16th International Congress of Metrology, 14004 (2013)
DOI: 10.1051/metrology/201314004

Metrology for solid-state lighting quality

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Abstract. This article presents a study on the measurement of visual comfort of lighting for interior environments.
As presented in the introduction, the proposed approach recreates in laboratory a realistic working places and living-room configurations in order to study visual comfort with subjective ratings and physical measurements in a controllable and reproducible way.
Hereby a subjective experiment is described, conducted at LNE with the participation 50 individuals. Four different tests are fully described reporting procedures, testing facilities and subjective results.
A model for assessing visual comfort is proposed and analysed. This model considers two parameters categories: discomfort parameters (related to specific effects such as glare and flicker) and comfort parameters (referred as general visual quality). All parameters are derived from spatial and spectral distribution measurements of interior lighting conditions. Finally, the obtained results with the proposed model are presented and commented with regards to subjective rating.

Introduction

New lighting solutions such as solid-state lighting (SSL) have a great potential for energy saving. Uptake by consumers relies not only on efficiency, i.e. luminous output dividing power consumption, but also on the quality of light. The ENG05 project, a three years international research started in 2010 and funded by the European Research Metrology Programme (EMRP), addresses measurement aspects of both quantity and quality of SSL. Along with a study on colour rendering metrics, a study on visual comfort has been performed and it is presented in this paper.

It's hereby suggested that visual comfort is a complex combination of several perceptual attributes correlated to luminance distribution and spectral content of lighting, with attributes having different impacts depending on the purpose of the environment, lighting levels and the presence and degree of glare conditions.

For interior lighting standards establish luminance levels and values of colour rendering index considering safety, visual performances and comfort and many studies deal with glare or flicker, but at present doesn't exist a metric able to predict the visual comfort of an environment. This is also partly due to the fact that visual comfort researches are based more on discomfort rather than comfort parameters [III, IV]. The reason probably is that a widely accepted definition of human comfort doesn't exists, even if several metric have been developed for quantify how much users appreciate environments, objects or interfaces in terms for example of usability and agreeableness in the domain of each senses [I].

To develop a measurement method assessing the perceived visual comfort of a lighting installation, it's first of all necessary to define the measurand, i.e. the "visual comfort" attributes with respect to visual stimuli in the field.

Therefore, the aim of this study consists in a contribution to the human visual comfort characterization, considering different kinds of environments and configurations addressed specifically to the comparison of LED luminaries versus traditional lighting technologies (fluorescent, halogen).

The chosen solution recreates in laboratory several realistic configurations - working places and domestic environments - in order to study visual comfort through subjective ratings and measurements of physical quantities, in a controllable and reproducible way. The rational has been to identify influent parameters and then to develop a model, predicting the perceived comfort of a specific lighting configuration.

1 Experiment design

The observers' panel consists in 50 individuals: 26 females and 24 males aged from 18 to 62 years. As the personal visual fatigue at the moment of taking the tests could have some relevance, the half of subjects participated to the experiment in the morning and the other half in the afternoon, with equal proportion of age

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Article available at http://cfmetrologie.edpsciences.org or http://dx.doi.org/10.1051/metrology/201314004

categories. Furthermore, as also the subjects' iris colour could be a significant parameter because of its relationship with glare sensitivity, a balanced repartition between observers with dark or light colour eyes has been managed (46%: dark iris).

Each subjective experiment session is conducted with three observers at a time.. The tests begin in a waiting room with a presentation explaining the purpose of the experiment and the test schedule. All participants fill a form indicating: age, gender, height, eyes colour, use of corrective glasses or contact lenses, their own psychophysical state and their self evaluation about their glare sensitivity.

Once this first introductory part is completed, each observer is invited to successively take part to four different tests in a predefined order. Several sequences were defined distributing randomly the order of tests among the observers. Each test starts with an explanatory phase about its specific purpose and specific instructions to perform it. For each subject the whole experiment lasted about 2 h taking into account a rest of 5-10 min after each test. Participants were both LNE employees and students of local universities, these last symbolically compensated for their time and travel expenses with a sum of 50 €.

