Exploring the relationship between LEDs Lighting, Urban materials chromaticity and People: measurements, design and evaluation

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ABSTRACT

The aim of the research was to define urban lighting design insights, by reflecting on the relationship between urban material properties (chromaticity and spectral reflectance) and specific LEDs based lighting spectral emissions to enhance the nightly image of cities and to achieve efficient solutions. A preliminary selection of urban material, representative of different "urban colourscapes", was then followed by the definition of several lighting receipts (illuminants) which were defined by three research hypotheses. An exploratory perceptive user assessment was set up and performed to derive some insights about the transformation of the user's perception about the same material with different SPDs, to significantly enhance the attractiveness and appeal toward the architectural and urban surfaces.

KEYWORDS

Lighting Design, Urban Material, SPD, textures, Spectral Reflectance, Chromatic Saturation, LEDs

Received 06 June 2017; **Revised** 7 July 2017; **Accepted** 1 September 2017

CITATION: Casciani D. and Rossi M. (2017) 'Exploring the relationship between LEDs Lighting, Urban materials chromaticity and People: measurements, design and evaluation', Cultura e Scienza del Colore - Color Culture and Science Journal, 08, pp. 65-74, DOI: 10.23738/ccsj.i82017.07

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1. INTRODUCTION

The literature review defines the *"urban colourscape"* (Lancaster, 1996) as the colour summation of the exposed elements perceivable in urban public spaces (Yin, 2003), both the natural objects (e.g. urban bare land, rocks, grass, rivers, trees etc.) and the artificial ones referring to urban buildings, structures, roads and furniture (Xiaomin and Yilin, 2009). It is defined both by urban single colours and by the whole visual effect made by the contrasts of different layers of the city and the general environmental luminosity (Valan, 2011). The urban colourscape influences the urban culture and style. The 75% of the main visual leading tonality is made from the combination of the hue of the walls, dependent by the inherent colour of building's materials or by surfaces paints (Bagordo, 2012). Several studies show that, the great part of historical urban colour is mainly dependent by the inherent colour of building's materials decided for their cheapness and easiness to be found, such as yellow or white paint (Bagordo, 2012). In more modern urban constructions, with new technologies and new materials, also new colours are used, following the fashionable trends in architecture with saturated coloured coats or luxurious façade surfaces and materials (Borsotti, 2012). The majority of available studies about this topic focused on the urban chromatography during the daytime, forgetting the importance of designing the chromatic image (Nasar, 1998; Lynch 1960) of the city by night (CIE 136 – 2000; Bellia, Agresta and Pedace, 2013) due to the use of artificial lighting design to shape the distinctive quality of the space. This is important to ensure the city beautification (Schanda, 2001), to increase the navigation in the urban nightscape (Van Santen, 2006) and to provide energy efficiency. This paper aims at investigating the urban colourscape by night, considering issues related to urban materials, lighting design practice and LEDs lighting technologies. The hypothesis is that, as LEDs based lighting fixtures are becoming more powerful, efficient and more sophisticated in terms of the provided different spectral power distribution (SPD), the urban lighting design could take into account users' experiences of the urban chromatography during the night-time.

2. RESEARCH AIM

Considering the fact that there are few studies exploring the topic, this research was aimed at pioneering the exploration of the relationship between urban material properties (chromaticity and spectral reflectance) and specific lighting spectral emissions that could enhance the visual appearance of facades, external walls and street surfaces. The study was performed through objective and subjective evaluations, by using both the quantitative and qualitative analytical method. The research hypothesis is that LEDs based lighting systems, applied in the urban space, can be customized for enhancing the perceived brightness, colour rendering and saturation of colours of materials of a specific urban space and, at the same time, achieving the scope of energy efficiency by wisely manipulating the SPD.

3. RESEARCH METHODOLOGY

A two steps investigation about urban materials and LED's based lighting systems was performed:

- Phase one: collection and preparation of highly recurrent urban materials that were grouped into clusters and measured into a laboratory set up.
- Phase two: definition of lighting receipts specific for the different categorized chromatic samples followed by an exploratory subjective assessment with users.

4. URBAN MATERIAL SELECTION

The investigation was performed with a preliminary survey about the most representative urban materials used in Europe, both traditional and modern ones, by collecting samples to be tested into a laboratory set up. The selection was aimed at covering a wide range of chromaticity: stones, bricks along with natural, varnished and treated (oxidated) metals. A small range of materials (20 samples) was measured (Figure 1).

4.1 URBAN MATERIAL MEASUREMENTS

Measurements of the spectral reflectance of surfaces (Figure 1) were performed using the Minolta Photospectrometer CM-700d. Each material was measured several times in different points of the surface because colours changed significantly in the same sample. After the calibration test, each measure was repeated five times to derive a mean measurement (Casciani, Musante and Rossi, 2014).

