Visual comfort in underground working environments

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Summary :

The scope of this paper is to present lighting design concepts on basis of adequate describing parameters for interior environments including comfort aspects (visual and non-visual); and to present design aids to enhance the quality of lit environments together with the efficient use of energy. In particular, visual comfort, performance and safety are discussed with regard to workers active in underground workshops, being deprived of daylight.

Résumé : Confort visuel de lieux de travail souterrains

Dans cet article, des critères de conception d'éclairage intérieur sont présentés sur base de paramètres adéquates, y compris les aspects de confort visuel et non-visuel. Ainsi, des moyens de conception sont traités en vue d'augmenter la qualité globale de l'éclairage et d'utiliser l'énergie rationellement.
En particulier, le confort visuel, la performance et la sécurité sont discutées pour des ouvriers d'un atelier souterrain de maintenance et de réparation; en absence de lumière de jour.

Zusammenfaßung : Sehkomfort der Untergrundarbeitsplätze

Dieser Artikel erläutert wie Kriterien bei der Innenraumbeleuchtung von Arbeitsplätze in der Praxis angewendet werden kann (visuelle sowie nicht-visuelle Komfortaspekte). Entwurfkonzepte sind erörtert im Hinblick auf höchstmögliche Qualität und rationelle Nutzung von Energie.
Schließlich wird Sehkomfort, Leistung und Sicherheit der Untergrundarbeitsplätze diskutiert; ohne Tageslichtbeitritt.

1. Introduction

The case in question is a maintenance and repair workshop for subway equipment and is situated four levels under ground level. Typical work is of mechanical (coarse and fine), electrical, electronical; painting and cleaning nature; other typical activity is stock management. Each activity within this complex scene requires a particular design approach.

The distinctive types of activities are located in separate working zones (so-called work stations) with specific tasks and working conditions.

All these activities are taking place in subsurface space without any penetration of (natural) daylight (the workers' activity scheme corresponds to extended daytime shift).

A new lighting equipment is installed, altogether with updated refurbishment, to meet the following objectives :

- Accident reduction through safety enhancement;
- Increase of the accuracy and the punctuality of the operations (with inevitable cost reduction and higher material efficiency);
- Counteracting of visual stress and fatigue;
- Facilitating work processes;
- Ameliorating of production process and overall work quality;
- Creating a comfortable working atmosphere to keep up morale and well-being of the workers.

Instruments supporting these objectives are the lighting levels, the brightness stimuli distributions, the light source qualities, colour aspects of objects and environment; and among others, ergonomical, logistical and organisational measures.

Initially, a questioning amongst the workers had pointed out the following significant issues :

- There is non-adequate lighting with regard to the visual task (complaints on lighting levels, glaring sources, low task contrasts);
- Some visual tasks themselves are explicitly complex;
- The working environment is depressing; the general degree of appreciation of the work is rather low;
- Commitment and motivation are sometimes a problem.

A complete lighting scheme for **relighting** has then been drawn for this particular ***case study*** and has been validated by means of lighttechnical measurements and evaluated by the workers.

2. Lighting criteria

In lighting applications, very much is related to the so-called *visual task.* In the case of easy to define or non-complex tasks, lighting design can be based in a first step on horizontal and vertical illuminances and on the ratio of both.

The complete visual scene can be characterised by a combined set of parameters as the luminance distribution in particular directions; glare control; the directional nature of the lighting; modelling and colour aspects.

From there, lighting design is to be seen as a harmonical composition of lighttechnical elements to a non-singular solution.

Lit environments are usually characterised by some "objective and measurable" quantities. Nevertheless, these parameters have proven to be inadequate in functional interior lighting with complex backgrounds, architectural elements and spatial structures, high luminance diversities and brightness transitions.

Lighting can be seen as a spatial distribution of light and as such, the directional qualities are by far hardly expressed by the "classical" two-dimensional horizontal and vertical illuminances.

Additionally, there is need to characterise at this point "modelling" i. e. the spatial restauration of objects by means of the lighting. This concept is of great importance within the overall quality of the lighting, especially in interiors and with difficult and critical tasks.

This characterisation is done by introducing lighttechnical parameters as the semi-cylindrical illuminance and the vector to scalar ratio. Modelling of three-dimensional surfaces has to be considered together with the *colour appearance* of lit rooms. It is often ignored that colour appearance is also determined by geometrical aspects of the light distribution.

In this context, visual implications are to be considered for a diversity of visual task surfaces consisting of metallic and non-metallic materials; in a glossy, matte or rough finish. It is obviously linked with the photometrical distribution of the lighting system and with the observer's viewing directions.