2 Subjective tests

2.1 Description of subjective test n°1 – Glare experiment

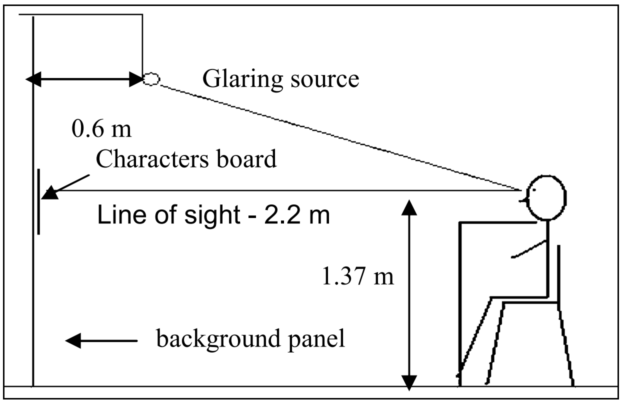
The goal of this test is to assess the glare sensation produce, in particular, by LED sources. The subjective ratings were compared with the Unified Glare Rating (UGR) formula of the CIE [VI] and the corrected CIE UGR formula for small sources [XVI].

Test n°1 consists in a simple set up where the observer look at a uniform luminance background where an overhead glaring source stands. During the experiment five different light sources were presented. The background consists in a large grey screen (2.7 m * 3 m) uniformly lighted by sources hidden to the observer's view. To the contrary, the glaring source is located in the observer's field of view and stands above a central display board (where random letters of different contrast and size are depicted) that he/she is asked to read. By design, glaring sources have almost no influence on the luminance background but the glare and the lighting sources are of the same type. Angles and distances between the observer's eyes plane, the display board and the glaring source were the same for all subjects. The observer's head leans on a chinrest and centre of the display board is used as a reference to fix the line sight (Figure 1).

For each test lamp, the observer shall read the board both with the glaring sources switched off and on and then rate the feeling of "glare" and "ease of reading" always in comparison to the conditions perceived with previous light source. With such test structure, the first lamp of the sequence has no rating and is used as reference. For all the time subjects read the board, they are asked to not look directly at the glare source.

All light sources are powered two hours before the beginning of the test in order to be sure they emit a stable luminous flux. Sources are also kept powered during the test and put in an opaque box behind the experiment set up when not used. A fast plug socket enables a quickly change of the lamps during the test.

Figure 1: Lateral view of the test n°1 set-up



2.2 Description of subjective test n°2 – Living room

The goal of this test is to assess visual comfort in a complex and common interior environment. A fully furnished and decorated living room is set up in the lab,. In the testing room (4 m x 4.5 m) six wall luminaries are installed and additional lighting sources positioned behind a large diffusing panel in the centre of the ceiling, are illuminating uniformly the setting.

During the test, the pupil dilation and the visual behaviour of the observers is recorded with a wearable eye-tracking system. This device is embedded in the frame of a pair of glasses and works with small cameras simultaneously recording images of the visual field and both the eyes.

Different lighting effects are created, mixing directed and non-directed lamps, the diffusing panel and lampshades. Details of the four configurations are given hereafter and the photographs took with an high definition CCD camera mounting a fish-eye lens are presented in Figure 2.

- **Halogen:** 6 halogen spot lamps mounted in the wall luminaires and 3 halogen bulbs through the central ceiling diffuser.
- **LED spot**: 12 LED spot lamps mounted in the wall luminaires.
- **LED diffuse n°1**: 12 LED diffuse lamps mounted in the wall luminaires and 3 LED lamps through the central ceiling diffuser.
- **LED diffuse n°2:** 12 LED diffuse lamps mounted with lampshades.

Two chairs at opposite corners of the room define the observer's positions (n°1 and n°2). Sitting in these two designated positions, each observer is asked to run one's gaze over the living room for 1 minute, from left to right.

When the observer leaves the room to answer to the questionnaire given, the operator changes lighting configuration for the next configuration.
The questionnaire includes rating of comfort, glare, colour rendering and the degree of similarity with observer's own living room lighting scenario. An open question is also given asking a personal definition of "visual comfort".