4.2 URBAN MATERIAL CLUSTERING

Depending on spectral reflectance, materials were clustered in different categories:

- *yellowish and reddish toned ones*, such as Bricks, Cor-Ten Steel, Dark and Light Brass;
- *reddish materials*, such as Porphyry Stone and red (RAL 3020) varnished

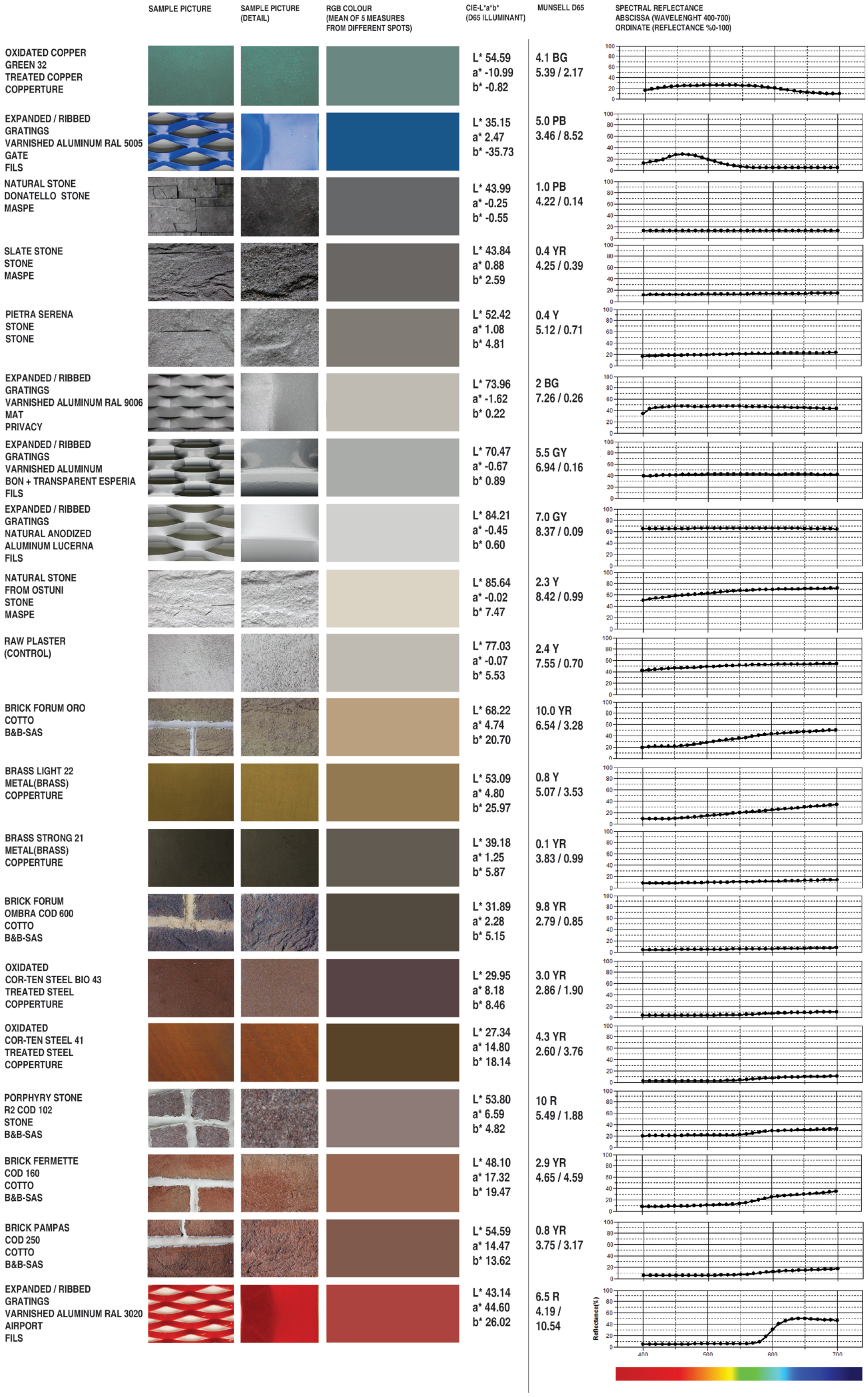


Figure 1 - Diagram of selected urban materials: two pictures of the sample under natural lighting, the correspondent measured colour given as a RGB uniform colour, the correspondent in the CIE L*a*b*, the corresponding Munsell chip plate when samples were lit by D65 illuminant and the measured spectral reflectance.

Aluminium;

- *green-bluish materials*, such as Green Oxidated Copper and blue (RAL 5005) varnished Aluminium;
- *clear grey materials*, such as Plaster, natural Aluminium, anodized Aluminium, clear (RAL 9006) varnished Aluminium, Ostuni stone;
- *darker grey and black ones*, such as Pietra Serena Stone, Slate Stones.

