INTRODUCTION

LED technology for street lighting has experienced constant progress during the last decade. LED package luminous efficacies have already come close to 200 lm/W [1], LED luminaire light distribution can adjust to almost any roadway, and LED adaptive systems provide the highest percentage energy savings [2]. Although the life of LED packages depends on many influencing parameters, the most important being electric current and temperature [3], it exceeds by far that of conventional light sources.

Subjective lighting parameters, like color appearance, color rendering and discomfort glare, are also very important, because they influence the overall impression created in the observer's eye-brain system. It is well known that the illumination of two streets intended for motorized or mixed traffic, which are characterized by comparable values of objective lighting parameters (luminance level, overall and longitudinal luminance uniformities, threshold increment and surround ratio), can be described as obviously different by observers [4], [5]. Contrary to the objective street lighting parameters, requirements for the subjective ones are rarely given in standards and recommendations.

An additional problem is related to LEDs. Due to the fact that spectral power distributions (SPDs) of LEDs are considerably different from SPDs of conventional lamps (high-pressure sodium (HPS), metal halide, etc.), new metrics are needed for both the LED color appearance and color rendering. However, there are no such metrics broadly used in the lighting community (there were a few attempts regarding color rendering [6], [7], but, to the best of our knowledge, none regarding color appearance).

Papers investigating peoples' perceptions of street lighting realized by LEDs of different correlated color

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temperatures (CCTs) are rather scarce. Petrulis *et al.* [8] established that within the CCT range of 1850 – 10,000 K the subjects preferred CCTs of 3000 ± 200 K for an illuminance level of 5 lx (approximately 0.3 cd/m^2), and CCTs of 3500 ± 250 K for 50 lx (around 3 cd/m^2). Based on the fact that the public preferred warm white (WW) light, the 2400 K LED retrofit kit was recommended in the pilot project dealing with the replacement of 194 decorative HPS street lights with LED ones in the town of Nantucket, USA [9]. A few tests on the lighting performance of LED packages with different CCTs included LEDs of 1870 K, 2490 K, 3007 K, 4075 K and 5020 K [10]. The following conclusions were made: dark adaptation in road lighting is much easier after being exposed to warm white than to high-CCT LEDs and low-CCT LEDs cause lower sky glow and better light transmission in fog or haze. Also, the subjects selected a CCT of around 3000 K as most suitable for road lighting. Within a pilot project carried out at the Stanford University campus, seven LED luminaires, four luminaires with ceramic metal halide lamps and a luminaire with an induction lamp, their CCTs ranging from 2700 K to 4000 K, were tested [11]. The best-evaluated luminaire was an LED one with a CCT of 2700 K.

When designing the illumination of a street intended for motorized or mixed traffic, the lighting designer has to select the color of light. However, there is no guidance regarding this issue. Both International Dark-Sky Association (IDA) [12] and American Medical Association (AMA) [13], the former due to the claimed negative effects of blue light on sky glow, nightscapes and nocturnal animals, and the latter to reduce the negative effects of exposure to short-wavelength light on human health, recently recommended that only LED packages with a CCT not exceeding 3000 K should be used for street lighting. However, Rea and Figueiro [14] and Houser [15] presented convincing reasons against this recommendation. Hecht [16] and Stark [17] presented a few examples of cities (New York, Seattle, Houston and Montreal) with a number of streets illuminated by early installed blue-rich (usually called cool white (CW)) LED lights, probably chosen due to their highest energy efficiency among all LEDs. In these cases public reactions showed that many citizens have not been satisfied with the achieved lighting performance, evaluating the installed street lights as too bright and bothersome, causing harsh glare and sleep problems. Unpleasant (cool, bluish) color of light and increased light pollution were also recorded.

In order to prevent negative public reactions, the street lighting designers avoid using CW LEDs. Instead, they usually select neutral white (NW) LEDs, which are more energy efficient than warm white LEDs. However, the difference between luminous efficacies of the commercially available NW LEDs of 4000 K and the WW LEDs of 3000 K (both with the same color rendering index (CRI) of 80) is only 6% [18]. The US Department of Energy predicted that equal luminous efficacies of WW, NW and CW LEDs would be achieved in 2025 [19]. Note that the consideration of mesopic luminance levels corresponding to the photopic luminance levels most frequently applied in street lighting (0.5 – 1 cd/m^2) enables energy savings not exceeding 5% when using NW instead of WW LEDs [20]. Therefore, in our opinion energy efficiency should no longer be the decisive criterion when selecting between NW and WW LEDs intended for street lighting, but the selection should be based on the preference of both drivers and pedestrians (only drivers if the street (road) is exclusively intended for motorized traffic). Of course, much more significance should be given to the results of the evaluation of the parameters related to traffic safety issues.

FIGURE 1. Part of the street chosen for the pilot project.

Research dealing with the comparison of the pedestrians' evaluation of the visibility and visual comfort on two street sections illuminated by 3000 K and 4000 K LEDs was carried out in Belgrade, Serbia [21]. The relevant lighting quality parameters of their illuminated sidewalks (light intensity, illumination of human faces, feeling of pleasantness of color of light and the reproduction of colors), as well as the overall impression, were subjectively compared using a questionnaire. The respondents rated the 3000 K LED installation as a better solution regarding each of the considered lighting parameters, especially regarding the color of light and the overall impression. However, it was concluded that additional research, including evaluation by other age groups and by drivers, is needed before reaching a final conclusion.

