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Visual Comfort with LED Lighting

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Abstract

A widely accepted definition of human comfort does not exist, but several metrics have been developed to quantify how much users appreciate environments, objects or interfaces. For visual comfort one of the most widely accepted approach is "that comfort is not discomfort", because it is easier to provide quantitative and qualitative evaluation of visual discomfort parameters rather than comfort parameters that we don't have a definition of. This paper presents the available suggestions and the results of a European research project about the visual comfort with LED lighting.

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Keywords: LED lighting CIE, glare, visual comfort, spectral distribution, normative

1. Introduction

A widely accepted definition of human comfort does not exist, but several metrics have been developed to quantify how much users appreciate environments, objects or interfaces. To define visual comfort two different approaches are usually considered: the most widely accepted approach is the "NON-annoyance approach" based on the assumption that "comfort is not discomfort". In fact it is easier to provide quantitative and qualitative evaluation of visual discomfort parameters rather than comfort parameters that don't have a unique definition.

Visual discomfort produces a lot of symptoms that can be clearly identified, understood and evaluated with subjective investigations: glare, difficulty in doing a visual task, annoyance, stress, and physical symptoms like headaches, pains, sore, itchy, watering eyes…. Unfortunately a mathematical model able to link these quantitative parameters to a discomfort index is under development and not completely known [1].

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The second approach is the "well-being approach" based on the evaluation of the positive effects induced by well-being and satisfaction: it needs methodologies to define and measure the well-being.

The most common comfort metrics for lighted environments are based on the "NON- annoyance approach" and consider discomfort glare as the most annoying disturb, and some other quality parameters of the lighted environment, like, luminance distribution, correlated colour temperature, contrast ...

1.1. Factors affecting visual comfort

To identify a comfortable environment is very easy, but it is not as easy to describe it: well-being and satisfaction doesn't produce a single and easily recognizable effect, but a generic condition of well-being. Usually in a comfortable lighted environment subjects don't experience visual discomfort and visual performances are not impaired.

International Commission on Illumination (CIE) documents, standards on lighting environments and available research results specify/recognize the following parameters as relevant for visual comfort in indoor lighting:

- Glare (from luminaires, daylight, bright surfaces like windows, …);
- Veiling reflections;
- Illuminance levels (work plane, surrounding, ...);
- Luminance ratios and uniformities;
- Colour rendering index – CRI;
- Correlated Colour Temperature – CCT;
- Flicker

For the visual comfort appraisal some researches also consider:

- Space and room appearance;
- Surfaces brightness and colour;
- Light distribution;
- Appearance of light and luminaires

Available guidelines and quantitative/qualitative parameters are indeed derived from studies conducted mainly with diffuse fluorescent lighting: several studies investigated if the same suggestions are still valid for LED lighting too. Some subjective experiments with LED lighting have been also performed, but as no standard setup nor reference LED sources and luminaires are defined, no clear indications can be extrapolated. Actually, in many cases, the results are inconclusive or of difficult comparison.

In SSL lighting the most relevant parameters of a lumainire, significantly different from those of fluorescent luminaire are: the Spectral distribution (considering also the directional variability) of the light source, the size and brightness of the light source and the luminaire appearance.

These parameters can lead to conspicuous differences on visual comfort perception and have been investigated in the research project EURAMET[1] EMRP JRP ENG05 "Metrology for Solid State Lighting". [2]

2. Available suggestions for visual comfort

In the recent years several researches were conducted to investigate the glare effects produced by SSL luminaires, in particular white LEDs, and to evaluate if the available glare measurement methods (especially the UGR and VCP models) are suitable for these types of light sources. CIE is aware of the problem and a Technical Report is available with a review of significant results [3]. This document states that available metrics for glare evaluation are suitable for SSL luminaires with a luminance distribution not significantly different from that of fluorescent luminaires.

[1] Euramet is the European Association of National Metrology Institutes and is responsible for the elaboration and execution of the European Metrology Research Programme (EMRP) which is designed to encourage collaboration between European National Metrology Institutes (NMIs) and partners in industry or academia.

2.1. Available metrics for glare measurement

In indoor lighting the main empirical systems able to quantify discomfort glare are the Unified Glare Rating (UGR) and the Visual Comfort Probability (VCP) systems.

2.1.1. UGR system

The UGR system, developed by the CIE in 1995 [4] is used for evaluating discomfort glare caused by lighting sources in interior lighting.

The UGR value is calculated from

$$UGR = 8Log\left[\left(\frac{0,25}{L_b}\right)\sum_i \frac{L_i^2}{P_i^2}\right] \quad (1)$$

Where:

L_b is the background luminance (cd/m^2), L_i is the luminance (cd/m^2) of each luminaire, ω_i the solid angle [sr] in the direction of the observer, and P_i the position index of each luminaire.

The UGR system is an interval scale where differences between values represent equally perceptible differences in subjective glare perception. The values run from 10 to 30, higher values suggest higher discomfort glare. A value related to lighting installation type can be provided as acceptable value, for example in office lighting a value of 20 or below is considered admissible as stated in [5].