Figure 2: on left column: observer's position n°1; on right column: observer's position n°2. From top to bottom, the four configurations: Halogen, LED spot, LED diffuse n°1 and LED diffuse n°2

2.3 Description of subjective test n°3 – Compartments

The goal of this test is mainly to evaluate the influence of sources colour temperature on visual comfort without the effects of colour rendering. The set up consists into four identical small compartments in a large room. Each compartment is featured with a chair, a table, a desktop luminaire and a partition wall with three circular diffusing light sources. On the table, several black and white pictures and two booklets with few colours are positioned as well as a b&w poster on the facing wall.

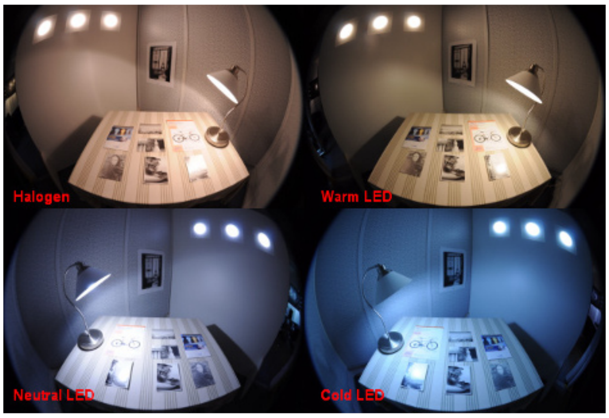
A special atmosphere is created with an average illumination of the table and a low illumination of the surround as can be found for instance in libraries and public transportation. We selected for the four configurations three LED sources of three different CCT (warm, neutral, cold) and one Halogen source for comparison.

All the lightings were powered two hours before the test and kept powered along the test enabling the observer to move freely from one configuration to another one. The physical characterisation of each compartment was done in the same conditions and thus integrating the very low parasitic light.

Firstly, the observer is asked to sit in turn in each compartment few minutes in order to get an overview of presented configurations. Secondly, each subject is requested to stay two minutes in each configuration and to rate for each configuration (1) the overall visual comfort, (2) the ease of visualization and (3) the apparent quality of documents. At the end of the test, the observer gives his preference ranking of all configurations.

Figure 3 represents the lighting configurations. Pictures were taken with a high definition CCD camera and a fish-eye lens, the white balance set for a CCT of 4000 K.

Figure 3: Pictures of test n°3



2.4 Description of subjective test n°4 – Office

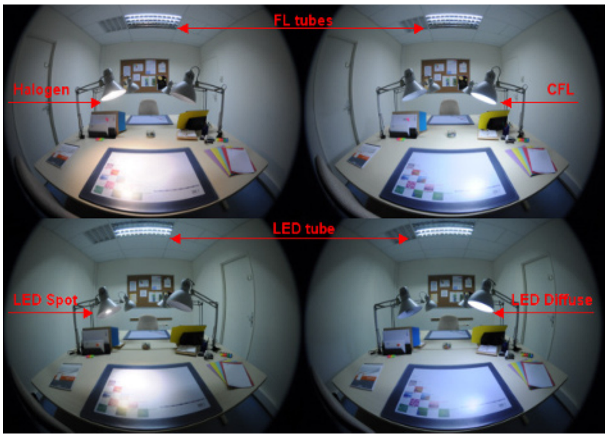
The goal of this test is to study visual comfort in an office environment. A room has been furnished and decorated as an office workplace with two desks. On each desk, at the top corners, two architect's luminaires are mounted and two ceiling luminaires placed.

Four symmetrical configurations are possible combining a desktop luminaire with a ceiling luminaire. The four combinations are obtained with an Halogen lamp or a CFL on the first desk combined with a FL tube in the ceiling luminaire, a LED spot or a LED diffuse lamp on the second desk, combined with a LED tube in the ceiling luminaire. Switches are clearly displaced and identifiable, allowing the observer to autonomously change form one luminous configuration to another.. All the lamps were powered two hours before the test and after each subjective assessment by an observer.

Firstly, the observer is asked to stay a few minutes in each configuration in order to get a quick overview of the presented configurations. Secondly, the observer is asked, for each configuration and in a predefined order, to read and write down some sentences copied from some posters hanged in front of each desk and then to rate their overall feeling of comfort, ease of writing and ease of reading. At the end of the test observers ranks the configurations according to their preference.

In the following Figure 4, all configurations are presented. Pictures were taken with a high definition CCD camera equipped with a fish-eye lens.

