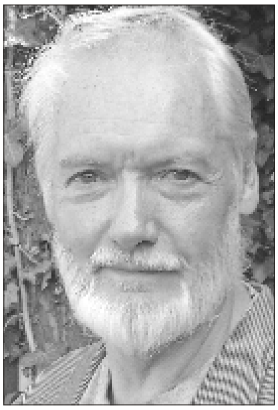
Planning for Good Indoor Lighting

by Rikard Küller



Rikard Küller, Ph.lic., D.Sc., is Professor at the School of Architecture, Lund University, Sweden, where he has been Director of the Environmental Psychology Unit and the Competence Centre for Light and Colour Research. In his research he has studied the impact of environmental light on human psychophysiology and for this area coined the term 'non-visual effects of light', which was introduced to the lighting society in his first bibliography in 1981.

Dr. Küller is an expert member of the Swedish National Committee of the CIE, the International Commission on Illumination, and has chaired an international technical committee on the Psychobiological Effects of Lighting within the CIE. The final report of the committee: The Influence of Daylight and Artificial Light on Diurnal and Seasonal Variations in Humans. A Bibliography, was published in 2001. It contains almost 1100 references to scientific papers, reports and books dealing with this subject.

Even if Küller is mainly involved in light and colour research, he also engages in research about work environments, hospitals for the elderly, urban environments, and traffic behaviour. He was one of the founders of IAPS, the International Association for People-environment Studies, and its first Chairman. He has published about 200 scientific papers and reports, amongst others a chapter in the Handbook of Environmental Psychology.

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Preface

Interior lighting constitutes one aspect only of the entire building. Sometimes, lighting is added during the last phase of the building design, or even when the building has been almost completed. Considering lighting already in the beginning of the design process will ensure a much better result, including not only the fittings and power supply of the artificial lighting system, but the shape and size of rooms and windows, and even the orientation of the entire building. Lighting should be an asset for everybody in that building during its entire existence. Whereas good lighting can be both satisfying and productive, bad lighting might cause annoyance, fatigue and stress. Thus, the design of the lighting will have consequences for the users for many years.

The idea behind this Building Issue is to present an overview of the most recent and updated knowledge about indoor lighting. The fact that most of this knowledge is based on research and experiences in highly industrialised countries, might have lent an undue technical touch to my presentation. In his study in Ghardaia, Algeria, Djamel Ouahrani found vast differences in lighting between traditional and modern buildings, and these differences affected many aspects of daily life. His results suggest how important it is to consider good traditional solutions, especially in developing countries with extreme climatic conditions. Due to the increasingly high cost of energy, many countries suffer from a severe electricity crisis. Therefore, the reader is advised to find simple low cost solutions, for instance by using natural daylight whenever feasible. For this reason, I have tried to add some comments on the cost-efficacy of various solutions.

I would like to express my sincere thanks to those experts who have taken the time to read and comment upon the manuscript, Dr. Helena Bülow-Hübe, Dr. Marie Claude Dubois, Dr. Thorbjörn Laike, and Research Officer Marianne Küller.

Introduction

Problem

As a result of urbanisation and industrialisation people spend more time indoors than ever before. Many buildings have small windows and contain large windowless spaces. As a consequence, the natural daylight outdoors has to be replaced by light from artificial light sources. If light affected vision only, this situation would be difficult enough. Since light also affects both well-being and health, the design of indoor lighting becomes a highly demanding task, which requires great knowledge and experience.

Only some professional architects and engineers have obtained specialised qualifications in lighting design. Still, in many cases any architect or building engineer may be required to provide advanced lighting installations in buildings as diverse as offices, schools and health care facilities. The main aim of the present Building Issue is to discuss various aspects of lighting in order to promote an understanding of the different requirements for good indoor lighting. A further aim is to provide practical recommendations for the specific kinds of environments mentioned above. Finally, by giving ample references to various sources of advanced information, it is hoped that the reader will be encouraged to proceed much further into the field of lighting design.

Method

The present report is a desk study based on established knowledge in the field of lighting application as well as the results of recent research. The point of departure is the author's experience from 25 years of lighting research and consultation. Whenever necessary, this has been supplemented with facts and recommendations from the most recent and updated lighting guides, standards and manuals. Finally, the draft has been submitted to the careful review of experts within the areas of daylighting and indoor lighting.

It should be made clear already from the beginning that some of the issues reported below may be controversial. Lighting recommendations are generally formulated in quantitative terms, such as recommended illuminance values (lx). However, good lighting indoors can only be provided if the lighting designer possesses a thorough knowledge of the various factors influencing lighting quality. In my experience, there has been a shift of focus from quantity towards quality in recent discussions of lighting. On the other hand, the introduction of computer software for lighting calculations may tend to shift the focus back to the realm of exact figures.