Apparently, designing lighting installations on basis of these novel concepts and parameters will strongly improve visual quality and comfort. Moreover, this approach implies efficient use of energy in lighting.

In working areas, factors improving the morale and the social climate of the workers can be considered as evenly important as the industrial process itself. This ergonomical objective is an intrinsic element of the (holistic) design of the workshop floor. It is explicitly of application in "hard to handle" working areas, with difficult tasks, at underground level, like this subway repair and maintenance hall.

In the ***case study***, typical issues of the visual task (and the origin of vision stress and fatigue) are e.g. :

- Glare (direct or reflected; glossy or mirror-like surfaces);
- Constantly changing viewing directions;
- Uncomfortable colours like dark red and bright orange;

- High adaptation needs because of high brightness patterning;
- Poor colour contrasts between work piece and close background.

The lighting criteria are anyway well covered in the Draft Standard CIE DS 008.3 (2001) [2].

2.1. Illuminances and luminances

The first step in lighting design consists of putting into words, describing and defining the performance needs of the occupant, translated towards visual requirements. In here, the occupant is effectively playing the role of observer of the illuminated environment.

Criteria defined in such a way are making up the **visual task**. Orientating one-self in an interior environment, reading a text on a sheet of paper, observing (coloured) visual information on a computer or display screen are examples of tasks which can be reduced to **flat surfaces** with a particular orientation (mostly in a horizontal or vertical direction).

A first problem occurs when attempting to translate the visual task into objective lighttechnical parameters, preferably easy to calculate and to measure.

The **brightness** sensation is for the greater part determined by differences or contrasts in luminance levels of surfaces in the visual scene.
Fulfilling the visual task is a combination of concentration of one's view on typical elements of the task (e. g. letters and words of a text; patches of a picture) together with the global visual assimilation of the information (groups of words, sentences; the image of the picture).

When regarding towards a particular task, i. e. fixating or directing one's look at a certain point of interest, the narrow and wide background must be considered as a major actor. A great diversity of colour and brightness patterns makes this background into a complex one.
As the eye is seeking for high luminant spots or for the highest luminance contrasts in the visual scene (apart from particularities as a birth mark or freckles in a face), the information is immediately transmitted to the brain; with relatively low luminant patches, it takes some time to build up an image of the scene.

Illuminance is a very poor predictor of luminance (except with perfectly specular reflectors or Lambertian diffusers, with known reflectances). Yet, a practical design parameter in interior lighting is the **horizontal illuminance** on nominal working or walking height.

Eventually the vertical illuminance is opted for for vertical tasks. The illuminances should be superior to biologically active levels (well above 750 Lux), preferably individually adjustable to yield constant luminance of a reference working task; or, on the contrary, to yield task lighting levels corresponding to daylight linked levels, this depending on the individual preferences of the observer. As artificial light of "daylight" type (colour temperature T_K = 4000 K to 4500 K) is sometimes experienced as uncomfortable and too harsh at lighting levels which are low relative to daylight levels, it is indicated to choose a "warm white" type of lamp instead ($T_K \approx 3000$ K). This effect is marked more sharply with older people, for reason of deficiencies in the visual system (scattering in the eye media). Another reason for choosing a warm light source to obtain less discomfort is the presence of mesopic vision luminance levels in quite a few interior environments.

Most objects occuring in our daily life are **three-dimensional objects** which are composed of curved concave and convexe surfaces. Here, the brightness description naturally holds true but can often be present as luminance contrasts on the object itself (in considering detection and recognition of visually relevant elements) !

Herewith, classical two-dimensional lighting parameters do not correlate very well with three-dimensional visual tasks, except in near-hypothetical conditions of perfectly diffuse lighting or when considering only averaged values within the visual field.

Modern, sophisticated lighting design has to take into account non-empty interiors as well. Calculation of lighttechnical parameters is herewith carried out more corresponding with real conditions and the lighting will be more adequate with the visual task.

In this ***case study***, the prescribed maintained values of horizontal illuminance are to be met anyhow; even with some tasks with normally low visual requirements. It is shown in [8] the highest correlation between the occurrence of work accidents and the lighting level is at relatively low illuminances (from 200 to 300 Lux in a continuous work scheme). From there, it is important not to let the illuminance level go down under the nominal values, albeit with low visual requirements.

The existing installation was built up with bare lamp TLD 36W and 58W based luminaires equipped with a white enamelled reflector.
General lighting was in this way corresponding to an average horizontal illuminance level of about 150 Lux. Additional HPL-N 400W based "High Bay" luminaires were added (at a mounting height of about 5 m i.e. less than 6 m !) to push up the lighting level in some of the zones. Some of the work stations had locally added TL-luminaires.