5. CUSTOMIZING THE SPECTRAL POWER DISTRIBUTION

Recently, the necessity to have a better method for characterizing the colour rendering quality of LEDs has increased the debate about the effectiveness of the traditional colour rendering metric (CIE-CRI) (Schanda, 2002; Bodrogi et al., 2005; Davis and Ohno, 2005). The traditional CIE-CRI is a fidelity metric, used to measure the ability of a light source to render a defined set of colour's samples in comparison to a reference illuminant (Commission Internationale de l'Eclairage, 1995). On the other hand, *"fidelity"* is not always the desirable property of a light source, because, in some situations, the colour saturation is preferred (Judd, 1967; Smet et al., 2011; Houser, Tiller and Hu 2004). In relation to this, some studies were recently performed in residential and retail contexts (Knight, 2013; Rea and Freyssinier, 2013), showing that a wide range of chromaticity can appear *'white'* or *'minimal tint'* and that such chromaticity do not belong to the Black Body Locus (BBL). With illuminants with chromaticity below the BBL, colours of the items appeared more striking and white objects appeared brighter. In this regard, LEDs can perform a sharp spectral variation, optimizing their SPDs in order to maintain high CRI while increasing the ratio between the lumen output and the optical power of the light source (Luminous Efficiency of Optical Radiation, LER).

5.1 SELECTING THE METRICS OF COLOUR RENDERING INDEX

In order to design a set up for a perceptual evaluation of the appearance of urban materials (and their colours) in relation to different SPDs, a set of illuminants for two different values of correlated colour temperatures (CCT), 3000K and 5000K, were designed to compare different CCTs and different SPD, in order to obtain better chromatic rendering or more vivid colours in relation to red/orange and green/blue materials or to render more luminous and texturized the appearance for the grey ones.

For the evaluation of colour rendering, three different indices have been considered:

- CRI (R_a) for the evaluation of colour fidelity;
- CQS (Q_a) (Davis and Ohno, 2010) which uses the saturated chromatic samples and does not penalize the increase in the score of saturation without tint distortion. Some illuminants were built to maximize several chromatic samples in relation to the previous clustered categories (e.g. red, red/yellow, green/blue). The CQS method defines the gamut area scale Q_g that is calculated as the relative gamut area formed by CIELAB a*, b* coordinates of the 15 colour samples illuminated by the test illuminant. The Q_g value is normalized by the gamut area produced by the CIE D65 and multiplied by 100.
- TM-30-15 is a standard for quantifying colour rendering properties of light sources, published by the Illuminating Engineering Society in 2015. This Technical Memorandum describes a method for evaluating light source colour rendition, quantifying the fidelity (closeness to a reference) through a Fidelity Index (R_f) and gamut (increase or decrease in chroma) through a Gamut Index (R_g) of a light source (TM-30-15, 2015). The method also generates a colour vector graphic that indicates average hue and chroma shifts, which helps in interpreting the values of R_f and R_g. This graphical representation is very useful to understand the difference between two SPDs with the same value of R_g index (i.e. 100) in rendering the appearance of different colour samples. In particular, $R_g > 100$ means an average increase in saturation; $R_g < 100$ means an average decrease in saturation.

6. EXPLORATORY SUBJECTIVE ASSESSMENT OF LIT MATERIALS

6.1 DESIGN OF THE EXPERIMENT: MATERIALS SELECTION AND LIGHT BOOTH

The second part of the research about the relationship of lighting and urban materials was focused on testing a smaller amount of material samples under different lighting conditions in a controlled experimental light booth equipped with LED lighting sources. In each different categorized chromatic and material cluster, the most representative samples were chosen in order to represent different hues (red/ yellow/green-blue/clear grey) but also different application in the city (facade, pavement, basement, monuments, roofs) (Figure 2).

The light booth is a small chamber (80x76x58cm) with internal surfaces in achromatic medium grey ($\rho = 0.36$) and LEDs lights sources placed at the top of the booth. It is equipped with 5, separately controllable channels: Phosphor converted cold white (5000K), Phosphor converted warm white (3000K), generic Red LED with a dominant wavelength of 624 nm and a typical Spectral Half-width (nm) $\Delta\lambda_{1/2}$=20 nm, generic Green LED with dominant wavelength of 505 nm and a typical Spectral Half-width (nm) $\Delta\lambda_{1/2}$=30 nm, generic Blue LED with dominant wavelength of 455 nm and a typical Spectral Half-width (nm) $\Delta\lambda_{1/2}$=20 nm.

