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The impact of spectral characteristics of light sources on the subjective perception of historical objects

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Abstract. The nighttime illumination of historic buildings affects their aesthetic perception and environmental impact. White light, imitating daylight, is often used for architectural lighting today. In order to improve the visibility of the object and details, it changes the image of historic buildings, characterized by soft night lighting. Recent findings also show the negative impact of light on nocturnal ecosystems. This paper discusses observer acceptance of various modern LED light sources with different spectral composition. In the laboratory settings, subjective perceptions were gathered through questionnaires assessing lighting quality and spatial impression. Data suggest that eye adaptation to light and the immediate lighting conditions has a strong effect on the subjective evaluation. Further, the ability to differentiate and correctly describe differences between the lighting was limited if lights were not observed in one scene. In general, good acceptance of warm light has been found. Our findings confirm that selection of light source spectral properties can provide sustainable solution that preserve historical heritage and minimize negative impacts on biodiversity and light pollution.

1. Introduction

Visual perception plays a dominant role among human senses and visual information accounts for approximately 75–90% of all sensory input. Light entering the eye interacts with the human visual system [1], enabling the perception of shapes, contrasts and colours in the visual field. Light also exerts significant non-visual effects on the human organism, particularly in regulating circadian rhythms and other biological processes [2]. The magnitude of non-visual responses can differ from the visual ones based on the spectral composition of the light due to the shift in the peak sensitivity of the two systems. To express and predict the physiological effects of light on human, the Melanopic Equivalent of Daylight Illumination (mEDI) was introduced in 2018, along with a calculation toolbox [3] closely followed with recommendations [4]. This provided necessary knowledge base for "integrative lighting systems", sustainable solutions integrating the visual and non-visual effects of light. Also, it has been already included into the tools for assessing the quality of the built environment [5] and novel parameter U500 [6] has been introduced to quantify of the impact of light spectra on biodiversity.

In outdoor light installations, particularly in the architectural lighting, monitoring obtrusive light helps minimise the impact on the environment and prevents light pollution, which can affect

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ecosystems over vast distances and creates alarming increase of light at night (LAN) with a global estimate of 2.2% annually [7]. The growing understanding of its impact on ecosystems also highlighted the effect of the spectral composition. The most widely deployed lighting technology today, LED, typically contains significant content of short wavelengths that were not present in previously used outdoor lighting sources, such as conventional high pressure sodium lamps (HPS) and gas discharge lamps. From an environmental perspective, it is the short wavelengths that have the greatest impact on local ecosystems [8].

Choice of light also affects human visual perception, particularly in terms of colour recognition, contrast sensitivity, and spatial and detail perception [1]. Human visual system adapts to different lighting conditions over time. The visual experience of illuminated objects is influenced by previous light exposure, adaptation status and individual light memory. In the night environment, dark adapted eye is highly sensitive to high contrast and glare. The way light interacts with different materials and background elements affects the visibility of architectural details, textures and spatial proportions [9].

Today, lighting technology allows for the precise selection of light colour and spectrum, or even offers luminaires that can change colour on demand. The selection of white light sources has expanded significantly, offering a broad range of correlated colour temperatures (CCT), spanning from cool light (CCT > 5000), resembling daylight, to very warm light (CCT < 2000 K), closely matching the tungsten light or flame colours used in the past. Bright, neutral white lights with a day-like character allow us to achieve high visual comfort, visibility of colours and details. However, they can alter the historical authenticity of buildings. A decade ago, 4000 K was the dominant choice due to its higher energy efficiency and better availability of technology. Over time, there has been a gradual transition towards eliminating cold lights [10]. Currently, Prague has a warm white light with a CCT of 3000K listed as a reference value in the lighting manual [11]. However, scientific studies suggest that even this CCT may be perceived as too cold by eyes adapted to a nighttime environment [12] signifying that relatively little is known about light parameters and their acceptability for night-lighting installations in a historical context. It raises a question about which lighting colours and surface luminance are the most suitable for different applications from the perspective of public aesthetical acceptance. This laboratory study investigates the subjective evaluation of lighting in a night environment, using luminaires with different spectral composition.

2. Study design

This study examines the subjective evaluation of visual comfort under warm-spectrum lighting in a dark, nighttime environment. It assesses the visual appraisal and acceptance of such illumination and examines the capability of observers to differentiate between light samples with varying spectra, luminous outputs, and contextual factors, including the colour and texture of the illuminated surfaces.