According to the above, the purpose of this study was to initiate broad research aimed to determine the preferred color of light of LEDs from a driver's point of view. Therefore, both objective and subjective evaluation of the relevant lighting quality parameters was done. The former included two surveys based on detection of small targets and pedestrians, and the latter a survey with actual driving. To the best of our knowledge, surveys investigating the drivers' subjective impressions by involving actual driving are very rare [22]–[24]. Although there was research showing that the driver's behavior on the street is similar to that in a driving simulator (this conclusion was reached considering various hazardous scenarios) [25], the authors do not consider that driving simulators can replace actual driving when analyzing the influence of color of light on driving performance.

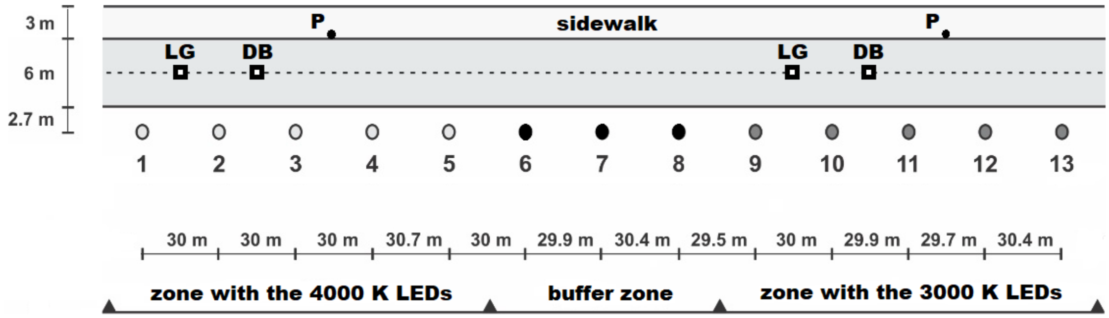

FIGURE 2. The street geometry with the pole and target locations (P – pedestrians, LG – light-green cube, and DB – dark-blue cube).

II. METHOD

A. SETTINGS

The research (pilot project) was realized on the Milutin Milankovic Street in Belgrade (shown in Fig. 1), intended for two-directional traffic. The whole street was previously illuminated by HPS luminaires. For the purpose of this research, one street section was illuminated by LEDs of 3000 K, and the other by LEDs of 4000 K.

Each street section (test zone) was illuminated by five luminaires. The mean pole spacing was 30 m (Fig. 2), and the pole height 8 m (the luminaires were mounted on the poles by brackets 1.2 m long). The traffic volume in the street is low during the night, which enabled performing all of the necessary photometric measurements (using a CCD camera). A buffer zone with three poles (Fig. 2) was provided between the two street lighting installations to prevent influence of one test zone on the other (the buffer zone luminaires were switched off during each of the three surveys). On the web-based user interface of the applied telemanagement system (Owlet [26]) the luminaires with the 4000 K LEDs were numbered 1–5, the luminaires in the buffer zone 6–8, and the luminaires with the 3000 K LEDs 9–13 (Fig. 2).

All luminaires were of the same type (24 LEDs, 1 A, 80 W, IP66, IK08, glass protector, body of high-pressure die-cast aluminum, adjustable slope) and with practically equal luminous intensity distributions. The luminaires belonging to the first test zone (CCT = 3000 K, CRI = 80 and the luminous flux = 7800 lm) were recently installed, and those illuminating the second test zone (4000 K, 80 and 7900 lm) were installed in 2015 (the participants did not know when the luminaires of each type were installed). The tilt angle of the former amounted to 9°, and of the latter to 7°. All luminaires were equipped with a dimmable driver and luminaire controller, enabling the same luminance level in both test zones, which was important for both objective and subjective evaluation.

The initial roadway luminance level (L_{av}), the overall and longitudinal luminance uniformities (U_o and U_l, respectively), the threshold increment (TI) and the surround ratio (SR), calculated assuming the roadway surface standard reflection class of R3 and the average luminance coefficient (Q_0) of 0.08 cd/(m^2 · lx) [27], are presented in Table 1 for both test zones (their values were calculated using the professional street lighting software Ulysse 3, developed by the Schréder Group and based on the CIE 115-2010 [28] and CIE 140-2000 [29]). Immediately after the luminaires were installed, the luminance levels (measured by a CCD camera) were very close to the calculated ones: 1.46 cd/m^2 (3000 K LEDs) and 1.50 cd/m^2 (4000 K LEDs) [27].

TABLE 1. Photometric parameters describing both lighting installations.

L_{av} [cd/m^2]	U_o [%]	U_l [%]	TI [%]	SR
		3000 K LEDs		
1.49	40	80	11.4	0.53
		4000 K LEDs		
1.47	46	82	11.4	0.54

B. SURVEYS REFERRING TO OBJECTIVE (QUANTITATIVE) EVALUATION

Two surveys based on the quantitative street lighting parameters were performed: one devoted to the detection of small targets and the other to spotting pedestrians.

In the 1990s the street lighting concept based on small-target visibility (STV), mainly promoted by Adrian [30]–[32], was adopted by both CIE [33] and ANSI/IESNA [34]. Emphasizing that in both documents a low target reflectance of 20% was adopted, the recommended STV values ranged from 5.0 to 7.5 (for the luminance levels between 0.5 cd/m^2 and 1 cd/m^2) in the CIE document, and from 1.6 to 4.9 (for the luminance levels ranging from 0.3 cd/m^2 to 1.0 cd/m^2) in the ANSI/IESNA document.