The intensity of each colour is set up by a PWM constant voltage LED driver controlled by the DMX protocol: the DMX controller is an electronic board connected to a laptop through an USB port. A dedicated software running on the laptop was used to select the required lighting mixture for the experiment (Figure 3). The average illuminance measured on the surface of the sample was about 70 lux which

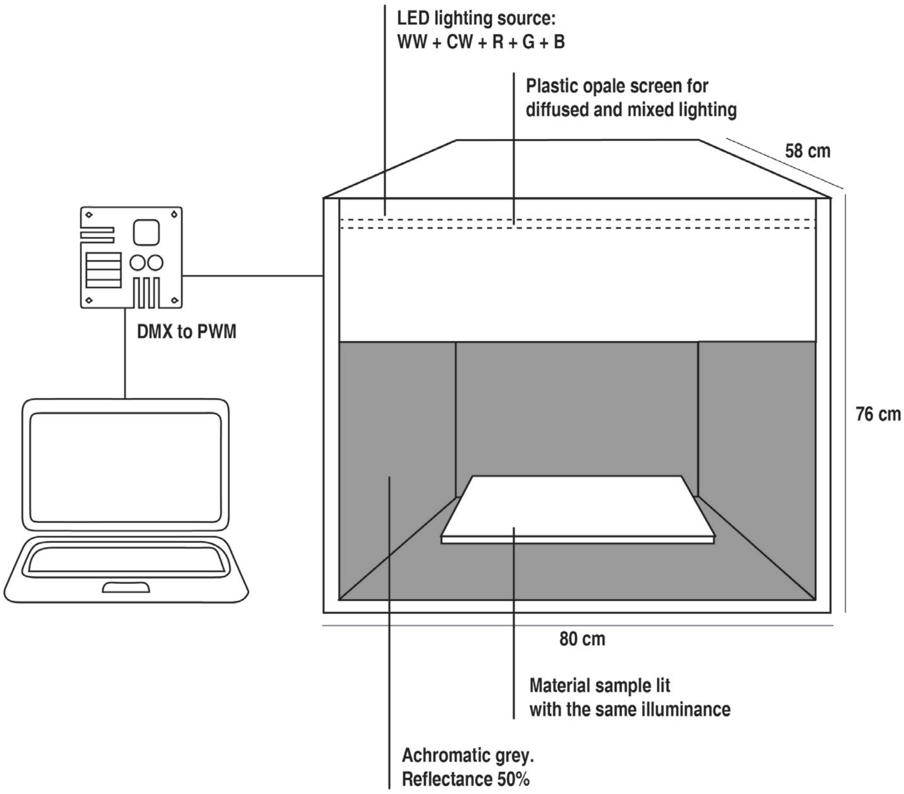


Figure 2 - Selected urban materials for the experiment from left to right: Oxidated Copper Green, Ostuni Natural Stone, Brick Forum Oro, Brick Fermette Cod 160, Porphyry Stone

Figure 3 - Lighting booth set up: main features and dimensions

was considered a suitable average value for architectural lighting in urban spaces.

6.2 DESIGNING THE ILLUMINANTS: EXPERIMENT HYPOTHESIS

To properly evaluate the gamut area (tint distortion and increase/decrease of saturation), it is important to select colour samples whose reflection's spectra cover all real current and future pigment absorption's spectra to preclude gaming. Gaming means that the SPD of an illuminant could be tailored in order to improve the score of the index, but do not improve the fidelity of a specific colour plate: in fact it is possible to introduce a small perturbation in the visible spectrum to exploit specific details of the reflectance samples used for colour rendering index calculation (Smet et al., 2013). For this reason, TM-30 colour sample dataset has been chosen for evaluating the gamut area of each proposed illuminant.

Hypothesis 01:
High colour rendering of the materials

Two illuminants with a high value of CRI and CQS (at least 90) and with different colour temperatures were proposed (3000K-5000K). In particular for the high colour rendering 3000K illuminant (Figure 4):

- $Q_1>90$ and $Q_2>90$ for materials clustered in Red group;
- $Q_7>90$;$Q_8>90$ for materials in Grey group;
- $Q_2>90$;$Q_3>85$;$Q_4>90$ for Yellow-Orange group;
- $Q_{10}>95$;$Q_{11}>95$;$Q_{12}>95$ for Green/Blue group.

For the high colour rendering 5000K illuminant (Figure 5):

- $Q_1>90$ and $Q_2>85$ for materials clustered in Red group;
- $Q_7>90$;$Q_8>90$ for materials in Grey group;
- $Q_2>85$;$Q_3>90$;$Q_4>95$ for Yellow-Orange group;
- $Q_{10}>85$;$Q_{11}>85$;$Q_{12}>95$ for Green/Blue group.