Laboratory design: The lighting laboratory comprises two spaces: an adaptation room illuminated by candlelight and a main testing room designed for the installation of five independent luminaires projecting light on vertical surface, see Fig. 1. Two of these luminaires (positions 1 and 2) are visible to the observer at the same time. The dim light from these sources also ensures safe movement in the room without compromising the necessary adaptation of the eyes. The reminding three luminaires (positions 3, 4 and 5) are each located in their own enclosed light booth, which is luminously isolated from the surroundings. This ensures that they are not affected by any other light source, nor does their illumination affect the surroundings.

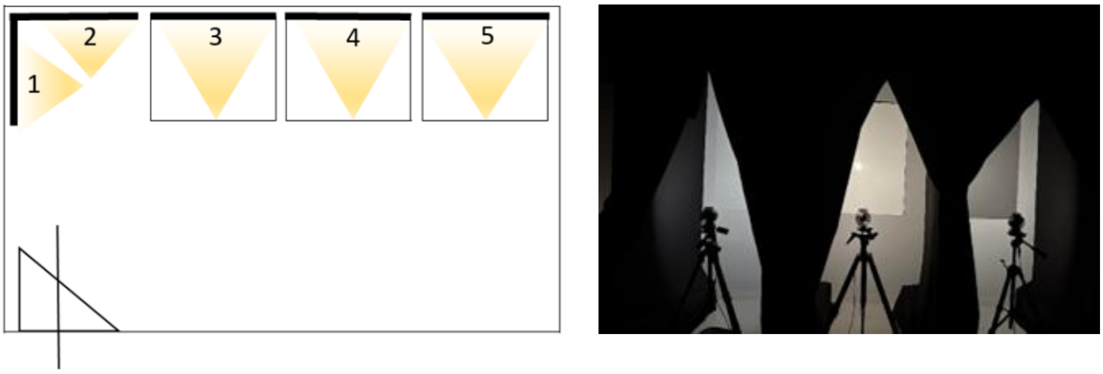

Figure 1. Spatial concept of the testing room. Position of luminaires 1 – 5 (left); photo of the configuration C (right).

The experimental setup consists of three consecutive lighting configurations which are alternated in the test room, see Table 1.

The configuration A differed in light spectrum. Light sources from 2200 K to 4000 K were aligned for same illuminance on the white, matte carboard surface. In configuration B and C, light position 1 and 2 were used as a general lighting with the main purpose to allow safe movement in the room and its evaluation has not been analysed. The configuration B exhibited variability in luminous output and the resultant surface luminance. On the testing position B3, B4, B5, light sources with same CCT (2200 K) and various luminous outputs (setup on 100%, 25%, 50% of the luminaires lighting power), provided surface luminance from 5.565 cd/m^2 to 20.969 cd/m^2. The sources in the lighting configuration C had same light parameters (CCT 2200 K, luminance output 25%) but the surfaces of the illuminated area varied in texture (matte to high glossy) and colour (reflectance 46 % - 81 %). An illustrative photo of open booths in the configuration C can be found in Figure 1 on the right.

Study protocol: During the study, each participant entered the laboratory 3 times to evaluate above-described lighting configurations. The order of viewing the lighting samples was fixed, from position 1 to position 5. For each visit, participants were asked to evaluate the installed light sources using a visual analogue scale questionnaire (VAS), with questions based on three subjective parameters: light quantity (bright light/dim light); perceived lighting colour (warm light/cold light); and visual appreciation (like/dislike).

Table 1. Lighting parameters in three experimental configurations

Lighting configuration	Position of the luminaire				
Main tested parameter	**1**	**2**	**3**	**4**	**5**
A CCT [K]* (U500)	2 700 (10.4 %)	2 200 (6.5 %)	4 000 (21 %)	2 700 (10.4 %)	3 000 (14 %)
B Luminous power setup (Surface luminance [cd/m^2])	-	-	100 % (20.96)	25 % (5.56)	50 % (9.40)
C Illuminated surface** (Surface reflectance)	-	-	Light grey (81 %)	Glossy white (97 %)	Dark grey (46 %)

* see Fig. 2 (left) for spectral characteristics of the light sources;
** see Fig. 1 and Fig. 2 (right) for detail of configuration C.