Research about the psychobiological effects of light has become a strongly expanding subfield of lighting research. Another source of controversy is recent findings from this research, for instance, that the lack of light may cause fatigue and sadness. There will be reason for anybody dealing with lighting application to assimilate this new knowledge, which will undoubtedly lead to the reformulation of present lighting standards and criteria. Some attempt has been made to consider this new knowledge in the present report.

Organisation of the Report

The first part of the report (*General Considerations*) describes the various factors affecting good indoor lighting, such as the daylight entering the room through windows and the different kinds of artificial lighting installations. Furthermore, various kinds of effects of light on humans are described, including visual and general health aspects. In the second part of the report (*Recommendations*), recommendations are formulated for three kinds of indoor environments: offices, schools and health care facilities. The most common room types in each of these buildings are discussed. Due to the briefness of the present report, it was deemed necessary to include both a section on sources for further information (*Additional Sources of Information*) and an extensive list of recommended literature.

In addition to the use of tables and calculations, successful lighting design often requires physical measurements both in mock-ups during the design process and once the building has been erected, in order to make the final installations. There might also be a need for follow-ups once the building is occupied (sc. Post-Occupancy Evaluation). For these reasons, a brief section on measurements has been included (*Measuring Light and Visual Efficiency*). As is the case in most professional fields, the field of lighting contains a great number of terms and definitions. In order not to unduly burden the main text, some of these definitions have been gathered in a glossary.

General Considerations

The Indoor Environment

From the physical point of view, the indoor environment may be considered in terms of different components, such as lighting, colour design, acoustics, ambient temperature and air quality. In a good indoor environment, these factors should be maintained within zones of comfort. In some cases, it might be possible to obtain adequate results by means of straight-forward calculations, comparing the outcome with recommendations based on previous research. At other times, personal experience and a thorough understanding of the problem area will be necessary. Lighting constitutes one such area.

Because some of the above factors interact, they should not be treated independently. For instance, the amount of light and its spectral composition will influence the visual impression of the colour design and also the actual room temperature. Therefore, the total indoor environment is more than the sum of these factors. When it comes to the total impression, subjective methods developed within the field of Environmental Psychology may be used in order to measure user satisfaction and the pleasantness of the indoor space.

Before even considering the physical environment, the lighting designer should have a clear picture of the activities that are to take place in the various rooms, and the individuals or social groups, who will work there. The obvious reason is that some activities and certain individuals demand better or stronger illumination than others (*cp. Individual Differences*). At the same time some flexibility will be desired, since a certain space might be used for different tasks or by different persons. The ultimate criterion of a successful lighting design is the continuous well-being of various users at different times of the day and different seasons of the year.

Daylight Indoors

In a room with windows or other openings, there will of course be daylight from solar radiation during the light hours of the day. Depending on its way of entry, this daylight will consist of light coming directly from the sky (including sunlight), outdoor reflected light and indoor reflected light (*Figure 1*). Traditional buildings with openings towards a courtyard might almost exclusively receive the reflected component of daylight. The daylight in the room will vary with the time of day and year, the weather conditions (cloudiness, etc.), and the reflectance of the surrounding buildings and ground, as well as of the interior walls, floor and ceiling (*Table 1*). For instance, a light floor will reflect the daylight deeply into the room, whereas a dark floor will absorb much light and make the whole room darker.

The size, shape, position, orientation and number of windows will influence the daylight indoors, as will the framing and transmittance of the glazing. Today there exists window glass with different characteristics regarding spectral transmittance and reflectance, energy conservation,