For both the illuminants, the main colour rendering differences were located in the green sample (Q_6), the orange sample (Q_2) and light blue (Q_{11}) sample, so it was expected a good colour rendering for red and yellow materials (bricks and porphyry stones) and for green/bluish ones (oxidized copper plate). All the illuminants developed according to the

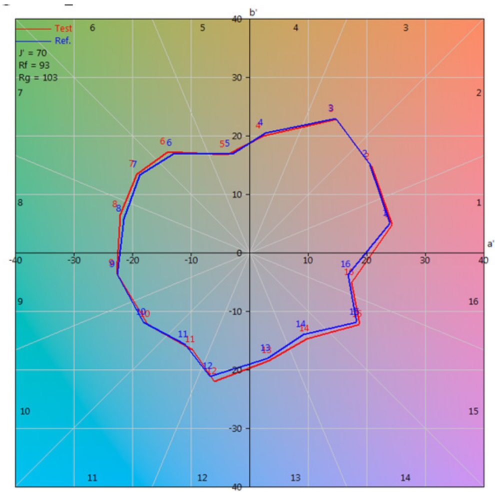


Figure 4 - (left) TM-30 Gamut Area Plot: Test is a 3000K illuminant (high fidelity colour rendering index); Reference illuminant is a blackbody at 3000K

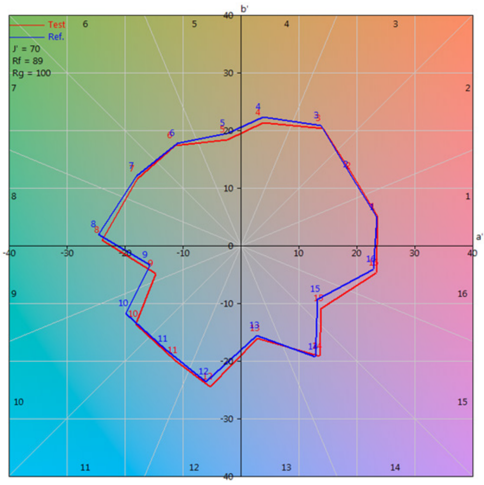


Figure 5 - (right) TM-30 Gamut Area Plot: Test is 5000K illuminant (high fidelity colour rendering index); Reference illuminant is daylight at 5000K

hypothesis 01 were constrained to be near the BBL (Δu'v'<0.01). This hypothesis was defined for permanent floodlighting of historical buildings and monuments whose image should be preserved and whose colours and textures of original material should be rendered in their original and true majesty (Schanda, 2001).

Hypothesis 02:
Enhance colour saturation for more vivid and luminous appearance of the material

The use of more saturated coloured lighting in the city was hypothesized useful for creating more interesting, pleasurable experiences, for accenting elements, enhancing volumes and in particular the architectural materials, for creating a more pleasant environment (Gardner, 2006; Van Santen, 2006; Schwendinger, 2009). Three different illuminants were designed: 3000K, 3149K and 5000K, for obtaining more vivid colours in red/orange and green/blue materials and more luminous and texturized appearance for the grey ones. To reach this scope, a set of SPD with enhanced gamut area and low colour distortion were designed (CQS>80): on the basis of the literature review, the chromaticity of this light source was placed below the BBL on CIE 1976 (u',v') colour space. In relation to this, some works were recently published showing that a wide range of chromaticity can appear *'white'* or *'minimal tint'* and that such chromaticity do not belong to the BBL (Knight, 2013; Rea and Freyssinier, 2013).

The warm illuminant (3000K) with high saturation was designed to increase the saturation for colour samples in the orange-red, blue and green area. This illuminant was expected to increase the lightness and to enhance the perceived saturation of yellow/orange/red and green/bluish materials (Figure 6).

The warm illuminant (3150 K) with moderate saturation was designed with high values of CQS for the samples Q_1>95 (deep red), Q_4>90 (gold yellow) and Q_{12}>90 (deep blue). This illuminant was expected to increase the lightness and to enhance the texturization of clear/white/grey materials (Figure 7). The main difference between this illuminant and the previous one is the value of CIE colour rendering index, which is R_a=67 for the high saturation SPD and 95 for the other.

The cold illuminant (5000 K) with high saturation was designed with a low value of fidelity colour rendering index (R_a=67) and an increase of saturation for colour sample in the orange/red, azure, violet and in the green area (Figure 8).

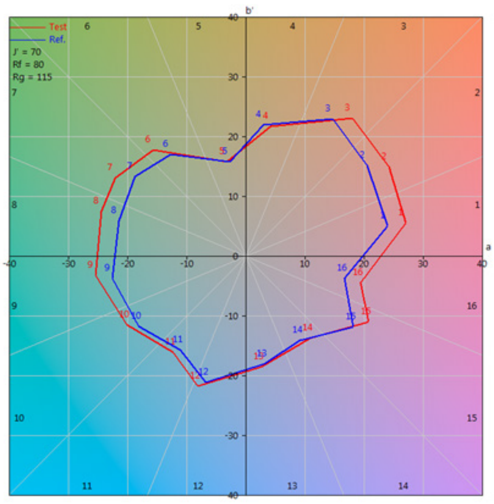


Figure 6 - (left) TM-30 Gamut Area Plot: Test is 3000K illuminant (high saturation); Reference illuminant is a blackbody at 3000K