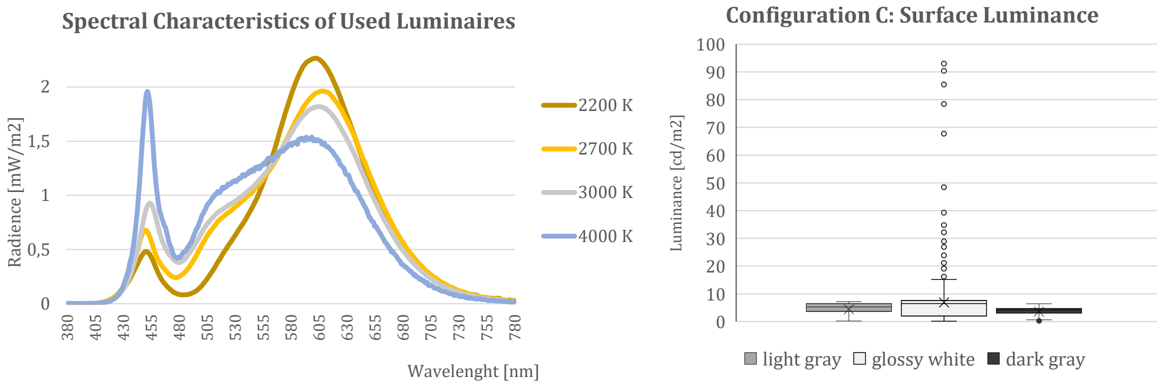

Figure 2. Spectral composition of the laboratory light sources (right); surface luminance on the illuminated surface in configuration C, measured at horizontal section at the eye level, i.e. 120 cm (right).

Total of 65 volunteers (30 male, 35 female, aged 17-28 years) participated in the study. They were informed that the study was part of research on architectural lighting of historic buildings but were not instructed to evaluate accordingly. Study has been performed in the evening hours, after sunset. To provide the dark adaptation of the eye, participants were asked to spend at least 10 minutes in the adaptation room before entering to the laboratory as well as during the short breaks between testing.

Data analyses: Statistical analyses were performed in Jamovi software [13]. Based on the result of Shapiro-Wilk normality test, data does not meet the requirements of a normal distribution. The nonparametric Kruskal-Wallis tests were used for analyses, followed with pairwise comparisons for post hoc analyses.

3. Results

Participants were asked to rate different light sources based on three subjective parameters: light intensity, perceived CCT, and visual appraisal in three different lighting configurations.

Test A –Variance in light spectrum

Lighting configuration A tested the subjective evaluation of light of different spectra. It showed the ability to discriminate between the correlated colour temperature of the various light sources ($p < 0.001$) and significant differences in their visual evaluation ($p = 0.004$), see Figure 3.

The results of the colour temperature identification highlight the crucial role of the lighting context in the perception of lighting scenes, as demonstrated by the evaluation of the same source (CCT 2700 K) presented together with another light or as a single source in a lighting scene. When multiple light sources were perceived simultaneously, such as A1 (2700 K) and A2 (2200 K), respondents were able to distinguish small differences in CCT and rated 2700 K as rather cold light. In contrast, in the evaluation of isolated sources, objective assessment was more challenging and more affected by the prior lighting. Isolated 2700 K light (A4) was perceived as a very warm light when preceded by the 4000 K light (A3).

Overall, the lights were rated as pleasant, with median vote at 59 (out of 100). In the evaluation of isolated light sources A3 - A5, sample A3 (CCT 4000 K) was the least popular with a