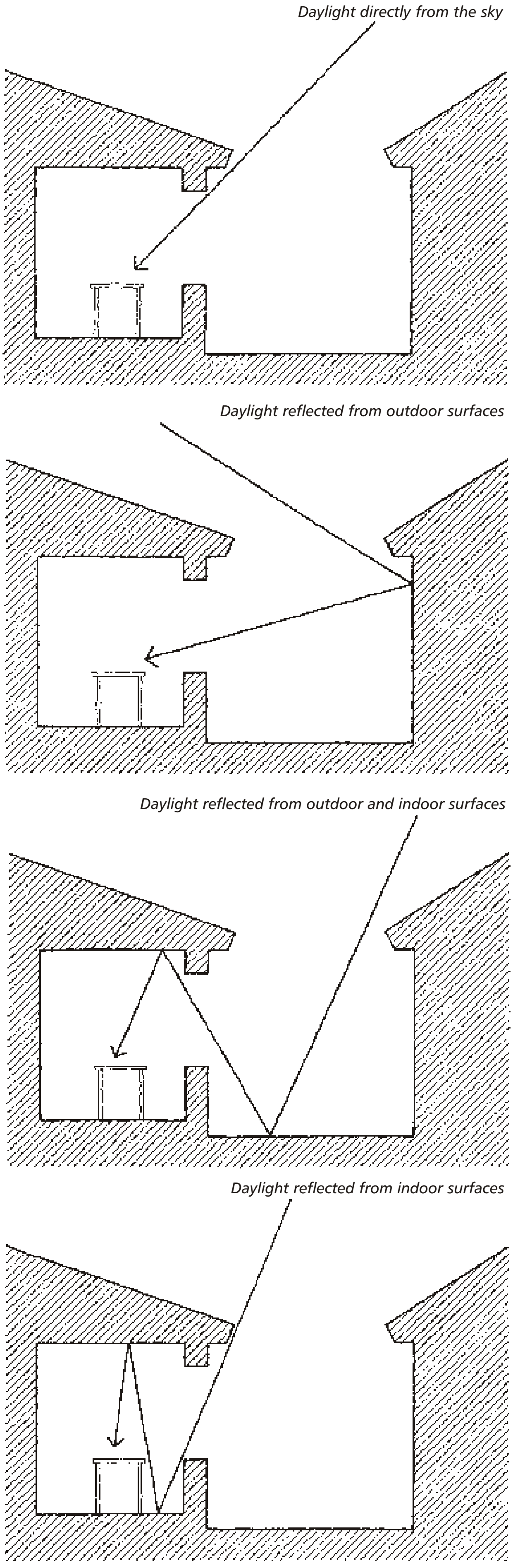

Figure 1 Section showing the different components of daylight outdoors and indoors.

Table 1 Reflectance of different materials under diffuse daylight conditions

Material or fabric	*Reflectance %*
Glass mirrors	80 – 99
White plaster	85 – 90
White paint	75 – 90
Metal surfaces	40 – 80
Textile fabrics	30 – 70
Light wood	35 – 65
Limestone	40 – 50
Grey paint	15 – 60
Concrete	20 – 40
Brickwork	20 – 30
White sand	20 – 30
Classroom chalkboard	20 – 30
Dark wood	10 – 20
Grass lawn	10 – 20
Earth	10 – 20
Window glass	10 – 20
Black paint	5 – 10
Road asphalt	5 – 10

noise reduction and fire resistance. The transmittance of light through window glass may vary from 0.8 or 0.9 for single clear glazing to less than 0.6 for low-emittance multiple glazing, provided that the windows are clean. There is also special glazing for solar control with an even lower transmittance. In order to improve the indoor climate by means of passive ventilation it might be advantageous to include unglazed window openings (*Figure 2*). The so-called daylight factor may be calculated and employed in order to specify the proportion of daylight in a room in relation to the daylight outdoors (*Figure 3*). In order to obtain the average daylight factor of a room at an early stage of the design process, specific equations can be used (*cp. Calculations and Computer Aided Design*).

In modern architecture, the reduction in thickness of the exterior walls and the increased use of glazing in the facades has made the design of good daylighting more difficult. Various kinds of shading devices might be necessary

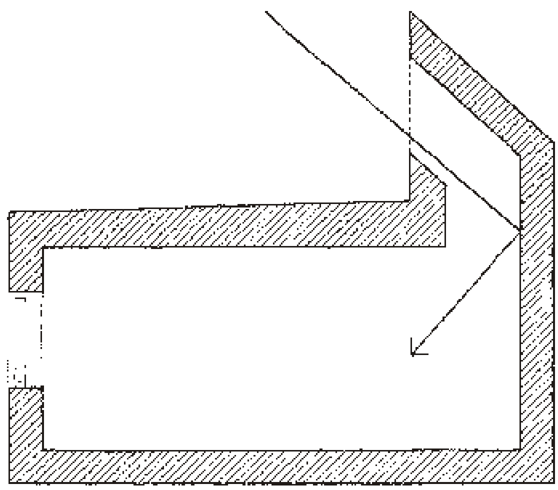

Figure 2 In countries with hot climate unglazed windows may be used in order to avoid overheating. Netting should be applied for protection against insects.

not only to avoid overheating but also to control the interior lighting and avoid glare from the windows. Among the various types of devices are fixed exterior overhangs, exterior awnings (including the Italian type), exterior jalousies and window-shutters, exterior and interior Venetian blinds, sunscreens, curtains, solar films and coated glass. (Further details can be obtained from the manufacturers.) There is still a lack of reliable information about the impact of the various types of shading devices on interior lighting and visual comfort.

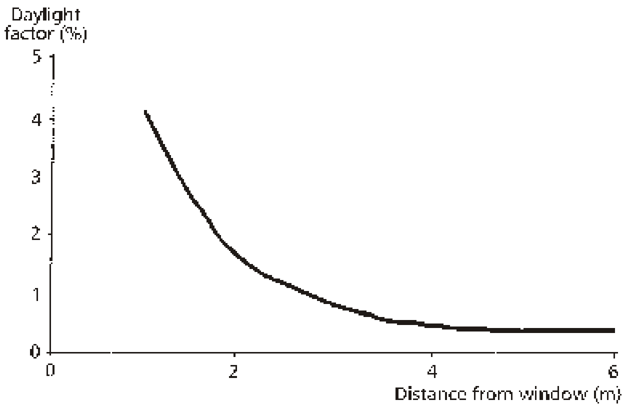

Figure 3 The daylight factor is much higher close to the window than further into the room.

