Architectural Aspects of Healthy Lighting

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ABSTRACT: Recent discoveries on the effects of light on human well-being lead to new demands for lighting solutions. In addition to the visual comfort criteria (e.g. sufficient task illuminance, absence of glare) additional non-visual criteria are being formulated. Non-visual effects of light include influences on the biological clock and direct stimulation of the human brain. Triggering of these effects occurs through recently discovered receptors in the human eye. In this process the vertical illuminance at the eye is a key factor. Also the dynamics of light in terms of intensity, spectral composition and direction during the day play a role.

Because the vertical illuminance at the eye is the dominant parameter in healthy lighting in design of architectural spaces special attention must be paid on vertical (ill)uminances. Current electric lighting installations for instance only provide horizontal task illumination. Daylight through vertical window openings is potentially a much better source for healthy lighting. In the Knowledge Center Building and Systems TNO-TU/e ongoin research is taking place to determine human lighting demands and the find suitable and sustainable solutions.

An example demonstrates solutions that satisfy the traditional demands for visual comfort and performance as well as the additional demands for well-being, alertness and productivity. Solutions include the use of advanced daylight systems, low energy electric lighting and electronic controls.

Conference Topic: 3 Comfort and well-being in urban spaces
Keywords: light, daylight, electric lighting, vertical illuminance, health, comfort, architecture

1. INTRODUCTION

Since the introduction of electric lighting the time people spend inside buildings during daytime is enormously increased. The consequences of the shift from a dynamic illuminated exterior to a static interior environment are incalculable. During daytime it is essential to receive sufficient light at the eye. According to recent studies at mainly medical institutes light entering our eyes not only enables us to see. The non-visual photoreception affects the circadian rhythm and stimulates directly parts of the brain that are influencing e.g. the cognitive functions and operating capacity [1]. Triggering occurs through recently discovered receptors in the human eye. Therefore the vertical illuminance at the eye is a key factor. The vertical illuminance corrected for human anatomic restrictions is called retinal illuminance. At present there are no criteria for this vertical and retinal illuminance. Current lighting recommendations for office lighting are based on visual criteria and require horizontal illuminance levels of 200-500 lux [2]. However this is not very relevant for biological stimulation where the amount of light falling on and entering the eye appears to be important [3].

The stimulation by light of psychobiological effects demands high illuminance levels. Insufficient light levels could cause lower concentration, reduced performance and decreased well-being. High light levels have a positive effect on the human alertness, health and vigilance. Exact values are not yet known, but threshold values for the retinal illuminance to give biological stimulation are assumed to be of the order of 1000-1500 lux [4]. Also dynamics of lighting in terms of intensity, spectral composition and direction during the day play an important role. Literature [1,5] shows that non-visual receptors in the human eye are more sensitive to short wavelength light (420-480 nm) and illumination of the nasal part of the human retina is more effective for the non-visual photoreception.

![Figure 1: Dynamic light dosage [4]: in the morning a high level to support wake-up, then a decrease to the standard level, after lunch a high level to compensate the post-lunch-dip. After ±15h00 the level will rise to decrease tiredness (especially in winter)](image_url)

With low static, vertical illuminances the chance is increasing that humans will doze off: tiredness
increases and alertness decreases. Light dosage for a healthy lighting environment not only means determination of intensity but also of timing and spectral composition. Light should be applied where and when it is demanded, see figure 1.

Healthy lighting is preferably based on daylight as the primary (natural) light source. Daylight continuously varies in intensity and spectral composition and therefore it is a suitable light source for healthy lighting. When daylight is insufficient or even absent (shift work) then additional electric lighting can be used. Current electric lighting installations are only adjustable in output level (often used for energy savings through daylight responsive controls), not in colour temperature.

An additional benefit of daylight through vertical window openings is that it offers information about the weather and the time of the day. Daylight as source to create a healthy light environment is an additional argument for promotion. This will provide an extra, interesting stimulus for the design of healthy luminous environments, including recommended office layouts and worker position in relation to daylight openings.