UGR is based on results coming from fluorescent lamps when is applied to sources significantly different, the UGR results are less reliable. In particular for “small” sources (<0.005 m2) UGR values overestimate glare, while for “large” sources, like ceiling luminaires, underestimate.

Therefore, in 2002 the CIE published a Technical Report [6] with formulations and recommendations for small and large sources in agreement with new results and practical experience. In this technical report, the CIE defines source characteristics to applied specific small sources UGR formula:

$$UGR = 8Log\left[\left(\frac{0,25}{L_b}\right)\sum_i 200\frac{I^2}{r^2 P_i^2}\right] \quad (2)$$

where

I is the luminous intensity (in cd) toward the eyes,

r is the distance (in m) between the observer’s eye and the light sources.

Whit this formula discomfort glare from “small” or “extremely small” sources is not directly related to luminance (applicability of luminance concept to point source), but to luminous intensity.

2.1.2. VCP system

The Visual Comfort Probability (VCP) system, developed by IESNA in North America, is defined as “*the probability that a normal observer does not experience discomfort glare when viewing a lighting system under defined condition”* [7].

The VCP is a prediction of discomfort glare of a lighting systems expressed as percentage of observers that will judge acceptable and comfortable that interior lighting. The value scale runs from 0 to 100: VCP 0 value means that no one is comfortably with that lighting arrangement (all observers bothered by glare), while a value of 100 means that all observers are comfortably with the lighting arrangement. The VCP value for a given lighting system is derived from correlating photometric and geometric characteristics of reference lighting to observers discomfort glare assessments. To avoid performing subjective tests for every luminaire, the correlation between photometric and geometric luminaire characteristics and subjective glare evaluations has been established empirically using a reference room equipped with direct lens fluorescent luminaires. The reference test conditions, for witch the VCP is calculated, are as follow:

- Lighting system providing an illuminance of 1000 lx on reference surface in the room

- Room surfaces with 80% ceiling cavity reflectance, 50% wall reflectance, and 20% effective floor cavity reflectance
- Luminaires mounting heights above the floor of 2.6, 3, 4 and 4.9 m
- Room range scale to include square, long-narrow, and short-wide rooms
- Observation point 1.2 m in front of the center of the rear wall and 1.2 m above the floor
- Horizontal line of sight looking directly forward
- Field of view of 53° above and directly forward from the observer

The use of reference test room and lighting arrangement allows organization to provide VCP tabulation of their luminaires and comparison of luminaires glare assessment even before designing a specific lighting layout.

IESNA states that VCP system can only be used for evaluating discomfort glare produced by fluorescent lamp luminaires, because the values were derived empirically using subjective tests with fluorescent luminaires. Therefore IESNA clearly states that discomfort glare produced by "small" sources, like incandescent lamp, or "large" sources, like ceiling luminaires, or non-uniform sources, like parabolic reflectors, cannot be evaluated with this system.

2.2. Recent research

CIE report highlights [3] that discomfort glare caused by SSL luminaires with SSL clearly visible, is not easily assessable. The research review stated in [3] indicates that:

- With equivalent average luminaire discomfort glare, glare from non uniform stimulus seems greater than of a uniform stimulus, if the luminaire is at the line of sight [8]
- The glare perception decrease both for uniform and non-uniform luminance luminaires if the luminaire is above the line of sight [9]

The main factors of influence on the applicability of glare metrics are:

- Geometry, i.e. dimensions and position of sources;
- Photometry, i.e. uniformity of luminance distribution and brightness;
- Radiometry, i.e. spectrum of the sources;

Their values and influence must be checked to define the applicability of methods, because can be strongly different from those of fluorescent luminaires.

The CIE review [3] states that new formulations of existing quality metrics and evaluation of SSL behavior on discomfort glare are needed. Unfortunately some of the available results are inconclusive: researches tested a lot of different combination of luminaires, LEDs, geometrical position, luminance level and subject adaptation levels.

Takashi et al. [8] conducted a study on the geometrical factors of influence to propose a “revised” UGR. They proposed a new P_i, useful for matrix light sources, based on subjective tests comparison between matrix light sources and uniform light sources at different luminances, in different position respect the line of sight. The experiment results show that:

- P_i is mainly affected by the relative angle between line of sight and light source;
- Matrix light sources have larger P_i than uniform light sources;
- Discomfort glare of matrix light sources can be evaluated applying the revised P_i to UGR system

Kasahara et al. [9] conducted a study to clarify and evaluate geometrical and photometrical factors of influence on discomfort glare. They considered as possible discomfort causes: luminaire arrangement, number of LED lights and distribution on lighting source surface. The subjective evaluation results show that:

- Discomfort glare can be reduced using lens or other means able to diffuse light;
- If the number of LED increases, with the same light source area and illuminance provided, glare decreases;
- If the total area of the light source increases, with the same LED number, although the Boundary of Comfort and Discomfort (BCD) average luminance decreases, the level of the decrease is smaller than the level of the area increase.
- If the number of LED lights increases in proportion with the area, with LED spacing constant, although the BCD average luminance decreases, the level of decrease is smaller than the level of the increase.