Artificial Lighting

Depending on their function, artificial light sources may be classified as general lighting, local lighting and accent lighting. The purpose with the general lighting is to supply adequate overall room illumination. It may be regarded as a complement to daylight through windows, especially mornings and evenings and, in countries far from the equator, during the dark season. General lighting will always be needed in large indoor spaces where the distance to windows exceeds several meters.

The general lighting must be sufficient in terms of illuminance (lx) and colour rendering (R_a) (*Table 2 & 3*). Luminaries should be arranged in order to avoid glare, reflections and unwanted shadows. The traditional solution in offices, and the like, has been ceiling-mounted downlighting with fluorescent tubes. Nowadays, general illumination may also be provided by means of a combination of pendent downlighting and uplighting (*Figure 4*). This solution is often preferred for a number of reasons (see below). Systems for individual regulation of the general lighting level may increase comfort and sensors for automatic switch-off in empty rooms may lower energy consumption, thus saving money. Today, such systems are increasingly common.

Local lighting by means of ceiling-mounted downlighting or combined downlighting and uplighting may be used instead of general lighting in small rooms, where it will provide sufficient overall light. Such lighting can also be used in larger spaces, for instance office landscapes, in order to optimise lighting levels and avoid glare and reflections. Local lighting by means of desktop lamps, etc., should be used whenever there is need for extra light. The traditional light bulbs are now being replaced by halogen lamps, compact fluorescent lamps or metal halide lamps that can be so bright as to cause eye damage. Therefore, the light source must be well screened off from the eyes of the user. In order to avoid unwanted reflections on desktops and visual display units (VDU), local lighting should be adjustable and placed besides, or above, but not in front of or behind the user (*Figure 5*). Because of the increased risk of visual fatigue, desktop lamps should not be used for prolonged periods of time, and never as the sole light source.

Accent lighting may be employed to create a specific psychological atmosphere. For instance, lamps with decorative shades may be placed on tables, walls or floor, but even chandeliers, etc., can be used in order to create a festive atmosphere. Accent lighting can also be used in order to expose a painting or an artefact. Spotlights are the sim-

Table 2 Recommended illuminance values for various rooms and indoor activities

Type of activity	*Illuminance (lx)*
Night-time circulation	1
Daytime circulation	100
Cloakrooms, toilets	100
Archives, store rooms	200
Hospital wards	150 – 300
Simple visual work	300
Conference rooms	300
Normal visual work	500
Offices	500
Classrooms	500
Lecture halls	500
Workshops, art rooms	500
Hospital consulting rooms	500 – 750
Demanding visual work	750
Hospital examination rooms	500 – 1 000
Difficult visual work	1 000
Drawing offices	1 000
Operating theatres	1 000

Table 3 Recommended colour-rendering indices for various indoor activities

Type of activity	R_a
Art work	90
Clinical examination	90
Hospitals, generally	80 – 90
Office work	60 – 90
School work	60 – 90

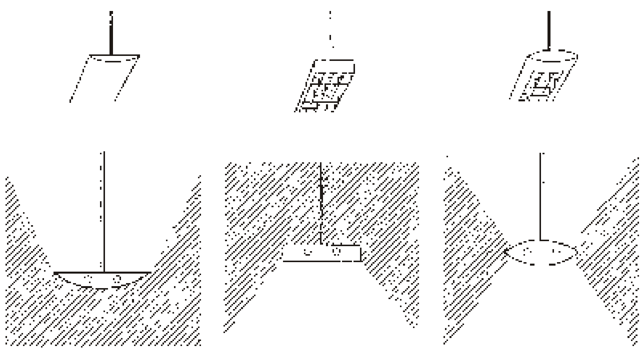

Figure 4 Some different types of luminaires.

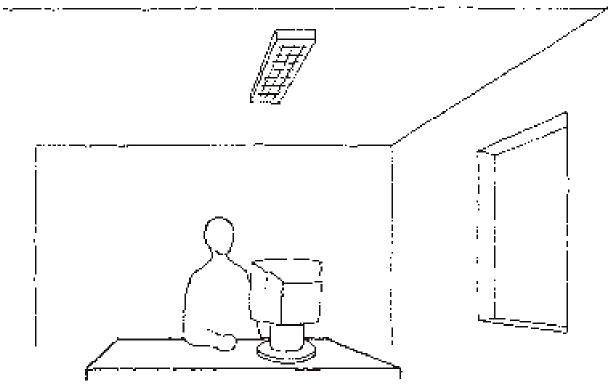

Figure 5 Good arrangement of a computer work station.

plest solution here, but ceiling-recessed downlights may be a more elegant, alas a more expensive, way to do this. Important signs, such as 'emergency exit', must be illuminated by accent lighting with separate power supply, or must be self-illuminating.