The current light condition in many buildings provides low illuminances. This will be demonstrated by two examples from recent studies: senior rest homes and office buildings. Then afterwards an example will be given to demonstrate solutions that satisfy the traditional demands for visual comfort and performance as well as the additional demands for well-being, alertness and productivity.

2. STATE OF THE ART

2.1 Senior rest homes

The light levels found in elderly houses in the Netherlands are too low for the visual function and to control the biological clock [6]. As a result of ageing the lens of the eyes of seniors transmits considerably less light to the retina than the lens of juniors. This makes the signals from the eye to the visual cortex, the biological clock and other parts of the human brain substantially weaker. Insufficient light exposure and subsequent less brain stimulus ends in a decrease of the circadian rhythm with more naps during the day and state of wakefulness during the night.

![Figure 2: Architectural healthy lighting in senior rest homes?](image)

Analogously, for senior people exact values for biological stimulation are not yet known, but the values are at least a factor 3 higher (3000 lux). In the apartments of 32 seniors various measurements have been made analysing lighting of the favourite chair and activities. A major activity for many seniors is to sit in their room and overlook the surroundings. According to this field-study two-third of the elderly people sit in the window zone. Only 13 % receives vertical illuminances higher than 3000 lux at the eye.

![Figure 3: Average vertical illuminance levels in ten Dutch elderly rest homes, sorted by room position](image)

Nearly 50% receive less than 1500 lux (40 -1200 lux), see figure 3. The levels for activities like reading and solving puzzles are difficult. The evening situation with electric lighting (see figure 2) is simply depressing. Too large windows with high contrast ratios, screening of disturbing sunlight and poor electric lighting are examples of reasons for unacceptable low illuminance levels in senior houses.

2.2 Office buildings

Mainly all offices in Western Europe are equipped with vertical daylight openings. On the basis of an evaluation [6] of ten office buildings in Eindhoven and Delft the actual lighting situation is shown. All offices have vertical windows and horizontal working planes (N=87).

![Figure 4: Average vertical illuminance levels in ten Dutch office buildings, sorted by room position](image)
Almost 40% of the working places, located in the window zone have a vertical illuminance less than 500 lux (measured in the period April-May). Illuminance levels above 1000 lux are found in only 10% of the cases (see figure 4).

In recent years, the luminance of computer screens was a main factor in determination of light levels in office environments. Many applications used a black background and the luminance of a CRT screen has a luminance between 50-100 cd/m². Also these screens have a high reflectivity resulting in frequent occurrence of glare. Low reflective TFT screens with luminances of 300 cd/m² are progressively replacing the CRT screens. The design methodology of office lighting is still assuming the outdated comfort criteria.

Figure 5: Working place with low illuminances (less daylight and less electric lighting) during a normal day

What leads to the low illuminance levels at the eyes of office employees? It is not possible indicate one or two variables as dominant parameters. Barriers for healthy lighting exposure are:

- Unfavourably positioned desks,
- Too large or too small daylight openings,
- Solar shielding that remains closed at times it is not really needed,
- Strongly shielded electric down lighting

In current practice the starting points for lighting design in buildings are related to performance and visual comfort in office buildings or cosiness in housing conditions. In future these criteria have to be extended with healthy lighting demands.

3. HEALTHY LIGHTING DESIGN

Lighting solutions have to provide sufficient light satisfying the human lighting demands at all times - throughout the year - and in some situations (e.g. shift work) also 24 hours a day. Daylight is the preferred source. In Nordic countries daylight is not always available and so also additional electric lighting is needed. Therefore energy efficient solutions are based on maximal use of daylight and integration of electric lighting.

Daylight can enter a space from many directions [8]. In this paper we will take a look at two basic solutions: top lighting (roof openings and light ducts) and side lighting (mainly windows).