For more than 20 work zone types the illuminance distributions on the work plane (as well as some luminance distributions) were measured.

Four different stages of recommended average illuminance can be distinguished here :

- 300 Lux : tasks with simple visual requirements;
- 500 Lux : tasks with moderate visual requirements;
- 750 Lux : tasks with higher visual requirements;
- 1500 Lux : particular tasks with accurate visual demands (small detail vision).

In practically all of the working zone types (*mechanical machinery, tools, upholstery, electricity, "bogie" pre-assembly, welding, wheel belts, axle bearings, wheel sets, gears, mechanics, coupling testing, compressors, pneumatics*) the measured values were lower than the recommended ones (at 500 Lux in most cases; the zone *"axle bearings"* at 300 Lux; the others at 750 Lux).

It appeared to be that on the workbenches, where a value of 750 Lux is recommended, some of the zones met the requirement (in terms of illuminance). On the workbenches of the zone type *"Pneumatics"* 1500 Lux applies as recommended value and this condition is not fulfilled.

When expressing luminance distributions in terms of luminance ratios, 4 stages can be considered here (in principle applicable only for matte surfaces) :

- 3/1 ratio between background of the task and the adjacent field of view;
- 10/1 ratio between background of the task and the peripheral field of view;
- 20/1 ratio between light sources/luminaires and their adjacent background;
- 40/1 ratio for the entire interior room.

Luminance measurements for the initial installation pointed out too high values for the light sources/luminaires (≥ 4000 cd/m^2; definitely higher than the "recommended" value of 2000 cd/m^2) as most of the lamps are observed as bare light sources. For the task itself, often a too low luminance or colour contrast was found.

2.2. Directional aspects and modelling

Directional properties of the lighting system (characterising the flow of light) can be expressed by the light vector and the vector to scalar ratio. In interior lighting applications based on artificial light and daylight it can be thought as a combination of a predominant horizontal and a predominant vertical contribution to the light flux. In this way, it is practical to use the ratio of the vertical to horizontal illuminance in function of the contribution of daylight and artificial light. When risking too high vertical to horizontal illuminance ratios due to considerable side-wall (day)lighting, ceiling mounted artificial lighting is increasing the horizontal component.

Modelling power of the lighting is the expression of the influence of the purely geometrical nature of light incidence on three-dimensional restauration (and colour appearance) of volumetric objects.
Some lighting systems (like spotlights) can have a strong directional character; others can have a strong diffuse character (like light ceilings imitating overcast sky conditions). Natural balancing between these two extrema and from there

correct modelling is to be preferred as spatial restauration is important with functional interior lighting.
In this way, the room can have "fill" light (eventually more or less diffused); and additionally, task desk lighting that should have for the most a direct character.

One has to bear in mind, diffuse lighting (associated with positive or negative luminance contrasts) will **always** create poor modelling and marked colour distortion with all metallic and most non-metallic surfaces.

As an example, in a meeting room, the information transfered is to the utmost of visual nature. Although this is hardly to express in absolute figures or percentages, body language, eye contact and facial expression are playing a major role here.

Likewise, it is of great importance to realise in exhibition lighting good modelling and colour vision of art works, paintings and sculptures. This holds even so for integral machine lighting in workshops.

Although the semi-cylindrical illuminance, the parameter for recognition, is describing the spatial density of incident light and therewith expressing a certain balance between frontal, sideward and backward lighting, the dynamical aspect of lighting of three-dimensional structures is more comprehensive than can be expressed by this parameter.

An easy to calculate (but to some degree difficult to measure) modelling parameter is E_{Cyl}/E_H , the ratio of the cylindrical illuminance E_{Cyl} to the horizontal illuminance E_H at a certain point. It expresses a balance between a "vertical" and a "horizontal" content. Good modelling is achieved when $0.3 \leq E_{Cyl}/E_H \leq 0.5$.
Lower values for E_{Cyl}/E_H correspond to harsh modelling with important cast shadows; higher values (up to 1) to depthless restauration in conditions of diffuse lighting.

As in the ***case study*** the tasks are consisting for a great deal out of metallic type surfaces, one has to consider for e.g. surface inspection directional, grazing lighting systems.
Here, general (mainly direct) lighting is complemented by working desk lighting (in this typical industrial environment, the role of the walls and the ceiling are anyway reduced compared with office lighting).