Some Common Light Sources

The most common light sources for indoor environments of the kinds described in this report are fluorescent lamps and the conventional light bulb (incandescent lamps). Fluorescent lamps are more cost-efficient and produce less heat. They are thus preferred, at least for general lighting purposes. In working environments all over the world, fluorescent tubes are by far the dominating light source. Fluorescent lamps exist in many shapes such as the conventional tube and the compact lamp. There has been a tendency during recent years to make the tubes thinner and smaller, which has considerably widened the area of application. Fluorescent lamps can vary widely in colour rendering (R_a) and colour temperature (K). (cp. section below.)

The incandescent lamp (conventional light bulb) produces less light and more heat than the fluorescent lamp and is therefore less cost-effective. On the other hand, the low colour temperature in combination with good colour rendering and absence of flicker still makes the light bulb very popular whenever a warm and friendly atmosphere is desired. It is often used in desktop lamps, bed-head lamps and the like, but even here it is nowadays being replaced by the compact fluorescent lamp.

In addition to the fluorescent lamp and the conventional light bulb, there exist other kinds, such as mercury, sodium, halogen and metal halide lamps, and new varieties appear all the time. The reader is referred to lighting manuals and manufacturers' product sheets for detailed information.

In this context one final point needs to be made and that concerns the matter of output depreciation and maintenance. When lamps get old they produce less light and, in combination with dirt accumulated on the lamps, luminaries, ceiling, walls and windows, the total output decreases considerably. After a couple of years, the total illuminance level of the room may become reduced to less than half of the original value. This depreciation must be compensated, partly, by oversizing the capacity of the original installation and, partly, by means of a maintenance program, including the exchange of old lamps, cleaning of luminaries and windows and, eventually, repainting of the room itself.

Colour Rendering and Colour Temperature

The capacity of a light source to reproduce different colours in a natural way is expressed by the colour-rendering index (R_a), with a maximum value of 100. Good colour rendering is required for certain visual tasks, such as graphic design and clinical examination (*Table 3*). Ordinary light bulbs have very good colour rendering, whereas the difference in colour rendering between different types of fluorescent tubes and other kinds of lamps is large.

The colour temperature of the light source can vary from 'warm', 'white', 'cool-white' to 'daylight', which means that the predominantly long wavelengths are gradually supplemented with shorter ones. At the same time, the yellowish impression is replaced by a slightly bluish impression. The choice of colour temperature of indoor lighting should be made with regards to both the daylight situation and the colour design and decoration of the room. The use of warm white light may not bring out the colours in a room decorated in blue and green. (Lamp manufacturers will provide detailed information about the colour rendering and colour temperature of different lamps.)

Visual Comfort and Performance

Visual performance can be defined as the ability to distinguish small items accurately and quickly, for instance, the small print in a textbook. Good performance depends both on the quantity and quality of lighting and on the characteristics of the visual object. Generally, performance will increase with increasing illuminance up to a certain level, which for conventional office work is around 500 lx. Also, the contrast between the item and the background is important. Black print on a white page is much easier to read than black print on a red or blue page. A glossy page, which reflects the light into the eye, will also reduce the contrast and impair the performance of the visual task.

Bright light will raise the adaptation level and lower the contrast sensitivity of the eye. Therefore, facing the clear sky through the window, or a white wall of high luminance, can seriously reduce the visual performance. A dark ceiling or dark window wall might cause discomfort or disability glare due to contrast. In order to ensure a good visual performance, the luminance levels of the major room surfaces should not exceed a ratio of ten to one and the ratios in the immediate visual field should be kept even lower.

In recent years, the introduction of personal computers with visual display units (VDU) has led to the avoidance of bright indoor lighting. The failure of lighting design to meet the requirements of VDU work places has resulted in drawn curtains and luminaries switched off. For reasons described below (*cp. Chronobiological Effects*) this situation is not acceptable. A careful design of the computer environment, avoiding reflexes from lamps, luminaries, and windows in the VDU, and reducing the contrast between the VDU and the immediate surroundings, will allow for a good visual environment with adequate brightness (*cp. Offices.*)

A lack of visual comfort can be caused by bright light, strong contrasts, glare and flicker. Some of these aspects have already been discussed above. However, there may be reason to make some additional comments. Glare is caused by bright light either directly from a lamp or the clear sky or from light reflected in a glossy surface, such as a VDU. Even if they frequently occur together, one may distinguish between discomfort glare, which causes feelings of discomfort, and disability glare, which actually impairs vision. In indoor environments, discomfort glare is quite common and – even if not consciously noted – in the long run it may cause visual fatigue and even general stress. Elaborate systems for glare evaluation and control have been developed, amongst others the CIE Collection on Glare (*cp. Lighting Guides and Standards*).