3. JRP ENG 05 Contributions in Visual comfort with SSL

Today SSL products are mainly based on single or array of LED chips or dies, with high-brightness and spectra with broad yellow peak – from phosphor conversion – and narrow blue peak - from the emission of the exciting LED. The LED source output presents also a very short response time and, depending on the electronic, important flicker or modulation. Luminaires are featured with lenses, diffusers, and reflectors to shape the radiated light from the LED point sources. The size and the luminance levels can vary in size from few mm to several tens of mm and in luminance from 10^5 cd/m² to 10^8 cd/m². In the JRP ENG05 research project, INRIM (Italian National Metrological Institute) and LNE (French National metrological Institute), arranged some experiments in order to analyse the influences of LED Lighting on visual comfort and on glare.

The research about the evaluation of glare effects due to SSL lighting is very large: review of performed experiments demonstrates that available metrics for discomfort glare are still applicable if the SSL sources or luminaires do not significantly differ, in term of intensity and luminance distribution, from fluorescent lighting (so with LED not clearly visible or with some kind of diffuser) [3]. Existing criteria seems not to be applicable for non-uniform sources with LED clearly visible, but a lot of available researches are still inconclusive [3].

At INRIM, two different tests dealing with studies on SSL glare were set up. The first one was arranged in order to test radiometric parameters effects on glare, while the second was about the influence of SSL lighting on pupil diameter. The first experiment was based on a vision test dived in two sections and fully described elsewhere [10]:

- First section: a set of eighteen targets, with different luminances, was generated and randomly positioned on a calibrated screen. The observer, had to click with the mouse on every target he can see. Two different neutral backgrounds luminances (9 and 22 cd m^{-2}) have been used, and presented alternatively to the subjects
- Second section: only the previously detected targets were visualized again on the screen, the subject must put them in order from low to high luminance.

During the whole duration of the experiment, the subjects experienced glare coming from a LED and alternatively in the round, from incandescent source, both shielded with a diffuser in order to consider only the differences induced in glare by the source spectrum. This experiment showed that

- the effect of glare is practically independent for the LED source and incandescent lamp, but a lower adaptation luminances (9 cd m^{-2}) LED ensures better performance for negative contrast.
- the effect of glare is practically independent from the glare source type at higher adaptation luminances (22 cd m^{-2}) while at lower adaptation luminances (9 cd m^{-2}) LED sources give better performances then incandescent lamps.

This experiment confirmed that SSL equipped with diffuser do not differ significantly from traditional lighting sources as well the effects on glare of spectrum characteristic.

In the second experiment, the research work was to monitor the effects of glare on pupil size considering different type of sources and retinal images in order to isolate the effects of dimension and spectral distribution of the emitted radiations [11]. These photo-biological effects are investigate to compare SSL sources with traditional lighting sources. In this experiment, observers stared at a black wood wall with holes of variable diameter (0.10 and 0.025 m). Behind each hole, three lighting sources were alternatively placed and covered by a translucent glass in order to get a diffuse and uniform lighted disc: a LED luminaire, an incandescent and a metal-halide lamps. Between the subject and the lighting sources, a pupillometric system was placed.

Experiment results highlight a significant influence of the source spectral distribution and observed target on pupil size: at given luminance, the LED source always gives a smaller pupil diameter, if compared to the other two tested sources (incandescent and metal halide lamps).

At LNE a very big experiment was set up to suggest a modelization of parameters that directly influence visual comfort, testing four different lighted environment [1]. This experiment showed that the UGR formula is well correlated with subjective rating in a simple lighting set-up, lamps in uniform background, and also in a complex environment of a living room with wall and ceiling luminaries.

The model for visual comfort set up coming from the LNE experiment gives to glare the maximum weight, so it is clear that glare is one the most effective parameters people uses to judge the comfort of a lighting installation.

4. Conclusion

In conclusion it is possible to say that available metrics for discomfort glare are applicable to LED lighting if the SSL sources or luminaires do not significantly differ, for intensity and luminance distribution, from fluorescent light luminaires. To improve and assure better performance and reliability of results, it is better to equip SSL luminaires with diffuser or to design lighting set up able to hide from the direct view the SSL.

Existing criteria seems not to be applicable for non-uniform sources with LED clearly visible, but it will be necessary to define what degree of non-uniformity is acceptable. Additional parameters in SSL glare evaluation can be LED interval, CCT, and observation angle.

A large amount of researches has been done up to now and is on going on glaring effect of SSL lighting, but a lot is inconclusive. Probably to define reference test conditions, with known luminance map distribution, to concentrate and coordinate all research efforts would be helpful for effective results, as happened for CIE DE2000 Color Difference Formulation. In this way it will be possible to test different parameters under the same reference conditions: in fact glare is a multidimensional sensation as a large amount of psychophysical quantities are.

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