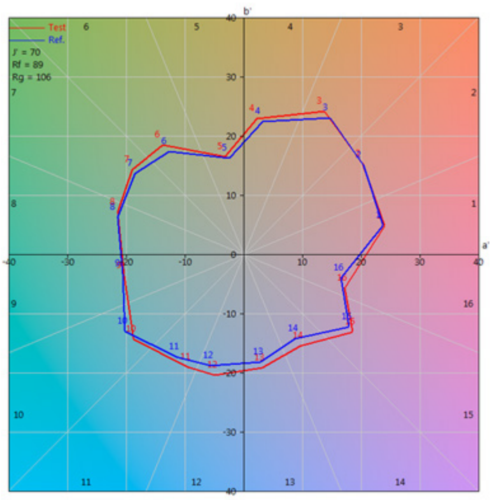


Figure 7 - (right) TM-30 Gamut Area Plot: Test is 3150K illuminant (moderate saturation); Reference illuminant is a blackbody at 3000K

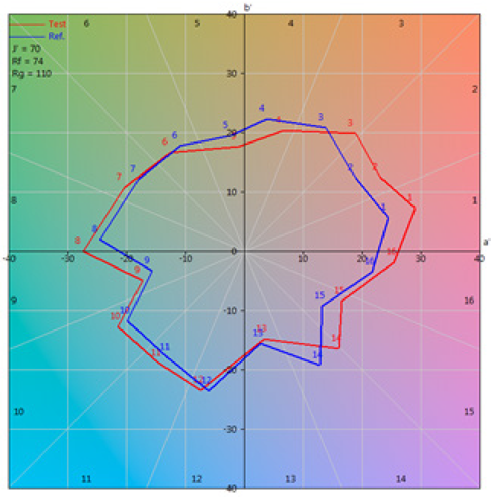
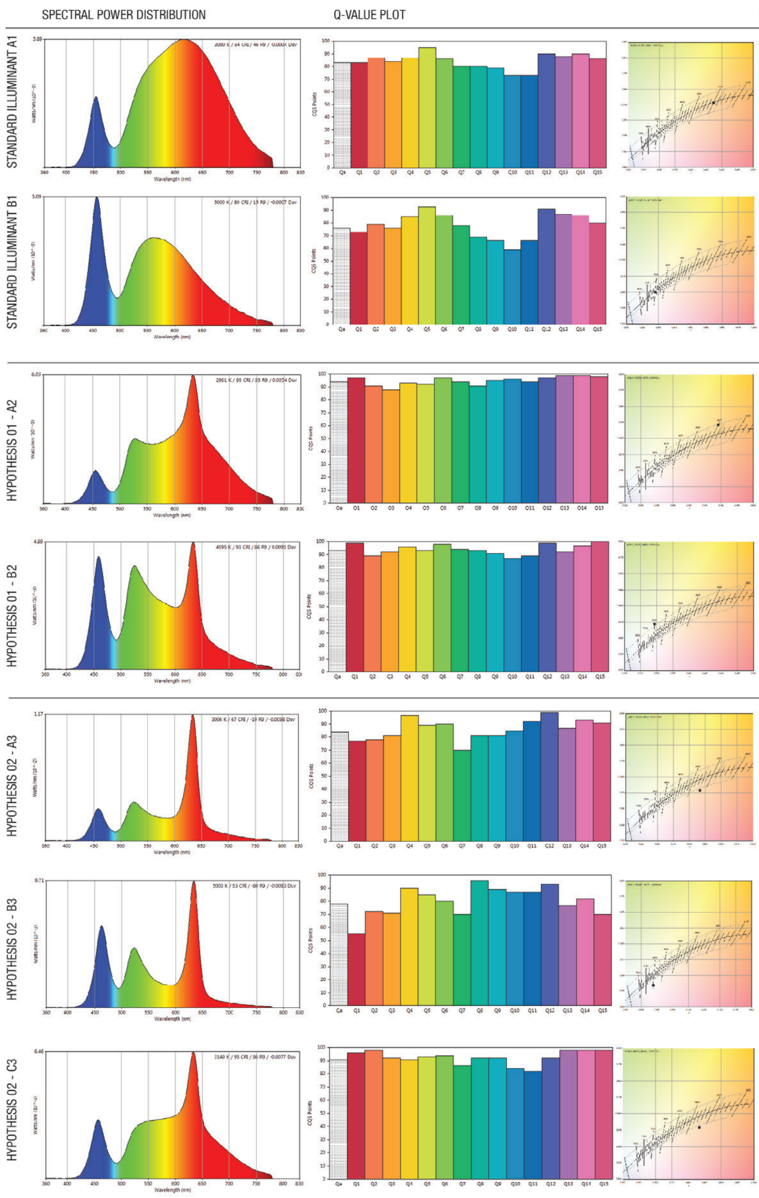