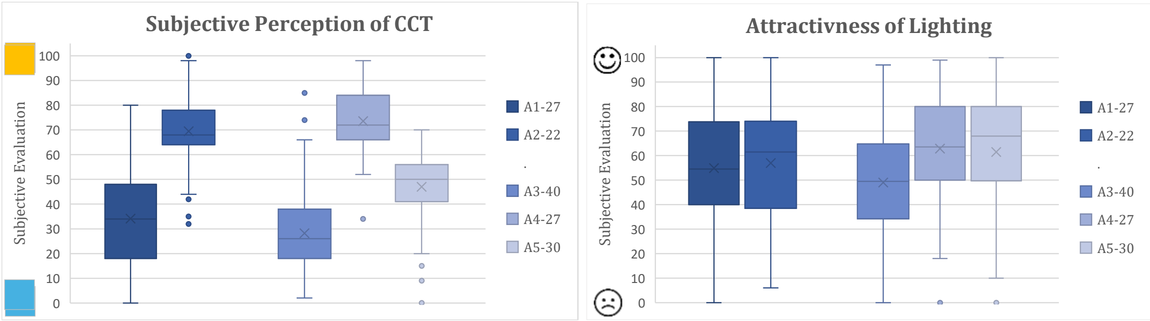

Figure 3. Effects of spectral composition on subjective assessment of warm vs. cold appearance of light (left) and subjective acceptance (right). Five light sources with different spectrum, but identical illuminance are coded according to its position in the laboratory setup (A1 to A5) and CCT (e.g. 40 for CCT 4000 K).

significant difference compared to samples A4, A5 ($p=0.04$ and 0.0017 respectively). Also, the variability in preference across different spectral settings suggests individual differences in perception, likely influenced by prior experience and personal expectations.

Test B – Variance in light output

Lighting configuration B tracked the subjective evaluation of different light output. Three visually isolated light sources with the same spectral composition (2200 K) were set to different lighting power (100%, 25% and 50% of total lighting output) and provided mean surface luminance values on white matte cardboard of 20.96 cd/m^2, 5.56 cd/m^2 and 9.40 cd/m^2, respectively.

The results suggest that respondents were able to discriminate the increase/decrease in luminance compared to the previous light source (light source effect, $p < 0.001$), but were unable to objectively determine the magnitude of the change. For example, there was no significant difference between the perceived luminance of light sources set at 100% (B3) and 50% (B5), which were not observed in immediate succession, see Figure 4, left.

The differences that were perceived in the surface luminance ratings had no effect on the visual attractiveness ratings, as the difference between the samples was insignificant, the analysis of subjective visual appraisal revealed only moderate positive correlation between light intensity and preference, see Figure 4, right.

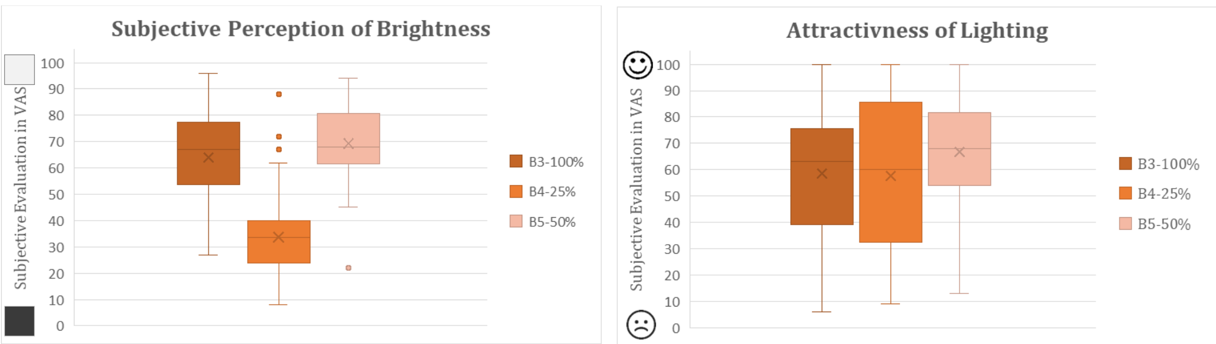

Figure 4. Subjective assessment of the surface luminance – rating of perceived brightness (left) and the visual attractiveness of the light (right), tested on three illuminated surfaces with different surface luminance, but identical spectral parameters. Lights are coded according to its position in the laboratory setup (B3 to B5) and actual lighting setup (% lighting power).

Test C – Variance in reflectance of the illuminated surface

The lighting configuration C tested subjective evaluation of light effected by the illuminated surface. i.e. how its colour and structure influence the perception of light of identical intensity and CCT. Light sources were tested against light grey (C3), white glossy (C4), and dark grey (C5) backgrounds.

The result shows significant differences in the assessment of surface discrimination ability (p=0.0038), but no effect on visual assessment, and see Figure 5.