Flicker from light sources may be caused by faulty power supply. Fluorescent tubes that become too old have a tendency to turn on and off in an irregular way. In both instances, the flicker is easily observed and should be remedied as soon as possible. However, there may also exist flicker of frequencies too high for the eye to detect, so-called non-visual flicker. Such flicker occurs when fluorescent tubes provided with conventional ballasts are powered by alternating current (AC). Some types of fluorescent tubes give rise to very strong flicker of this kind. Even if it cannot be seen by the naked eye, the flicker can cause visual discomfort and fatigue and even general stress (*cp. Stress Effects*). It may be almost completely eliminated by using luminaries provided with electronic high-frequency ballasts. This new technique is currently replacing the conventional ballast, which will not only save energy but also increase the survival time of the lamps and allow for easy dimming control.

Aesthetic Effects

Without doubt, a successful lighting design will contribute considerably to the aesthetic appeal of the indoor environment. The view to the outside city or landscape, the size and proportions of the windows, the shapes and colours of the luminaries and lamps, the quality of the light itself and its articulation on the architecture and interior design, will influence the aesthetic character of the room. Most studies show that people prefer to work in environments with fair-sized windows. The most preferred size seems to be around 30 per cent of the facade area and most persons prefer to sit close to the window. There is also some support for the preference for clear glass. Glass with low-emittance coatings might may give a subdued and drab impression of both the daylight, the view to the outside and the colour in the room itself and contribute to a sense of enclosure. On the other hand, solar control glazing might be necessary in countries close to the equator in order to avoid excessive heat and glare.

Some correlations have been found between the physical characteristics of lighting, such as absolute luminance, luminance distribution, colour temperature and direct versus indirect lighting, on one hand, and lighting preference or overall aesthetic evaluation on the other. Often, these correlations have been established in laboratory experiments but have seldom been corroborated in real environments. In brief, there seems to be some consensus that completely homogeneous lighting will make a room look drab and lacking in aesthetic appeal, whereas a room with varied lighting and large differences in luminance level between the major room surfaces will look interesting and appealing. Light walls, ceiling and floor will make the room look larger, whereas dark surfaces will make it look smaller. A white ceiling, off white or light pastel walls and a slightly darker floor will emphasise the natural sense of solid ground and light as coming from above. Daylight lamps may be quite acceptable during daytime, especially in countries close to the equator, whereas warm or white light will be preferred during evenings and night-time.

Chronobiological Effects

Humans display a 24-hour diurnal rhythm of sleep and wakefulness, body temperature and metabolism, which is regulated by internal processes referred to as the biological clock. In order to keep time with sunrise and sunset, this clock must be synchronised by external cues, and here daylight is the most important factor. Light entrainment is most efficient during the onset of daylight in the morning and the offset during the evening. Therefore, it is important that persons working indoors are exposed to daylight through windows. The complete lack of windows may have a negative impact on well-being and performance.

The biological clock will become disturbed during night work, leading to severe sleepiness and an increased risk of accidents. Recent research has shown that, at least to some extent, these negative effects can be eliminated by having high illuminance levels during the night. The minimum lighting level required is uncertain at the present time, since different researchers claim to have obtained good results with anything between 1000 and 10 000 lx. Actually, it may be sufficient to employ the bright light only for a few hours every night.

A severe disturbance of the biological clock may also occur as a result of short day length and general lack of daylight during the winter in countries far north or south of the equator. This condition is known as Seasonal Affective Disorder (SAD) or, in less severe cases, as sub-SAD. Amongst the symptoms are severe fatigue, sleep disorders and sadness. Seasonal illness has been documented in localities as close to the equator as northern Argentina, southern USA and South Africa. The symptoms will become aggravated in windowless or otherwise dark indoor environments. On the other hand, working within two meters from a window or in a well-lit room will decrease fatigue and sadness. All types of artificial light seem to have some impact on the biological clock. However, white light is better than coloured light and general lighting much more efficient than task lighting.

Stress Effects

Visual stimulation of the eye is passed on to many different areas of the brain, amongst other related to eye movements and visual perception. There are also some more generalised effects of the visual stimulation, which means that the character of the visual environment may influence the arousal level of the central nervous system and even the heart rate and the production of stress hormones.

For instance, long-term exposure to bright light may cause general stress. Among the possible sources of this effect are glare from naked lamps and reflections from glossy objects in the visual field. Another source of stress is flicker from fluorescent tubes, especially in rooms lacking in natural daylight. The light emitted from a fluorescent tube will be modulated in synchrony with the power supply. An alternating current of 50 Hz will cause flicker of 100 periods per second. Even if such flicker will normally not be discovered by the naked eye, it will reach the brain by means of the visual pathway, and increase the arousal of the central nervous system. Young persons are most vulnerable to flicker from fluorescent tubes. Amongst the effects reported are eyestrain, headaches, disturbed performance and increased secretion of stress hormones.