Figure 8 - TM-30 Gamut Area Plot: Test is 3150K illuminant (moderate saturation);
Reference illuminant is daylight at 5000K

Lighting receipts (illuminants)

LEDs lighting receipts were both based on the previously described hypothesis and were conceived in order to perform the lighting perception assessment with the users. The reference illuminants were designed in two CCT and with a standard CRI (A1 @ 3000K CRI 84 and B1 @ 5000K CRI 80) and were compared for each material in order to understand people inclination in choosing one CCT or another (the results of this part of the experiment are not discussed in this paper).

The illuminants with high CRI (93) were also designed in two different CCT (A2 @ 3000K and B2 @ 5000K) and compared with the reciprocal reference illuminants. The illuminants with a SPD with enhanced gamut area and low colour distortion were designed in the two CCT (A3 @ 3000 and B3 @ 5000K) and were used in comparison with the reciprocal reference illuminants for coloured materials. More than this, a moderate saturated warm illuminant (C3 @ 3150K) was designed to be compared with clear achromatic materials. The horizontal illuminance (E_h) values were set up and measured to be equal throughout the experiment and between the different illuminants (Figure 9).



CCT	CRI	CQS(Q_a)	Q_g	LER (lm/w)	
3000K	84	83	1.006	278	
5000K	80	76	0.917	305	
2991K	93	94	0.892	279	
4995K	93	93	0.943	307	
3006K	67	84	1.406	281	WARM HIGH SATURATION
5003K	63	78	1.233	270	COLD HIGH SATURATION
3149K	95	91	1.220	280	WARM MODERATE SATURATION

Figure 9 - Representation of selected SPDs for reference illuminants, hypothesis 01 and hypothesis 02

6.3 LIGHTING ASSESSMENT

In order to test the lighting influence in perceiving urban materials and to investigate the impact of the lighting design on the appearance of materials, a qualitative and quantitative cross-cultural investigation from users perspective was conducted. 26 volunteering normal colour vision students (53% Male – 47% Female; average age 28 years old; 40% Italy, 13.3% Brazil; 13.3% Lebanon; 33% Ecuador, Colombia, Philippines, Turkey, France) participated to the test. The test consisted in watching the selected 5 materials [Figure 2] under 7 different lighting conditions (illuminants) coupled in opponents for a pairwise comparison:

- Reference Illuminant (A1-B1) vs Hyphotesys1 (A2-B2);
- Reference Illuminant (A1-B1) vs Hypothesys2 (A3-B3-C3).

Participants were adapted to each lighting condition and were asked a series of questions in order to assess the naturalness of the appearance (e.g. realism and colour fidelity), the enhancement of texturization (e.g. tri-dimensional appearance), the enhancement of colours vividness (e.g. saturation) and the augmented luminosity (e.g. brightness) of materials. An Ishihara test was performed preliminarily to check eventual colour blindness between participants. During the perceptive tests, the order of the questions and materials was randomized.

7. RESEARCH RESULTS

A preliminary elaboration of data was performed with a statistical analysis (Likelihood ratio) in order to identify the main perceived differences between the lighting receipts. The quantitative statistical data were supported by qualitative reflections derived from the interviews performed during the experiment. This was aimed to depict a more complete and clear understanding of the relationship between lighting and urban material perception from the user perspective. Qualitative descriptions were re-written, analysed and mapped in relation to statistical elaborations (Table 1).

The naturalness and realism of urban materials

The coloured (red, yellow, green/bluish) and the achromatic urban materials, under the illuminants with high CRI (A1 @ 3000K and B1 @ 5000K), were not perceived as more natural and better rendered by the participants. The majority of them *"could not notice a big, appreciable difference"* and showed problems in remembering the colour rendering of the material in natural conditions (*"under the sunlight"*). Participants noticing the realism of materials enhanced by the illuminant with high CRI perceived it as *"improved if compared with the previous (reference) one"*, *"looking more natural"*, gaining in *"three-dimensionality and depth of the grouts"* in comparison to the reference one, which was perceived more *"flat and uniform"* (e.g. Porphyry Stone). On the other hand, other participants perceived the materials under the high CRI illuminants as deviating the real colours by oversaturating in the yellow bands and lacking naturalness (e.g.Ostuni Natural Stone).