Although traffic safety considerably depends on the drivers' ability to detect and recognize small obstacles on the roadway, the STV concept has never been broadly used. As a consequence, the recommended STV values were not included in the updated CIE document from 2010 [28], and in 2006 the IESNA roadway lighting committee withdrew STV as a mandatory design metric. However, at the same time IESNA retained STV as a fine-tuning tool for road lighting installations designed using the standard (luminance) criteria.

Since the street lighting design was based on the luminance criteria in both zones (see Table 1), the first survey referring

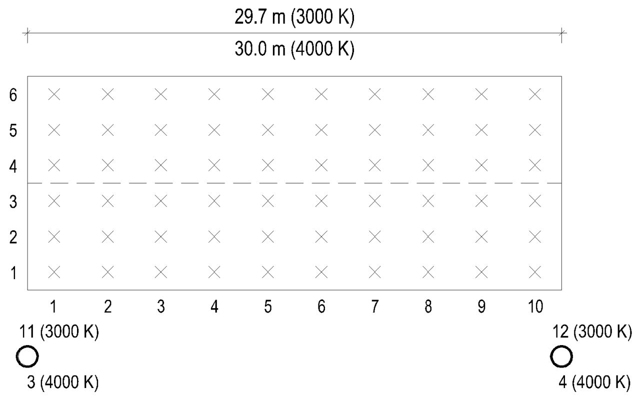

FIGURE 3. The 60 grid points at which the small target was placed (the camera was positioned left of pole 3 (11)).

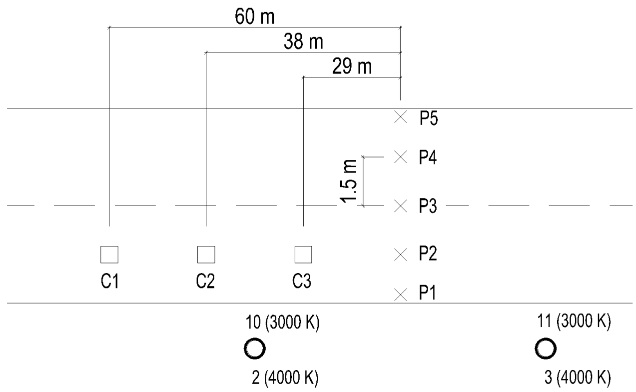

FIGURE 4. Positions of the pedestrian and camera.

to objective evaluation was devoted to the comparison of the tested 3000 K and 4000 K street lighting sections regarding the STV values. Within the second survey (also devoted to objective evaluation) the test zones were compared referring to the drivers' ability to spot pedestrians.

1) SURVEY BASED ON THE STV CONCEPT

This survey was based on the ANSI/IESNA conditions from 2000 (when the target reflectance was changed from 0.2 to 0.5 [35]), confirmed in 2014 [36]. They are as follows:

- flat target (18 cm × 18 cm), with diffuse reflectance of 0.5, is placed normal to the street axis at each of the regular calculation grid points,
- observer-to-target line is parallel to the street axis,
- observer is always positioned 83 m from the target (the visual angle is fixed to 7.45 min), the observation height is 1.45 m, and the viewing direction is almost horizontal (the downward viewing angle is 1^{o}),
- observer is 60 years old,
- contrast threshold is calculated according to Adrian's model [31], assuming an observation time of 0.2 s, and
- background luminance is calculated as the average of the luminances of the center points at the bottom and top line of the target (the latter corresponds to the roadway point positioned 11.77 m behind the target).

Between poles 11 and 12 in the 3000 K zone, as well as between poles 3 and 4 in the 4000 K zone (see Fig. 2), the 60 (= 6 × 10) regular grid calculation (measurement) points were selected as in Fig. 3 (there are two traffic lanes on the case street and neither of the two pole spacings exceeds 30 m) [29]. A light-green (18 cm × 18 cm) target, made of cardboard (with the diffuse reflectance of 0.46 (close to 0.5), measured by a spectrometer GL Spectis 1.0 possessing a tungsten halogen lamp with the color temperature of 2854 K and an input optical system with a fixed visual angle of 2^{o} [37]), was placed at each grid point. The observer (a CCD camera (luminance meter) LMK 98-4 [38]) was located in accordance with the above stated ANSI/IESNA conditions [36], its location being adjusted to each grid point.

Before taking photos, using the CCD camera and the telemanagement system, the luminance levels in both zones were adjusted to a value of 1 cd/m^2, which corresponds to the M3 street lighting class [28]. The same luminance adjustment was also done for the two other surveys. All surveys were performed when the street was dry.

A photo was taken for each target position, using the high-dynamic-range imaging (HDRI) technique, which allows the capture of scenes characterized by both high and low luminance levels (several camera images with different exposure times were taken and then converted into a unique luminance image).

2) SURVEY RELATED TO THE DETECTION OF PEDESTRIANS

A procedure presented in [39] was applied, based on the analysis of the photos of a pedestrian crossing the street and calculation of two types of luminance contrast.