Stress may also be caused by the colour, complexity and contrast of the visual field as a whole. For instance, a room with wallpaper patterned in strong colours may be a sufficient cause of heightened arousal for some individuals. Warm colours, such as red and orange, will be more arousing than cool colours, such as blue and turquoise. Mixing light and dark areas may also be stressful. One example, which is seen far too often, is the workplace facing a window, where the light from the sky is much brighter than the picture on the visual display unit (VDU).

Whereas too much glare, flicker, colour and contrast may lead to increased stress, persons working in dark environments for prolonged periods of time may come to suffer from sleepiness and fatigue. The presence of windows is highly desirable for the prevention of such under-stimulation. In windowless environments, the production of activity hormones may become deflated, especially in persons with sedentary and monotonous work, and the need for sleep may increase. Some persons working in completely windowless spaces may experience claustrophobia. In hospitals, post-operative patients in intensive therapy units may experience more delirium if the units lack windows. There is even some support for the notion that patients, in rooms with windows facing a brick wall, may have a longer post-operative hospital stay and need more medication than patients with windows facing nature.

Individual Differences

Individual lighting requirements are largely determined by the characteristics of the visual system and foremost of the eye itself. Good visual acuity requires a near perfect optical quality of the eye (with or without eye glasses) and good night vision and colour vision require a healthy retina of the eye including both rods and three types of cones.

The eyes of a young, healthy person are more sensitive, and accordingly need less light in order to perform a certain visual task, than the eyes of an old person. When the eye grows old, its optical qualities deteriorate, and, therefore, old persons need more light and are more disturbed by glare. Already at the age of 20, the sensitivity of the eye begins to decrease and, at the age of 50, a person may need much more light in order to perform as well as the 20 year old. Apart from the natural ageing of the eye, pathological conditions, such as a blurring of the lens (visual cataract), are common among elderly persons.

Some persons seem to be more susceptible to discomfort glare and to strong light. These persons tend to avoid strong daylight and, indoors, may draw the curtains and switch off the general lighting. Other persons seem to prefer bright light outdoors as well as indoors. The reasons for this difference in light preference in persons with normal eyesight are largely unclear.

Recommendations

Offices

Traditionally, the lighting of single person offices and office landscapes has been by means of daylight through windows and regularly arranged ceiling-mounted fluorescent downlighting supplemented with desktop lamps. Nowadays, most office work involves VDUs, and this has increased the need for more flexible lighting. One solution is to use pendent luminaries, which combines downlighting and uplighting, and place them in close proximity to each work station (*Figure 6*). Since much office work is still of the traditional visual kind, and also for reasons mentioned above, illuminance levels of 500 lx or more are still required (*cp. Chronobiological Effects*). On the other hand, this might create problems for work with VDUs. This dilemma might be solved through individual control of illuminance levels by means of multiple string switches or dimmers on the luminaries. It is recommended that the light sources in offices have a colour-rendering index (R_a) of or above 80, but a somewhat lower value might be acceptable (*Table 3*).

VDU-work puts high demands on the organisation of the work place and its orientation with respect to windows, as well as to the quality of exterior and interior shading devices. The VDU must be placed in such a way that light from neither windows nor lamps is reflected in the screen (*Figure 5*). Light-screen monitors are generally to be preferred to dark-screen monitors because their luminance differs less from ordinary printed text and from the interior of the room itself. In work involving VDUs it becomes even more important than in ordinary office work to keep the differences in luminance levels within a minimum. Accordingly, a VDU must never be placed in a position that will force the operator to face the window. In order to maintain the desired illuminance level of 500 lx or more, and still avoid excessive glare, the flexible lighting installations must be rearranged whenever a work station is being relocated. Unfortunately, experience tells us that this is seldom done. Detailed lighting instructions must therefore become part of the maintenance plan of the building.

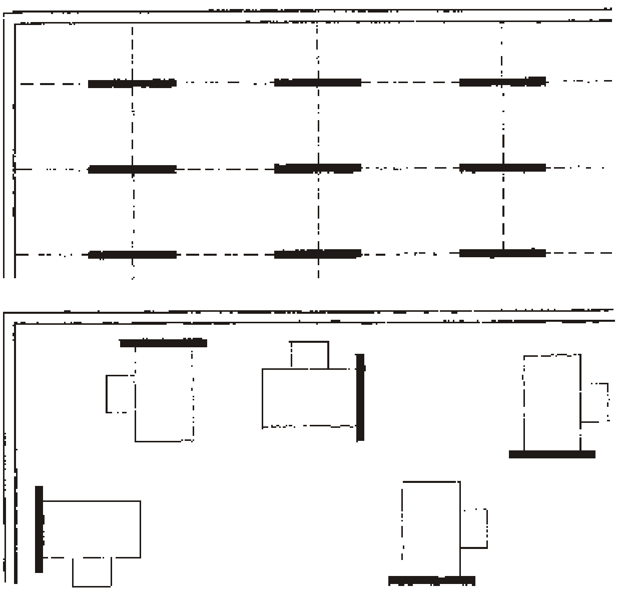

Figure 6 Traditional (top) and flexible (bottom) arrangement of luminaries in an office landscape.