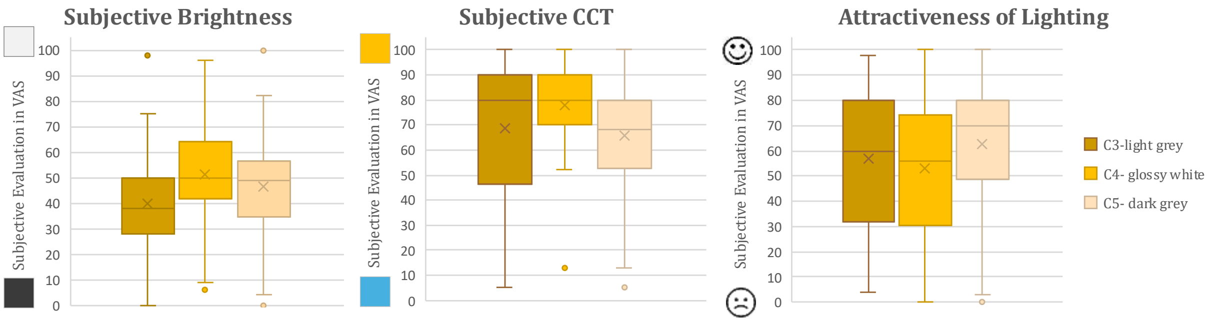

Figure 5. Subjective assessment of background influence - assessment of the visual appraisal (left) and brightness (right). Group of light sources with identical light spectrum (C3 to C5, 2200 K) and illuminance and different background are coded according to its position in the laboratory setup (C3 to C5) and parameters of the illuminated surface.

The colour of illuminated surface significantly affects perceived brightness of the light sources, with the white glossy surface (C4) enhancing perceived intensity due to higher reflectance, while the dark grey surface (C5) reduced it by absorbing more light. Perception of the neutral light grey surface (C3) varied among respondents, suggesting an influence of personal preferences. These findings underscore the role of illuminated surface characteristics in lighting design, emphasizing their impact on visual perception and illumination effectiveness.

4. Discussion

This study confirmed the role of individual eye adaptation and light memory limitations in subjective perception. The human eye is highly adaptive to changes in light conditions and dynamically adjusts its sensitivity depending on ambient light and contrast. As a result, participants were able to precisely describe shifts in perceived brightness and colour temperature if they could see the light sources simultaneously, but only report the direction of the change, when transitioning between different lighting conditions. After period of time, when their lighting memory was affected by another visual stimuli, the ability to describe changes in perceived brightness and colours decreased noticeably.

In terms of preference, warm white lighting was perceived to be the most visually and aesthetically pleasing. This is consistent with previous research that suggests that warm lighting creates a more pleasant and historically authentic atmosphere [14]. The lower preference for neutral white light supports the notion that daylight-mimicking light can appear too harsh and alter the natural appearance of historic materials. The use of warm light (CCT 3000 K, U500 14%)

and very warm light (CCT 2200 K, U500 6.5 %) was equally popular in our data, suggesting the potential for alternative sources that are better suited to respect the needs of wildlife.

Perceived brightness and colour perception was also affected by the illuminated surface properties. In our data, at white glossy surface the light source appeared significantly brighter probably due to higher reflectance, while a dark grey background reduced the perceived brightness by absorbing more light and the colour perception moved to the colder light. This suggests that illuminated surface, as they can significantly alter the visual perception, needs to be considered when choosing light sources for historical buildings, where the material can play an important role in the aesthetics.

The data also suggest that lighting with higher intensity may improve the visibility of an object and details but does not necessarily translate into increased attractiveness of the illuminated scene. In contrary, the study revealed no direct link between intensity and subjective preference. This finding is particularly important for the lighting design of heritage buildings, where excessive brightness can lead to eye fatigue rather than a better viewing experience. Instead, a more balanced level of intensity combined with warm colour temperatures appears to be the most favourable approach.

5. Conclusion

This study highlighted the role of eye adaptation and prior lighting conditions as a key factor in subjective perception. Our findings support the fact that human eye is highly adaptive to changes in light conditions and dynamically adjusts its sensitivity depending on ambient light and contrast. In the night environment, lighting with very low CCT is fully acceptable while daylight-mimicking light is seen as less pleasant. These findings provide valuable guidance for the presentation of historic buildings. Next to the focus on spectral balance and light intensity, future lighting designs should carefully evaluate the visual context and environmental needs. By integrating these considerations, it is possible to create sustainable lighting designs that improve visibility and visitor experience while preserving the authenticity of historic buildings, minimizing light pollution and negative impacts on ecosystems.

Acknowledgements

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