3.1 Daylight

Daylight is not only seen as the natural and therefore preferred light source but also associated in indoor lighting with discomfort from glare and high contrasts. In daylight design small details can be extremely important factors in success. Daylight should be treated with respect and care. It is important to avoid dark elements in window frames. The contrast between dark frames and the sky can easily exceed an acceptable contrast ratio (generally for daylighting a ratio of 1:30 is the limiting value) and subsequently lead to glare.

Also using sloped or curved elements in or around windows may not only lead to interesting architecture but also to less glare and reduce the need for the use of shading. Evaluation of design should not only be based on daylight factor calculations but also be based on evaluation of the visual environment from the user perspective (see table 1 and figure 7).

Table 1: User perspective from position a, b and c

<table>
<thead>
<tr>
<th>User position</th>
<th>Horizontal view</th>
<th>Fisheye view</th>
</tr>
</thead>
<tbody>
<tr>
<td>At a desk oriented perpendicular to the façade (a)</td>
<td><img src="image" alt="Horizontal view" /></td>
<td><img src="image" alt="Fisheye view" /></td>
</tr>
<tr>
<td>At a desk parallel to the facade (b)</td>
<td><img src="image" alt="Horizontal view" /></td>
<td><img src="image" alt="Fisheye view" /></td>
</tr>
<tr>
<td>At a desk in the back of the room (c)</td>
<td><img src="image" alt="Horizontal view" /></td>
<td><img src="image" alt="Fisheye view" /></td>
</tr>
</tbody>
</table>

3.1.1 Top Lighting

In general horizontal daylight openings (rooftights) are more efficient than vertical windows. Daylight comes from all over the sky instead from at most a half hemisphere. On the other hand there is potentially more glare from direct sunlight, especially for daylight openings in unshaded roofs.

Small roof lights, such as light pipes, are also possible glare sources as they create a bright spot in the ceiling. This can be solved using a diffuser or other distributing device at the bottom, but this greatly reduces the efficiency of the device.
3.1.2 Side Lighting
By designing windows the following recommendations should be taken into account:

- Potentially daylight from windows can provide a useful daylight contribution for task lighting up to a depth of two times room height. If we look at the vertical illuminance than for a person sitting in the back of the room looking towards the façade there is sufficient daylight on the eye for about half of the working hours;
- The windows should not be too large, start for instance with glazing in 20% of the area of the face and locate these windows above 0.9 m in the façade.
- Some windows should provide an interesting exterior view. In fully glazed buildings some rooms may lack privacy, especially to the exterior. In some case this will result in additional use of shading.

An example of application of these recommendations is found in the reference office, explained in paragraph 2.3.

It is important to pay attention to the vertical luminances in the room. Most daylight systems are designed to bring daylight deeper into the room, offering more uniformity on the work plane. From the biological point of view the design criterion should be more aimed at improving vertical illuminances on the walls. The problem is that often bookcases etc cover the walls. They should preferably be located in the back of the room. When for some reason the vertical illuminances from daylight are relatively low then the distribution of the daylight may be improved by a suitable daylighting system.

2.2 Electric light
One of the main disadvantages of the current lighting systems in is that ceiling mounted luminaires are generally perceived as bright elements in a relatively dark ceiling even when the finish of the ceiling is white. Also the retinal illuminance is low due to the emphasis on the horizontal output. An easy way to boost retinal illuminance without loosing the efficiency and the required horizontal task illuminance level is to use pendent luminaires. These luminaires provide sufficient light on the task (task illuminances up to 1000 lux) while at same time creating a pleasant ceiling with a luminance of 100 cd/m². Application of pendent luminaires is found in the reference office, explained in paragraph 2.3.

When ceiling mounted luminaires designed for VDU work are used often the walls are underexposed then wall washers can improve the lighting conditions.