Simulating a pedestrian crossing the street, a person dressed in dark clothes was positioned at five points along the middle line between poles 10 and 11 in the 3000 K zone, as well as between poles 2 and 3 in the 4000 K zone (as shown in Fig. 4).

The observer (the CCD camera) was positioned 29 m, 38 m and 60 m from the pedestrian target (the stopping distances when driving 50 km/h, 60 km/h and 80 km/h, respectively, and assuming thinking time of 1 second [40], [41]). Simulating the driver's eye position, the camera was placed in the symmetry axis of the lane closer to the poles (see Fig. 4) and at the height of 1.5 m. The camera was directed towards the pedestrian points 1 m above the roadway. A photo was taken for each target and camera position (15 photos for each test zone). A photo corresponding to pedestrian position P2 and camera position C2 in the 3000 K zone is presented as an illustration (Fig. 5).

Each photo was treated using the camera software and in accordance with the procedure given in [39]. First, a figure of the pedestrian was framed by a line, and then another line, encircling the previous, was drawn (the distance between the closest points of the two lines was approximately equal to the width of the pedestrian figure). Afterwards, the target

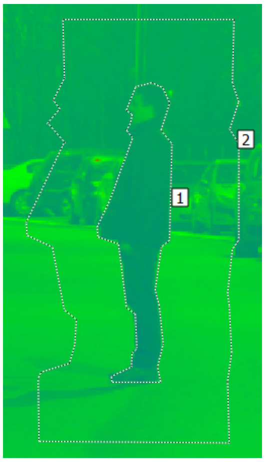

FIGURE 5. A photo of the pedestrian.

luminance (the mean luminance of the area covered by the figure of the pedestrian), the background luminance (the mean luminance of the area determined by the inner and outer lines), as well as the standard deviations of the target and background luminances, were determined.

The first applied contrast metric was the standard (Weber) contrast, conveying helpful information on the polarity of the contrast value. It is defined as

$$\text{Weber Contrast} = \frac{L_t - L_b}{L_b}, \tag{1}$$

where L_t and L_b is the target and background mean luminance, respectively. The second one was the Doyle contrast metric, defined as

$$\text{Doyle Contrast} = \left[(L_t - L_b)^2 + (\sigma_t - \sigma_b)^2\right]^{1/2} \tag{2}$$

(σ_t and σ_b is the standard deviation (dispersion) of the target and background pixel values, respectively [39]).

The Doyle contrast metric takes into account the luminance non-uniformity within both the target pedestrian and his/her background. This contrast metric is important for this survey, because a significant luminance non-uniformity existed in the test field.

C. SURVEY REFERRING TO SUBJECTIVE EVALUATION

The survey was based on a questionnaire asking the drivers to select the more suitable lighting solution regarding six parameters, as well as the overall visibility. The respondents were also asked to answer three additional questions. The first two were related to the selection of the best lighting parameters in each of the two lighting installations, and the third to the choice of the most significant lighting parameter from a driver's perspective.

The questionnaire used in Djokic *et al.* [22] served as an initial questionnaire for the survey. It was finalized by the focus group that consisted of five authors of this paper, their colleagues from the academic community (four) and experienced street lighting designers (six). At the focus group meeting, each question of the initial questionnaire was thoroughly analyzed and its necessity, clarity and terms which might confuse the respondents were discussed, after which the focus group made a few changes in the initial questionnaire. First of all, only the subjective impression of the driveway light intensity (and not of the overall driveway and sidewalk light intensity) was considered, because it is correlated with the street luminance level. The focus group removed the question referring to the driveway light uniformity, because the geometry of both lighting installations and the photometric characteristics of both types of luminaires were almost identical. This way, the number of questions was reduced, which was favorable due to the short exposure of the drivers to the test zones (one driving cycle (in both directions) lasted about 1.5 minutes). In addition, due to the short length of both test zones, there was no need to consider the longitudinal luminance uniformity. The other basic questions from the initial questionnaire (regarding the color of light, glare and spotting of pedestrians and obstacles) were not altered. Finally, the questionnaire contained six main questions covering the considered lighting quality parameters (noticeable when driving). Instead of referring to the overall impression (the initial questionnaire), the seventh question was modified to relate to the overall visibility. The two additional questions from the initial questionnaire were slightly modified: the respondents were asked to choose up to two (instead of one) best street lighting quality parameters among the six offered. In order to determine the most significant street lighting quality parameter from a driver's point of view, the focus group created a new (third) additional question.

Since quantitative evaluation of the lighting parameters was not considered possible due to the short time of exposure in the test zones, all members of the focus group agreed that the respondents should only select the better of the two lighting solutions regarding each parameter.

In order to explain the survey procedure and the terms used in the questionnaire to the participants, an introductory session was held just before driving. The questionnaire was read and the participants raised a few questions (about the meaning of driveway (the answer was that it excludes the sidewalk) and visibility (the answer: it excludes visual comfort), as well as the role of the co-driver), which helped them completely understand both the terms and the whole procedure. In order to increase the participants' motivation to give honest answers and concentrate when evaluating the considered street lighting parameters, they were informed that the survey results could contribute to the adoption of a strategic decision regarding the use of appropriate LED color of light in street lighting.

1) PARTICIPANTS

The survey participants (45 males and 8 females) were between 21 and 67 years of age (22 were younger than 25, and 23 were aged between 25 and 35). Besides possessing a valid driving license, each participant confirmed that he/she is an active driver with normal eyesight. The research organizers did not consider necessary to conduct any visual screening of the participants, because they did not wish the participants to belong to any particular group regarding their vision, but to represent a wide population of drivers. This is why the participants' age belonged to a wide range and both genders were engaged.