Figure 4: Pictures of test n°4



3 Optical characterization

In this section, the LNE facility to characterize optical environment is presented as well as observers' biophysical parameters.

Concerning spectrum data and luminance measurements in specific positions, two instruments have been used:

- a CS1000 spectro-radiometer, featured with a lens and used in conjunction with a white diffusing plate for spectral irradiance measurement. The spectrum has been measured at several locations: at the centre of field of view and also at relevant points, for instance to measure chromatic variation of some lightings;

- a CDS2100 spectro-radiometer, used with a cosinus-head to measure the full irradiance spectrum at the eye's position in a 2π geometry.

To characterise the field of view, we used a gonio-photometric camera. This system is composed of a photometric camera (ILMD) mounted on a two-axes goniometer. The system imaged the whole field of view.

The camera's lens has an optical aperture of 15°, 9 x 8 images are needed to cover the angular field of ± 67.5° horizontally and of ± 60° vertically. This field is the relevant field of view for human vision.

For each measurement, the camera took 8-bit pictures with 3 optical setups: no density and two different densities. For each optical, setup the image acquisitions were performed with 3 integration times, leading to a set of 648 images of 1024x1024 pixels. A computer program built a 2D luminance map in spherical coordinates (Teta, Phi). This luminance map was an array of floats and was obtained from these 8-bit images with respect of angular direction, integration time, and optical densities.

The absolute luminance calibration of the photometric camera has been performed, with the photopic filter and the neutral densities. The camera response against integration time and the uniformity of the lens for different focus setting has been measured. Geometrical calibration of the camera and the goniometer were also performed

Figure 5 presents an example of a luminance map. This reconstructed living room is the subject of the picture. A logarithmic scale is applied in order to have a better representation of luminance for visual purpose.

Figure 5: Luminance map

The last characterization tool is the SMI Eye-Tracking Glasses system, used during the experiment n°2 and providing biophysical measurements. A calibration on each observer is done before starting the test, permitting to the system do acquire information about the subject's eye and then define a model for it. The eye-tracker is worn like a normal pair of glasses: these mount three cameras and some infrared LED for creating the corneal reflections.

The software BeGaze® combines inputs form the two cameras directed to the subject's eyes with images recorded by the one directed to the scene observed. Through the analysis of corneal reflexes that determines the position of eye bulbs in each moment, a map of the observer's gaze is obtained. Pupil dilation is also monitored during the entire recording. This binocular eye tracker performs automatic parallax compensation and so it delivers very reliable and accurate data over all viewing distances.

Blinks detection is also available and this information might be interesting in particular in the presence of glare sources, as a probable index of visual fatigue.

4 Results

All results are hereby summarized. Numbers in tables represents the mean score obtained from questionnaires considering all subjects, on a scale from 1(low) to 5 (high).

4.1 Subjective results of test n°1 – Glare test

Table 1: Subjective results of the test n°1

Solution	Perceived Glare	Difficulty to read
LED spot	3.93	3.49
Bare LED	3.33	3.27
Halogen	2.94	3.16
LED diffuse	2.43	2.90
LED tube	1.57	2.65

A very good Pearson correlation has been obtained (coefficient = 0.996) between the "difficulty to read" and the "glare perception" but a much greater range for glare perception (2.36) than for difficulty to read (0.84). That means that people are more sensitive to discomfort than impairment of reading.

4.2 Subjective results of test n°2 – Living room

Table 2: Subjective results of the test n°2

Solution	Visual Comfort	Perceived Glare	Colour rendering	Similarity factor
Halogen	4.84	1.46	2.74	2.14
LED diffuse n°1	4.68	2.44	2.98	2.08
LED diffuse n°2	4.88	1.38	2.64	2.14
LED spot	4.92	2.10	2.90	2.14

It can be noticed that visual comfort is not correlated to glare and so deduced that glare perception is not the only factor influencing visual comfort. The range of "similarity factor" is very small (0.06), however, it can noticed that the configuration rated as the less comfortable obtains the lower degree of similarity (1= extremely close to home configuration; 2= relatively close to home configuration; 3= not so much; 4=away to home configuration). For colour rendering, contradictory results are obtained: the relative spectral distributions of solution LED diffuse n°1 and solution LED diffuse n°2 are very similar, but these solutions give the best and the worst subjective scores for colour rendition over the 4 configurations. It can be assumed that the difference of light distributions and luminance levels yielded to different appraisal of colour rendering for sources of same spectra.