2.2.1 Electronic control systems
Modern electronic lighting control systems can perform several tasks:

- Energy savings
  The most important is to limit the use of energy. Daylight responsive controls in a well-lit office room can reduce the installed power of around 8 W/m² to an effective value of 4-5 W/m² without loss of visual comfort.
- Biological rhythms
  As explained in the introduction the lighting does not need to be uniform and constant in time. Electronic controls can realize practically any desired regime such as the one in figure 1
- Dynamics in colour/colour temperature
  Depending on daylight availability and mood people are comfortable at different colour temperatures. This is very personal so electronics can provide presets or adjustable environments through remote controls. The various possibilities will be shown in the presentation.

3.2 Reference office
The reference office has the dimensions 5.4 x 3.6 x 2.7m and is located in the Dutch climate on the top floor of a two story-high building, facing west. The façade contains the arrangement as defined in task 27 of the International Energy Agency [7] containing two vertical glazed daylight openings. The façade is provided with Venetian blinds. The windowsill is at a height of 0.9 meter above the floor, (see figure 6). The colour of the walls and ceiling is white ($\rho=0.85$) and the carpet on the floor is mixed blue ($\rho=0.20$). The large desk in front of the window and the table at the back has a light wooden desktop ($\rho=0.40$).

![Figure 6: Reference room with suspended luminaires and a daylighting system](image)

Other furniture in the room is a black bookcase and chairs with black seats. The electric lighting in the room exists of two rows with each two suspended luminaires with mirror optics, located parallel to the façade (see figure 6). The four suspended luminaires (ETAP R40D10) with high frequency 80 W lamps have a mutual distance of 2.7m and hang 0.6m under the ceiling.

![Figure 7: Floor plan with user positions](image)
Position a is located in the window zone parallel to the window, facing the right sidewall. At the end of the desk, in the middle of the room, position b is located perpendicular to the window. There is a working place or table for conversations in the back of the room. In position c a person is seated with his/her face directed facing the window.

Table 2: Indication of illuminance levels in the reference room

<table>
<thead>
<tr>
<th>User position</th>
<th>$E_{\text{horizontal}}$ at the desk</th>
<th>$E_{\text{vertical}}$ at the eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>At a desk perpendicular to the façade (a)</td>
<td>1050 lux</td>
<td>1100 lux</td>
</tr>
<tr>
<td>At a desk parallel to the façade (b)</td>
<td>1050 lux</td>
<td>1400 lux</td>
</tr>
<tr>
<td>At a desk in the back of the room (c)</td>
<td>800 lux</td>
<td>1200 lux</td>
</tr>
</tbody>
</table>

An indication of illuminance levels for the horizontal illuminance at the desk and the vertical illuminance at the eye for the different user positions are presented in table 2. All values satisfy both the current standards and meet the criteria for a healthy lighting environment. In the presentation and in further research the judgement of users and more measurements of luminance and illuminance will be presented.

4. CONCLUSIONS
Healthy lighting is a lighting solution that satisfies the visual as well as biological demands of people. To meet the biological demands the illuminance at the eye is the key parameter. Based on current knowledge a minimal required level of 1000 lux is assumed.

A survey of current lighting conditions in typical buildings (living and working environments) shows low vertical illuminances that do not meet the criteria for healthy lighting. Light dosage not only means determination of intensity but also of timing and spectral composition. Evaluation of design should not only be based on daylight factor calculations but also be based on evaluation of the visual environment from the user perspective.

Daylight is the preferred source to create a healthy lighting environment. This will provide a way to boost retinal illuminance without losing the efficiency and the required horizontal task illuminance level is to use a luminous ceiling (e.g., suspended luminaires). Modern electronic lighting control systems influence the energy savings, the biological rhythms and the dynamics in colour. Nowadays TFT screens with high luminances are progressively replacing the standard pc-screens but the design of the office lighting is still assuming the obsolete comfort criteria.

An office with the applications of daylight and electric lighting, as proposed in the paper, satisfy both the current standards and meet the criteria for a healthy lighting environment.

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REFERENCES