2) QUESTIONNAIRE

The questionnaire consisted of two sheets of paper. The front side of the first sheet was devoted to the respondent's data (his or her name, ID number, gender and age). On the other side there were seven main questions along with an explanation that each question should be answered by circling the letter (A or B) corresponding to the lighting installation evaluated as better. The second sheet contained the three additional questions.

The main questions were:

1) Higher driveway light intensity characterizes:

2) Better color of light characterizes:

3) Less glare caused by the luminaires characterizes:

4) Easier spotting of pedestrians characterizes:

5) Better detection of a light-colored obstacle (light-green cube) on the driveway characterizes:

6) Better detection of a dark-colored obstacle (dark-blue cube) on the driveway characterizes:

7) Overall, better visibility is provided by:

Each question was accompanied with the following two options:

(A) The installation with warm white LEDs

(B) The installation with neutral white LEDs

The first two of the three additional questions, answered by circling the number(s) in front of one or two of the offered parameters, were:

1) From the list below choose one or two best lighting parameters characterizing the warm white LED installation?

2) From the list below choose one or two best lighting parameters characterizing the neutral white LED installation?

The options offered for both of these questions were:

(A) Driveway light intensity

(B) Color of light

(C) Restriction of glare

(D) Spotting of pedestrians

(E) Detection of a light-colored obstacle on the driveway

(F) Detection of a dark-colored obstacle on the driveway

The third additional question, answered by circling the number in front of only one of the offered parameters, was:

3) The most significant street lighting quality parameter from a driver's perspective is:

(A) Driveway light intensity

(B) Color of light

(C) Restriction of glare

(D) Spotting of pedestrians

(E) Detection of obstacles on the driveway

A box for comments was also available.

3) PROCEDURE

The driving speed was agreed to be around 50 km/h (31 mph), corresponding to the most frequent limit in city streets. Contrary to the pilot project presented in Djokic *et al.* [22], the part of the street in which the survey took place was not closed for vehicle traffic. However, due to the location of the case street (commercial zone) and time of day, traffic density was very low.

Light of the other color could only be seen at a distance and, therefore, did not practically influence the driving ambient.

Dyble *et al.* [42] studied the influence of dimming on the color shift of white LEDs. They found that neither current dimming nor pulse width modulation (PWM) dimming (the latter was used in our research) caused a noticeable chromaticity shift for the phosphor-converted LEDs, which were used in our research. Therefore, it can be concluded that the reduction of the actual luminance levels to 1 cd/m^2 in both test zones did not cause a noticeable chromaticity shift in either of them.

Although the survey involved right-side driving only, its results can be considered general, because the current standards and recommendations [29], [43] do not make any difference between right- and left-side driving regarding the driver's position when calculating the objective street lighting parameters (the driver is located in the axis of each street lane).

While waiting for their drive, the participants were standing close to the 3000 K LED test zone, from which each drive started. They drove either the car provided by the survey organizers or, to accelerate the survey, their own car. Only the cars with headlights containing halogen lamps, which are still dominant in traffic, were used. Low-beam headlights were active during each drive.

Interior ambient lighting in all of the cars was turned off (a usual situation in practice), leaving only the effect of interior instrument lighting on the driver. However, this effect can be considered negligible [44].

In a study on the combined effect of road lighting and car headlights conducted by Bacelar [45], experiments were performed on a lit and unlit road to determine the effect of glare caused by headlights of oncoming cars on the driver's visibility. As expected, it was concluded that road lighting reduces the effect of glare from the oncoming car due to the improvement in the driver's visual adaptation. Another study [46] investigated the effect of dimming of road lighting (100%, 71% and 49% of the initial luminous flux) on glare caused by low-beam headlights of the oncoming car. Contrary to expectations, a statistically significant difference in glare was not found. In our research, only six participants met an oncoming car during their drive, which is why glare caused by the car headlights did not practically affect the answers.

The drivers were asked to carefully read the main questions before driving and pay attention to the relevant lighting parameters (light intensity, color of light, glare, etc.). The task of the co-driver was to remind the driver of these parameters a few times during the drive. As soon as the drive was finished

TABLE 2. Visibility levels corresponding to all 60 grid points (according to their notation applied in fig. 3).

LED CCT	Points	1	2	3	4	5	6	7	8	9	10
3000 K	1	-1.16	0.25	0.25	0.86	1.70	0.30	-1.96	-3.26	0.76	0.10
4000 K		-1.77	-0.72	0.67	0.24	-0.67	-1.54	-2.40	-3.01	-3.30	-2.43
3000 K	2	-1.30	-0.16	0.25	0.45	-0.08	-1.51	-2.14	-2.59	-2.40	-2.57
4000 K		-0.82	0.73	0.65	0.02	-1.25	-1.51	-2.86	-2.80	-2.96	-2.42
3000 K	3	-1.58	0.25	0.42	0.11	0.06	-1.30	-2.10	-2.83	-2.80	-3.88
4000 K		0.09	1.33	1.19	0.58	0.00	-0.95	-1.19	-1.62	-1.67	-2.05
3000 K	4	-1.40	0.43	0.56	-0.18	0.06	-0.96	-2.21	-3.12	-3.04	-3.47
4000 K		0.68	1.56	1.56	0.74	-0.05	-0.16	-0.72	-1.29	-0.38	-0.71
3000 K	5	0.22	0.28	1.22	0.36	0.53	0.08	-1.37	-1.93	-1.80	-2.77
4000 K		0.92	1.45	2.13	1.25	0.45	0.26	0.04	0.07	0.05	-0.07
3000 K	6	-2.34	-1.09	-1.21	0.99	0.69	0.35	-0.51	-0.37	-1.33	-1.18
4000 K		0.99	1.60	1.54	0.98	0.50	0.53	0.19	0.24	0.38	-0.37