4.3 Subjective results of test n°3 – Compartments

Table 3: Subjective results of the test n°3

Solution	Halogen	Warm LED	Neutral LED	Cold LED
Visual Comfort	2.78	2.42	2.76	2.32
Clarity of viewing	2.98	2.56	2.94	2.72
Quality of Documents	2.76	2.52	2.92	2.9
Parameters average	2.84	2.5	2.87	2.65
Preference ranking	2.62	2.26	2.76	2.36

It can be noticed that "cold LED" lighting gets a high rating for parameter "quality of document" and gets the lowest rating for "visual comfort". The contrast of the text on the documents, increased with CCT, can account for this good rating (as previously mentionned, documents are almost monochromatic).

The average of the three first parameters (visual comfort, visual clarity and documents quality) ranks the configurations in the same order that "preference ranking".

The "warm LED" configuration obtains the lowest ranking preference: it can be noticed that "clarity of viewing" and "quality of document" get the lower rating. In comparison, the Halogen configuration with similar CCT obtains greater results.

However, visual comfort ratings place "warm LED" before "cold LED" whereas preference ranking place warm LED after cold LED. That suggests that people could prefer a solution less comfortable in exchange for a better objects visualisation.

We conclude that preference is a combination of visual comfort and viewing quality not only explained by the CCT as configurations present small differences in luminance levels and chromaticity that could impact the quality ratings.

4.4 Subjective results of test n°4 – Office

Table 4: Subjective results of the test n°4

	A (HL + FL)	B (CFL + FL)	C (LED spot)	D (LED diffuse)
Comfort	2.54	2.84	2.12	2.46
Clarity of viewing	2.92	3.26	2.26	2.54
Ease of writing	2.88	3.08	2.42	2.64
Parameters average	2.78	3.06	2.27	2.55
Preference ranking	2.66	2.98	1.8	2.56

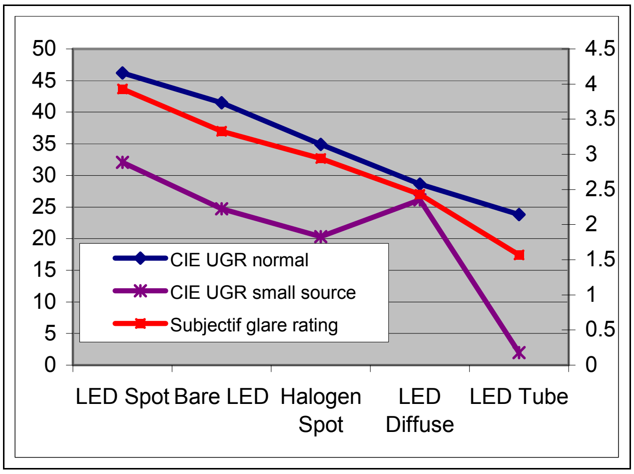
The configuration (CFL+ FL) obtains the best ratings for all attributes. It can be assumed that the uniform and smooth illumination of the room, of the working plane and of the display board account for these good ratings. We can also add that the luminaires are well adapted to these isotropic light sources. For instance the white reflector of the desktop lamp increases the effective light source size and then reduces the shadows when writing. LED solutions do not obtain good results. The LED tube generates a very sharp transition of illumination, with some banding effects, onto the display board, and it is a bit more glaring than the FL tube. That partly explains why the rating of "clarity viewing" is quite low for LED sources. The LED spot configuration gets the lowest ratings with a narrow lighting area on the desktop. For this test all quality parameters and preference ranking are strongly correlated.

5 Discussion

5.1 Preliminary assessment of glare

The first LNE subjective test was designed to assess the discomfort UGR glare formula against subjective ratings with LED light sources similar to those used in the other subjective tests (LED tubes, LED diffuse, LED spot). We found that the CIE UGR formula for normal source, applying to sources having a solid angle greater than 0.0003 sr, was working fine; four of our sources have a solid angle smaller than the 0.0003 sr limit.