2.3. Glare

The Glare Index System of the British Zonal (BZ) method for interior lighting [4] was developed a few decades ago as a simplified Hopkinson (GB) approach. It shows some serious deficiences with up-to-date light treating luminaires. The BZ method was conceived for general lighting and is favouring luminaires with diffusers like plexiglass over modern low luminance luminaires.
The origin of discrepancy can be found in the fact that the method is based upon the direct ratio R_d and not on the real photometry of the luminaire.
The direct ratio R_d equals the ratio of the light flux directly reaching the working plane to the underhemispherical light flux.

Eventually, a certain reflector controlled luminaire with a cut-off angle at $\gamma = 60°$ with the downward vertical can be assigned to a BZ 5 reference in a typical application. The considered luminaire is low luminant in the cut-off or shielding zone (L < 200 cd/m^2) and from there not presenting glare in corresponding directions; on the other hand, the BZ 5 reference luminaire is presenting important glare in that zone because of a considerable amount of lumens is emitted in that zone corresponding with an important solid angle.

Another glare system was developed by Bodmann-Söllner (DE) as luminance limiting curves of the luminaires; modified in the so-called European Glare Limiting Method which is still the most frequently used system today.

However, discomfort glare is determined nowadays with the help of the **UGR**, the Unified Glare Rating [3], for which it is recommended to use the formula instead of the derived tabular method or the luminance limiting curve method. It is in fact a combination of Einhorn (SA) and Hopkinson formulae associated with the position index of Guth (USA). A particular point to consider here is the observer's position and direction of view.
It is also present in the Draft Standard [2].

These methods are typically based on average luminances of the emitting surface of the luminaire. Peak luminances aren't considered, neither relatively low values around the average.
Nevertheless, **peak luminances** are affecting seriously visual comfort and are involving tiredness and headache. Typical inconveniences are disturbed concentration as the eye is attracted towards high luminant spots; decreased contrast and colour vision with veiling reflections; difficult focussing on the visual task on display screens when peak luminances are mirrored in the screen. Other elements of disturbance are the need for constant re-adaptation of the eye when switching viewing from high luminant spots outside the task to the task itself; the degradation of the visual system of the observer in function of age; the use of visual aids like glasses which are intensifying these inconveniences.

2.4. The Functional Colour

Colour aspects are playing a major role for the visual task and observation, be it in a *decorative* way as well as in a *functional* way; nowadays more and more.
The functional colour can be chosen in such a way to be effective against visual fatigue; to enhance the accuracy and the attentiveness of the industrial process; to improve the working atmosphere and the pleasantness of the environment.
Mainly, the effective characteristics of the visual function can be implemented; among others, the opponent colour concepts, to meet the objectives as stated in **§1.** (Introduction).

Opponent colours are colour pairs becoming white or grey when mixing.
These "complementary colours" or "contrast colours" are yielding as a matter of course high colour contrasts.

Anyhow, the basis of the visual observation remains either luminance contrasts; either colour contrasts.

One can indicate the following :

- The CIELa*b* system can be applied (based on Lightness, Hue and Chroma attributes); eventually the RAL® Design System can be used;

- The **background colour** is effectively affecting visual acuity (sharpness or depth of vision) and (luminance) contrast sensitivity;

- Object and background colour can be chosen as "contrasting" (different Hue but with no hard veiling background);

- The "useful" reflection factors in interior lighting are equaling to 0,6 – 0,9 for the ceiling; 0,3 – 0,8 for the walls; 0,2 – 0,6 for the working planes and 0,1 – 0,5 for the floor. These factors are important for the utilisation factor of the lighting installation (and are correlated with the colour's Lightness);

- For each working zone, the most appropriate background colour (wall, …) has been assigned in view of the dominant object colour. The domain of choice for the **"most functional" (background) colour** can be laid down (the workers voted on the colour choice out of a restricted set of possible solutions);

- For neighbouring zones, harmonically **balanced non-contrasting (background) colours**; eventually **transient colours** (f.i. green between blue and yellow) have been chosen when visual contact across zones is likely to happen. Also, all background colours shall have a similar value of Lightness and colour saturation (Chroma). Doing so will lead to a background remaining "background";

- Generally, object colours are varying in here from black, (dark and light) grey, metallic, copper, red, orange, yellow, other dark colours to a combination of the forementioned. For each zone, background colours are assigned by means of the colour wheel (complementary colours of the object colours within a certain tolerance area). Also, the choice is driven by the empirical (non-comprehensive) scale of colour contrasts between object and background (in descending order) : black on yellow, white on blue, black on white, white on red, white on green, white on black. In this way, the chosen background colour combination was Yellow (RAL H 070 90 20) – Green (RAL H 150 90 10) – Blue (RAL H 260 80 15).