(while the impressions were still fresh), the driver completed the questionnaire and handed it to the survey organizers. Only the drivers, and not the co-drivers, filled out the questionnaire, because the study conducted by Mayeur *et al.* [47] showed that the drivers' performances were lower than those of the passengers.

As mentioned above, the driving always started from the participant gathering area, which was illuminated and around 20 m distant from the first pole of the 3000 K zone (denoted by 13 in Fig. 2) – this way the drivers entered this zone from a bright light area. Leaving the 3000 K zone, the driver passed through the buffer (dark) zone, from which he/she entered the 4000 K zone. After driving through this zone and turning around, the driver entered the 4000 K zone once again (this time from a bright light area). Finally, after passing through the buffer zone once again, the driver entered the 3000 K zone (this time from a dark area). Let us emphasize that if the experiment was reversed, the results would have been practically the same.

Based on their temporal characteristics, three components of chromatic adaptation were identified: slow, fast and instantaneous chromatic adaptation, the first two affecting both color appearance and chromatic discrimination, and the third exclusively color appearance [48]. It was found that the full chromatic adaptation usually lasts up to 40 seconds, which was accomplished in our survey.

Since one of the questions referred to spotting pedestrians while driving, the drivers were expected to notice participants dressed in dark clothes, standing on the edge of the sidewalk in both test zones (their positions are shown in Fig. 2).

Emphasizing the importance of detecting small obstacles on the street [49], [50], two equal cubes (one light-green and the other dark-blue) were positioned in the axis of the driveway in each test zone (the positions of these four cubes are also shown in Fig. 2). According to the STV concept, the driver should see the target (cube) at subtended angles above 7.45 min arc (1 min arc $= \pi/(180 \cdot 60)$ rad). Taking into account that the stopping (thinking plus braking) distance corresponding to the speed of 55 km/h (slightly higher than 50 km/h, agreed for the experiment) amounts to 33 m (assuming thinking time of 1 second) [40], [41], the edge of cubes

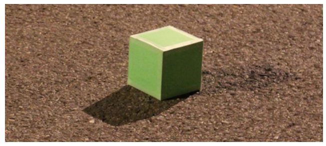

FIGURE 6. A light-colored cube placed on the roadway in the 3000 K zone.

needed for this experiment was:

$$a = 33\,\text{m} \cdot 7.45 \cdot \frac{\pi}{180 \cdot 60} = 7.2\,\text{cm},$$

which is why cubes with an 8 cm edge were made (a photo of the light-colored one placed on the roadway is shown in Fig. 6). Since the STV concept based on a single reflectance might sometimes cause misleading conclusions [49], both light-colored and dark-colored cubes were tested. All cubes were made of cardboard and filled with sand. The measurement of the reflectance (ρ) of the two cardboards was performed using the spectrometer GL Spectis 1.0 [37]. The measured reflectance of the dark-blue cardboard was 0.12, and of the light-green one 0.43.

The driver was asked to inform the co-driver as soon as he/she detects an obstacle or the pedestrians. At the end of their driving, a few drivers reported that they did not see the pedestrians or the dark-colored cubes at all (during the test, two dark-colored cubes were destroyed by the vehicle wheels and then replaced by spare ones).

III. RESULTS AND DISCUSSION

A. SURVEY BASED ON THE STV CONCEPT

For each of the test zones Table 2 contains the target visibility levels corresponding to all (60) grid points. In the 3000 K zone, for 29 points the visibility level was between 0 and 1, for 16 points between 1 and 2, for 10 points between 2 and 3, and for 5 points between 3 and 4, while in the 4000 K zone for 34 points the visibility level was between 0 and 1, for 16 points between 1 and 2, for 8 points between 2 and 3 and for 2 points between 3 and 4. The STV values (the weighting average visibility levels) for the 3000 K and the 4000 K zones, calculated using the procedure given in [36], amounted to 1.14 and 1.01, respectively. Besides their small difference, both STV values are low (close to 1). Therefore, this test

TABLE 3. Weber and Doyle contrast dosages for all pedestrian and camera positions.

Position of pedestrian	Position of camera	C1 (60 m)		C2 (38 m)		C3 (29 m)	
	Type of contrast metric	Weber	Doyle	Weber	Doyle	Weber	Doyle
1	3000 K	-0.02	0.05	-0.03	0.09	-0.05	0.41
	4000 K	-0.02	0.03	-0.03	0.04	-0.05	0.11
2	3000 K	-0.02	0.05	-0.03	0.05	-0.04	0.07
	4000 K	-0.02	0.03	-0.03	0.10	-0.05	0.12
3	3000 K	-0.02	0.02	-0.04	0.19	-0.05	0.13
	4000 K	-0.02	0.13	-0.04	0.54	-0.05	0.36
4	3000 K	-0.03	0.01	-0.04	0.71	-0.04	0.02
	4000 K	-0.02	0.03	-0.03	0.01	-0.03	0.01
5	3000 K	-0.02	0.01	-0.03	0.01	-0.05	0.05
	4000 K	-0.02	0.01	-0.03	0.07	-0.04	0.01

implies the necessity for additional tests regarding this matter (with different luminaires and luminance levels, as well as with small targets of different color and reflectance), needed to conclude on the relationship between LEDs and the visibility of small targets.