Saturated and vivid urban materials

All the coloured urban materials (red, yellow, green/bluish) under the illuminants with high saturation (A3 @ 3000K and B3 @ 5000K) were perceived as more vivid, more saturated and generally more colourful. In comparison to the

Table 1 - Statistical elaboration of data with *p≤0.05 **p≤0.01 ***p≤0.001 level of significance

LIGHTING RECEIPTS – ILLUMINANT COMPARISON WITH MATERIALS				PERCEIVED COLOUR FIDELITY AND REALISM	PERCEIVED COLOUR SATURATION AND BRILLANCE	
MATERIALS	REFERENCE ILLUMINANT	HYPHOTESYS 1	HYPHOTESYS 2	(%) RATING MORE NATURAL LOOKING MATERIALS IN HYPHOTESYS 1	(%) RATING MORE VIVID MATERIALS IN HYPHOTESYS 2	(%) RATING MORE LUMINOUS MATERIALS IN HYPHOTESYS 2
Oxidated Copper Green	A1	A2	A3	30**	90***	100***
	B1	B2	B3	62.5	100***	100***
Ostuni Natural Stone	A1	A2	C3	19.23***	-	96.15***
Brick Forum Oro (yellow)	A1	A2	A3	30.77***	92.30***	96.15***
Brick Fermette Cod 160 (red)	A1	A2	A3	46.15	100***	100***
Porphyry Stone	A1	A2	A3	20**	90**	90**
	B1	B2	B3	25**	75**	87.5***

reference illuminants, almost all the participants noted an *"enhancement of hue"*, an *"enrichment of chromatic rendering"*, an *"evidently saturation of colours"* that were *"better perceived"* as more *"saturated, vibrant, vivid"*: *"it looks more vivid, is like photography, better to look at, pleasant for the eyes"*. Urban materials appeared *"flat, pale and lifeless"* under the reference illuminants; meanwhile under the saturated illuminants they were perceived as *"more appealing"*, giving a *"chromatic balance"* and *"doing justice"* to the colours of the urban materials. In addition to this, *"when compared with the whiter grouts"*, many participants noticed different hues that were unperceivable before.

Brighter, more luminous and textured materials

All the coloured urban materials (red, yellow, green/bluish) and also the achromatic ones under the illuminants with high saturation (A3 @ 3000K, B3 @ 5000K and C3 @ 3149K) were perceived as more luminous and brighter, even if several participants explained that phenomena as a change in the CCT. The achromatic clear sample of material looked *"evidently whiter"* and details stood out in a more striking way. In fact, participants noted that the texturization was improved under the saturated illuminant: *"You notice more the imperfection"* and it was more evidenced the *"texturing and grit"*, meanwhile with the reference illuminants the material appears *"smooth"*. *"Grain becomes easier and faster to be perceived"* with the saturated spectrum that makes the materials *"less flat and with more details"* (e.g. in Porphyry Stone) by *"standing out more the three dimensions"*.

8. DISCUSSION, LIMITS AND FURTHER STEPS

This experimental study was conceived as a work about both measuring the properties of urban materials and hypothesising different lighting conditions to enhance their appearance properties. The study was also aimed at exploring the chromatic differences between urban and architectural materials in order to explore the urban colourscape at night, which is a particular topic of research in its infancy stage, from what stems from the literature review. More than this, the experiments highlighted the importance of the lighting conditions in which the urban materials are perceived: manipulating the SPD with specific characteristics can significantly change the user's perception of the same material and enhance the attractiveness and appeal toward the architectural and urban surfaces. All the hypotheses about the illuminants were derived both from lighting design practice and also from experimental studies conducted in different contexts (retail and domestic environments). In this regard, this experiment conducted on the urban material could be considered pivotal and the first on its genre for the applicative sector. The user assessment has been useful to confirm several hypothesis about the relationship between LEDs lighting, urban materials and people perception. Further steps of this study would provide a wider sample of participants to the experiment and the inclusion of experts' point of view on the topic. As a preliminary statement, this study can conclude that there is a wide margin for sophisticating and customizing the lighting receipts for specific urban materials in order to create better, more expressive and appealing nocturnal cities.

AKNOWLEDGEMENTS

We would like to thank the companies (B&B Sas, Copperture Snc, Fils and Maspe) that supplied the materials used to develop the experiments. In addition, we are really grateful to Konica Minolta for having provided the instrument CM-700d to perform and elaborate the measurements on the material samples. Finally, we are expressing our gratitude to all the users that were involved in the perceptive assessment at the Laboratorio Luce of the Politecnico di Milano. A special thanks goes to the Eng. Danilo Paleari that was part of the team in providing the test lighting booth used in the experiment.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The author declares that nothing has affected his objectivity or independence in the production of this work. Neither the author nor his immediate family member have any financial interest in the people, topics or companies involved by this article. Neither the author nor his immediate family member had a professional relationship with the people and companies cited in this article. Neither the author nor his immediate family member are involved in a legal dispute with the people and the companies cited in this article. No conflict of interest including financial, personal or other relationship with other people and organization within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, this work.

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