2.5. In need of Daylight

Humans are really in need of daylight as the ultimate light source and therefore, a lot of artificial lighting is bringing about health harm and complaints.

In underground working areas, "artificial" light is substituting the natural light source when lacking (or when impractical). In fact, there is no artificial equivalent to daylight, nor concerning the directional qualities (even diffused daylight can be appreciated to a certain extent whereas a clear blue sky is unsurpassed); nor for the level and the spectral content. A clear blue sky is merely direct sunlight, including UV ("full spectrum"), although one must keep in mind, indirect interior lighting is absorbing the UV radiation, *in casu* the (matte) wall paint is responsible for the indirect room component. Also, window glass is blocking UV.

With regard to the biological clock and rhythm, eventually (higher) appropriate lighting levels can be applied to displace the circadiane cycle (in this case study there is however no full night shift).

Briefly, daylight (<u>sun</u>light) ought to be considered in lighting design as much as possible as the light source *per excellency*, in view of health, safety, performance and comfort.

In underground environments, daylight conductors are the only components for daylight penetration; there is however no view out and a rather poor daylight "experience".

2.6. Room impression

A typical problem rising with lighttechnical parameters and concepts is their **representation of aspects of visual sensation**. Identical sensations of glare should imply identical index values; poorer sensations should correspond to lower values (seen as a limitation of glare). This does not hold always; therefore, new experiments need to be carried out with actual types of luminaires.

The visual impact of an interior environment is to be characterised by a **combined** set of parameters. These are for instance :

1. The horizontal and/or vertical **illuminance** (minimum and average values).

2. The **Contrast Rendition Factor** (CRF) characterising the contrast of the visual task (and the directional nature of the lighting). It is defined as the ratio of the luminance contrast of the visual task at a certain level of illuminance to the contrast of the task under diffuse lighting with the same task illuminance.

3. A **glare** limitation index system can be linked with the luminance distribution and the characterisation of visual comfort within the observed field. An additional practical test can be the so-called *A4 mirror test* on the desk in search of veiling reflections. Anyway, veiling reflections often can easily be avoided by a glossy paint or print : a small change in orientation of the task solves the problem of specular reflection for a particular observer position (except with diffuse lighting). What is more, colour appearance and vision of details and texture is very much enhanced (under direct lighting). Direct **veiling luminances** present in the visual scene, outside the line of sight, although in absolute figures not too important, can cause uncomfortable peripheral vision (for instance side-wall window daylight from overcast sky).

4. In particular applications where modelling is important, additionally to the contrast rendition and the visual comfort, a **modelling** index can be specified.

5. **Colour** aspects (the whole environment considered as a light source) : colour contrasts, colour rendering and colour temperature.

The lighting designer should consider all aspects, though one should not assign equal importance to all parameters for all types of applications. Consequently, the designer can "slide" or move to some degree of freedom the elements as with the pieces of a palette or puzzle. Obviously, some elements can work together; on the other hand, they can work against each other.
Lighting design becomes a **composition**, a symphony with accent or emphasis on one or another element **: it reflects the creativity and concentration of the lighting designer**. In this way, the indoor environment can be *para-metered* visually.
The power, dynamics and richness lies in the non-singularity [7] of the *solution*, although every application is asking for a specific approach.

In some applications putting more emphasis on higher illuminance levels and in other applications more emphasis on the light directions can be an outcome. A hardly visible cubic object in a diffuse lit environment can be made more visible by giving the lighting a more direct character or by darkening the background to some extent.

Indeed, the sum of lighttechnical quantities and elements, put one besides the other, never is the lighting itself, the **wholeness** itself. We can discover a hidden, inexpressed dimension in a lit room, unable to measure and to quantify; it is there where the art of the designer works. It is there an architecture of light is created, as light is interacting with space.

3. Renovation (relighting and refurnishing) of the case study

Two types of TLD 2 x 58W luminaires have been installed : a symmetrically low luminance aluminium reflector controlled luminaire (with variable lamp positions; IP55) for general lighting and a special industrial assembly line type luminaire with very low luminance and complete shielding of the lamp (special parabolic longitudinal reflector and cross louvres with variable curvature) for the work benches and work stations with high requirement tasks (complex; accurate; quality control; colour control).

Also, walls, ceilings and floor were repainted.

4. Conclusion

A working zone was renovated and equipped according to the criteria forementioned and has led to (visual) performance, comfort and safety; and not in the least to a self-maintaining, positive attitude of the workers.

5. Acknowledgements

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Picture 1 : Zone Upholstery, before relighting and repainting

Picture 2 : Initial individual workstation lighting causes disability and discomfort glare with regard to the visual task on the desk