B. SURVEY DEVOTED TO THE DETECTION OF PEDESTRIANS

For both test zones Table 3 contains two luminance contrast indicators for each of the five pedestrian positions and three camera positions.

Increasing the distance from which the photo of the pedestrian was taken, his figure appeared smaller. In order to normalize the contrast data, the calculated Weber and Doyle contrasts were multiplied by a light dosage coefficient, defined as the ratio between the pedestrian height (1.9 m) and the camera distance [39]. This way, the Weber and Doyle Contrast Dosages were obtained and, as suggested in [39], the comparison between the two lighting installations was based on their values, and not on the Weber (Doyle) contrast values.

Regarding the Weber Contrast Dosage values, it can be concluded from Table 3 that all of these values have the negative polarity, as well as that the 3000 K lighting installation provides a slightly better possibility for the detection of pedestrians (in 4 (out of 15) cases the absolute value of the Weber Contrast Dosage is higher for the 3000 K zone, while in only one case the opposite is valid). However, regarding the Doyle Contrast Dosage values neither of the two lighting installations is advantageous (in 7 cases Doyle Contrast Dosage values are higher for the 4000 K zone, and in other 7 cases the opposite is true).

C. SURVEY REFERRING TO SUBJECTIVE EVALUATION

The survey results are presented in Table 4. Regarding the main questions, Table 4 shows that a larger number of the respondents preferred the lighting installation with the 3000 K LEDs regarding the driveway light intensity, color of light, glare limitation, detection of small dark-colored obstacles and overall visibility, while the 4000 K LED luminaires were preferred for spotting pedestrians and detecting small light-colored obstacles, both important for traffic safety. However, convincing majorities only existed regarding the preference for the 3000 K LED color of light (41:12) and better detection of light-colored obstacles in the 4000 K LED zone (35:17). The former confirmed the obvious preference for warm white light from a driver's point of view regarding visual comfort, while the latter is in accordance with the findings presented in Hong *et al.* [51], stating that a better visibility of green objects corresponds to a higher CCT due to higher brightness and appearance perception of green objects.

TABLE 4. The number of respondents who selected each of the offered answers.

Main questions	Offered answers					
	A (3000 K LEDs)			B (4000 K LEDs)		
1	27			26		
2	41			12		
3	28			23		
4	22			28		
5 (ρ = 43%)	17			35		
6 (ρ = 12%)	27			22		
7	29			23		
Additional questions	Offered answers					
	A	B	C	D	E	F
1 (3000 K LEDs)	15	27	18	14	6	8
2 (4000 K LEDs)	15	7	13	20	20	11
3	16	4	7	14	6	/

The respondents evaluated the two test zones as practically equal regarding the driveway light intensity (27:26), while a small majority of the respondents (28:22) were in favor of the 4000 K LEDs for spotting pedestrians. In both cases the illuminated objects (roadway made of asphalt and the pedestrians' clothes) were dark, representing a possible reason for the absence of significant preference for a higher CCT lighting (Ju *et al.* [52] showed that lighting with a higher CCT is characterized by a stronger spatial brightness perception than the one with a lower CCT, but they did not consider dark spaces). The same explanation is valid for the results referring to the detection of small dark-colored obstacles (a small majority of the respondents (27:22) preferred the lower CCT lighting).

TABLE 5. The continuity corrected z-values, statistical significance indicators, and lower and upper bounds of 95% confidence.

Main questions		Number of respondents	z	p	Lower bound of 95% confidence	Upper bound of 95% confidence
1	3000 K LEDs	27	0.00	1.00	0.37	0.64
	4000 K LEDs	26	0.00		0.36	0.63
2	3000 K LEDs	41	3.85	< 0.01	0.66	0.89
	4000 K LEDs	12	-3.85		0.11	0.34
3	3000 K LEDs	28	0.56	0.58	0.41	0.69
	4000 K LEDs	23	-0.56		0.31	0.59
4	3000 K LEDs	22	-0.71	0.48	0.30	0.58
	4000 K LEDs	28	0.71		0.42	0.70
5 (ρ = 43%)	3000 K LEDs	17	-2.36	0.02	0.20	0.45
	4000 K LEDs	35	2.36		0.55	0.80
6 (ρ = 12%)	3000 K LEDs	27	0.57	0.57	0.41	0.69
	4000 K LEDs	22	-0.57		0.31	0.59
7	3000 K LEDs	29	0.69	0.49	0.42	0.69
	4000 K LEDs	23	-0.69		0.31	0.58

As for the first additional question, the two best lighting parameters for the 3000 K LED lighting installation were color of light (27 out of 53 respondents) and restriction of glare (18/53). The two best lighting parameters for the 4000 K LED installation (the second additional question) were spotting of pedestrians (20/53) and detection of small light-colored obstacles on the driveway (20/53).