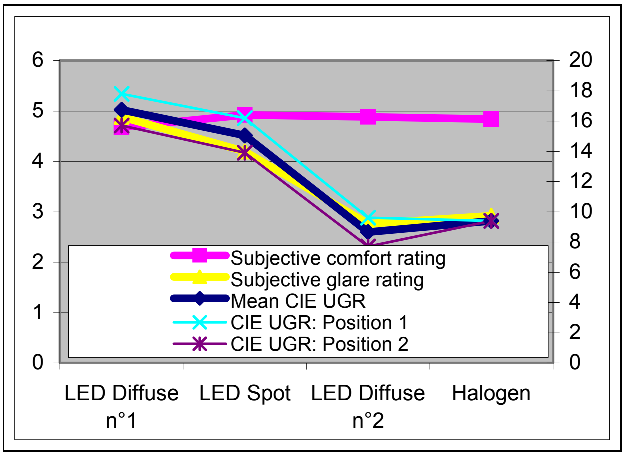
Figure 6: Comparison of UGR formula with subjective ratings



In the above Figure 6 and the following Figure 7 a good correlation between the CIE UGR for normal sources and the ratings of glare can be observed. In Figure 6 the effect of source size on the corrected CIE UGR for small source is represented: the "LED diffuse" has the greatest solid angle and the LED tube the smallest solid angle for each LED, that leads to a increased UGR value for the "LED diffuse" and decreased UGR value for the LED tube in comparison to subjective ratings. Hence, we use in our model the UGR for normal source as a correlate of perceived discomfort glare. It should be very important to address this problem for SSL because many SSL light sources have small dimensions (< 50 cm²) and the proposed correction of UGR does not seem to be well correlated with subjective ratings. The coefficients of Pearson correlation are 0.98 with CIE UGR and 0.87 for CIE UGR for small source.

In Figure 7, we observe a good correlation between subjective ratings and UGR calculation. This is interesting as experiment n°2 was performed in a recreated living room, which is a complex environment. That means that a reliable estimation of glare in complex environments can be obtained using CIE UGR.

Figure 7: UGR normal source and glare/comfort rating in the living room



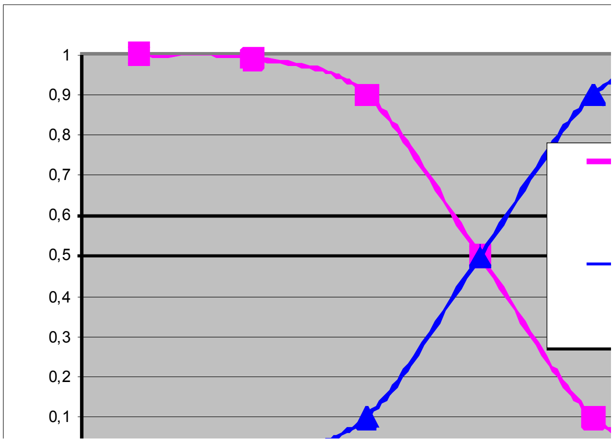
Note: on Figure 6, the scale is a relative scale, so glare could be over-evaluate or under-evaluate. In experiment of Figure 7, we found: imperceptible for a UGR of 07, just perceptible for a UGR of 13 and just tolerable of a UGR of 20.

5.2 Prediction model for comfort

With the support of these subjective results and physical measurements, a model to predicting the subjective preference using physical parameters has been built. Parameters are distinguished into two groups: parameters creating uncomfortable effects (like glare and flicker) and others parameters related to quality (as illumination levels, distribution, colour appearance, and so on).

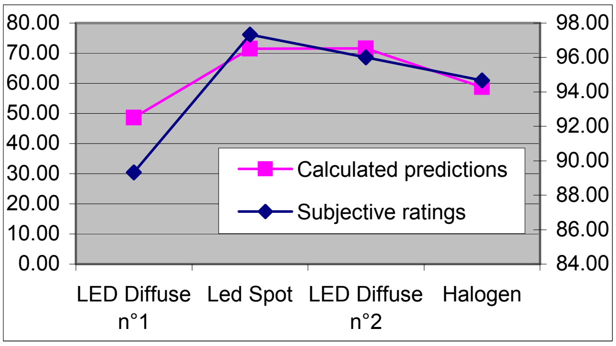
The model is based on this assumption: if discomfort glare is too high, the configuration could not be comfortable. But without any glare; the configuration could be uncomfortable too (but not due to glare); especially if the comfort parameters are not good (as show on figure 7).