Regarding the third additional question, the two most significant street lighting quality parameters from a driver's point of view were the driveway light intensity (16/53) and spotting of pedestrians (14/53), which was expected. A significantly smaller number of respondents considered other parameters important. Since the smallest number of participants distinguished the color of light, they obviously neglected the importance of visual comfort when compared to traffic safety.

Note that a small number of respondents were not able to decide on particular questions.

In order to check how statistically significant the obtained results related to the main questions are, the one sample z-test for proportions was applied, with the results presented in Table 5. For each of the questions the continuity corrected z-value for the difference between the observed and hypothesized proportion of 0.5, the statistical significance indicator (p) and the 95% confidence intervals (their lower and upper bounds) were calculated using IBM SPSS Statistics.

As can be seen from Table 5, the one sample z-test for proportions showed no statistically significant difference in subjective impressions of the 3000 K and 4000 K LED installations regarding most of the considered parameters (cases characterized by $p > 0.05$). The only exceptions are the color of light ($p < 0.01$ (statistically very significant), in favor of the 3000 K LED installation) and detection of the light-colored obstacle ($0.01 < p < 0.05$ (statistically significant), in favor of the 4000 K LED installation). These findings are in accordance with the data given in Table 4.

It is interesting that Djokic *et al.* [22], comparing street lighting installations realized with HPS lamps (CCT = 2000 K) and the 4000 K LEDs, found that most of the respondents preferred the color appearance of the 4000 K LEDs. However, the respondents participating in the present survey found that the color appearance of the 3000 K LEDs was more appropriate than that of the 4000 K LEDs. A possible explanation could be derived from the significant difference in color appearance between HPS lamps and the 3000 K LEDs (the former cannot be described as lamps emitting white light).

The respondents gave the following comments:

- The dark-colored cubes could not have been seen in either of the tested zones (four respondents had comments similar to the stated one),
- The light intensity should have been higher in both zones (one respondent), and neutral white light provided better visibility and greater similarity to driving by daylight, while warm white light gave an impression of artificial light which negatively affects the driving conditions (one respondent).

The following two conclusions can be derived from the above comments:

- the comments (although given by two participants) were only in favor of the 4000 K LEDs, and
- four comments on the poor visibility of the dark-blue cubes (in both test zones) confirmed that small obstacles with very low reflectance are not appropriate for the assessment of drivers' performance in night conditions.

IV. CONCLUSIONS

One of the strategic issues in LED street lighting is the determination of the preferred color of light. For this purpose, this research was devoted to the comparison of both the objective (quantitative) parameters and the driver's subjective impressions (when actually driving) regarding street lighting installations realized by 3000 K (warm white) and 4000 K (neutral white) LEDs. The two test installations, set on the same street, had comparable photometric parameters (primarily the roadway luminance level (corresponding to the M3 street lighting class)) and equal color rendering indices.

Regarding the objective evaluation, a slight advantage was identified for the 3000 K lighting installation regarding the detection of both small obstacles and pedestrians.

The subjective comparison of the relevant lighting parameters of both lighting installations was performed using a questionnaire. The participants, aged between 21 and 67 (45 males and 8 females), were asked to select the more appropriate of the two installations regarding each of the six considered lighting parameters, as well as to compare their overall visibilities.

A larger number of the respondents evaluated the 3000 K LED lighting installation as the one that provides somewhat better overall visibility. The preference for the 3000 K LEDs was also expressed for most of the analyzed parameters, emphasizing that both exceptions – spotting of pedestrians and detection of small light-colored obstacles on the driveway – are related to traffic safety. However, convincing majorities only existed regarding the preference for the color of light (in favor of the 3000 K LED installation) and detection of a light-colored obstacle (in favor of the 4000 K LED installation), which was confirmed by the statistical analysis.

The conducted research had several limitations/challenges:

- research regarding both objective and subjective evaluation was performed under a dry roadway surface; the results which could be obtained under a wet roadway surface might be different,
- only the luminance level of 1 cd/m^2 was applied,
- a small target of only one color and reflectance was used for the objective evaluation; in addition, although used for decades and thus applied in this research, the STV method represents only a theoretical estimate of the visibility,
- only car headlights with halogen lamps were involved,
- the survey was performed under very low traffic conditions,
- drivers' age was not addressed, although it considerably affects glare, and
- LEDs of a single spectral power distribution corresponding to the correlated color temperature of 3000 K (4000 K) were applied.

As explained in subsection II.C, due to short driving which involved subjective evaluation of numerous lighting parameters, there was no possibility for quantifying visual performance. However, experiments intended to collect quantifiable visual performance data from the participants regarding both small target and pedestrian detection can and should be carried out in future studies in order to provide precious data for the final conclusion. Such experiments could be based on object detection time and object miss rate. There are two possibilities: to use driving simulators (representing a significantly easier approach) or real driving. The latter would provide more reliable results, but it would be complicated to realize. The major problem would be how to precisely register the time of the object appearance and the time of its detection by the driver, in order to obtain the object detection time. An additional problem would represent the determination of the car position at the moment of the object appearance.

Due to these limitations and the fact that the research results showed a mild preference for the 3000 K LEDs, the presented pilot project can be considered as an initial step of a broad research needed to decide on the preferred color of light from a driver's point of view, offering a track and guidelines for future research in this field.

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