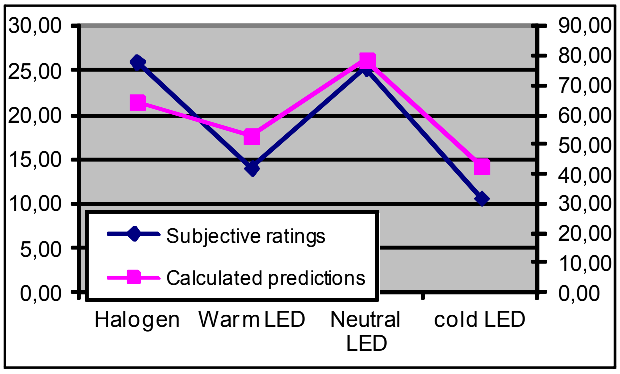
Figure 8: Weighting functions for discomfort and comfort parameters

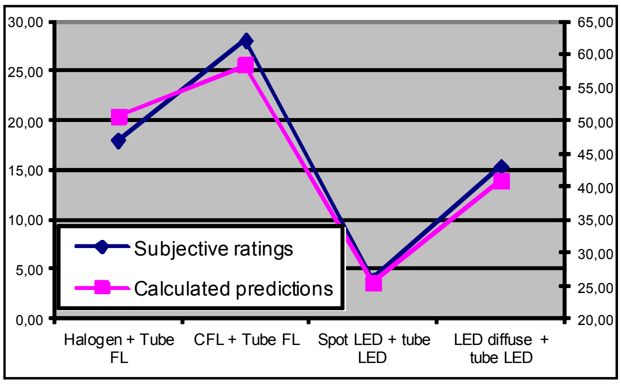


In conclusion, 13 quality parameters have been identified, relative to: light levels, light distribution, 3D shadowing, CCT and mixing CCT effects, colour rendering, luminaire appearance, and specific parameters of the lighting like light on the areas of interest. The impact of these parameters has been adjusted and weighted using the subjective results. The following Figure 9 plots both the subjective results and the comfort level predicted by the model.

Figure 9: Subjective results and calculated visual comfort in the 3 configurations (living room, compartments and office).







The model leads to high coefficients of Pearson correlation respectively 0.94, 0.91, 0.97 for experiments n°2, n°3 and n°4.

Conclusion

Authors are perfectly aware that this study just covers few interior lighting configurations, important parameters of visual comfort of lighting environments have been identified in this study. This simple developed model can serve as a basis for visual comfort assessment for further studies on interior lighting environments.

The results obtained using the proposed model yields to good correlations with the subjective ratings of visual comfort. Few discrepancies between model predictions and subjective assessments of visual comfort are not explained: subtle effects of light source spectra and aesthetical effects can account for these discrepancies.

A key point that deserves to be highlighted is that the discomfort glare determination for small light sources needs more developments. Different papers [XVI, XVII, XVIII] dealing with glare of small light sources, combined sources and LED sources are not consistent with each other: the outcomes of these studies are either that the CIE UGR for small sources lead to under-evaluated or over-evaluated glare and different alternative formulae are proposed. In the case this performed experiment, the results of CIE UGR for normal sources presented good correlation with the subjective ratings of discomfort glare.

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6 Résumé

Cet article présente l'étude de la mesure du confort visuel et de l'éblouissement pour des scénarios d'éclairage d'intérieur.

Notre approche, décrite dans l'introduction, a été de recréer en laboratoire des configurations réalistes pour étudier le confort visuel dans un environnement contrôlable et reproductible dans le but de relier la notation subjective et les mesures physiques.

Ensuite nous décrivons l'expérience qui a été mené au LNE avec 50 personnes. Quatre tests sont décrits avec les protocoles de test, les résultats subjectifs et la caractérisation du champ visuel.

Un model de confort visuel est proposé et décrit. Ce model sépare les paramètres en deux catégories : les paramètres d'inconfort (éblouissement, papillotement) et les paramètres de confort qui reflètent les aspects de qualité du confort visuel. Tous les paramètres sont décrit avec leurs principes d'implémentation dans notre modèle.

Pour finir nous présentons et commentons les résultats obtenus avec ce modèle.