Desktop lamps might be used in both the single person office and in the office landscape in order to improve the visual performance whenever required. However, these lamps should not be used permanently and certainly not as the only light source. In order to create a friendly and aesthetically pleasing atmosphere, decorative lamps can be used as design elements, and accent lighting can be employed in order to illuminate paintings and other decorative objects. Since all these small lamps might cause undesired glare and reflections, their exact placement should be carefully examined.

Conference rooms both with and without windows are common. Mostly the conference room is somewhat elongated with a centrally positioned large table and a screen for visual display on one of the shorter walls. The luminaries can either be distributed evenly in the ceiling or pendent over the central table. Facilities for shutting out the daylight and dimming the luminaries should be provided. However, there are some problems that need to be discussed here. In a conference room with windows, some persons will have their backs to the daylight whereas others will face it. The artificial illumination should be bright enough to eliminate these possible contrasts and to allow for reading of small print without causing undue glare. The ceiling-mounted downlighting will solve these difficulties, but, at the same time, may give a dull impression lacking in aesthetic appeal. Luminaries placed over the table may cause glare and reflections in the table surface. Probably the best solution will be to use a combination of general and localised lighting as well as accent lighting for decorative purposes.

In addition to the spaces already mentioned, an office building will usually contain copying rooms, canteens, toilet rooms, corridors and stairs, and sometimes a foyer with a reception desk and a cloakroom (*Table 2 & 3*). Even if the lighting may differ considerably from one space to another, the differences in illuminance level between the adjacent spaces should not be excessive. Otherwise moving from one space to the other may cause discomfort and even require some time for adaptation of the eyes. Many of the smaller spaces are likely to lack daylight, which puts a high demand on the quality of the artificial lighting.

Schools

In addition to the types of spaces mentioned above, such as offices and conference rooms, the school environment includes classrooms, lecture and assembly halls and workshops of different kinds. Perhaps the most important space is the classroom, because it is here that the pupils and teachers will spend most of their day. For the purpose of reading and writing an illuminance of 500 lx is required. Even if questioned by some, in my view the classroom should be provided with windows on one of the sidewalls. Research both on preferences and general health effects support this view. As the general population, pupils are likely to be right-handed. In order to avoid shadows when writing, windows on the left wall are to be preferred. Depending on latitude and orientation, this will put demands on efficient shading devices in order to avoid glare, direct sunlight and excessive heat. North of the equator windows to the east, south and west demand special considerations, whereas, south of the equator, windows to the east, north and west will have to be similarly dealt with. Skylight windows in the ceiling are to be avoided, partly for risk of excessive heat and, partly, because they do not provide a view towards the outside environment.

Some developing countries suffer from an electricity crisis, which makes it important to exploit daylight as much as possible. In small village schools used only during daytime it might be sufficient to use daylight only (*cp. Daylight Indoors*). However, if the school is to be used also during the dark hours it must be provided with artificial lighting. The general artificial lighting of the classroom may consist of either ceiling-mounted downlighting with fluorescent tubes or a combination of downlighting and uplighting. In this respect, the classroom does not differ from the office landscape. The ceiling-mounted luminaries may be arranged in rows parallel to the window wall, with the desks aligned between these rows. This arrangement will reduce glare from the work material. In order to compensate for declining daylight, each row of luminaries should be provided with a separate switch (*Figure 7*).

Specific demands include the possibility to darken the classroom for slide shows by means of blinds or curtains, as well as a dimming device for general lighting. Local lighting should be provided for the chalkboard and the teacher's desk. In the former case, ceiling mounted fluorescent luminaries screened from the eyes of both pupils and teacher are recommended. For pupils seated close to the chalkboard and the inner wall, problems may arise due to chalkboard glare from the windows. This may be checked through the appropriate use of the blinds or curtains. In addition, the teacher should be provided with a well-screened desktop lamp with an easily accessible switch.

The lighting demands of workshops for arts and crafts classes depend on the kind of work to be performed. Artwork involving coloured materials may take place in ordinary classrooms or in spaces lit in a similar way (*Table 2 & 3*). If windowless spaces are used, great care should be taken to assure lighting with a high colour rendering index (R_a). Computer work with VDUs should be carried out in office-like environments (*cp. Offices*). Laboratories for physical, chemical and biological work, as well as mechanical workshops, may require special lighting based on the visual requirements of the various tasks and for reasons of protection and safety. The reader should consult the appropriate lighting guidelines and manuals for industrial work.

Lecture halls and assembly halls are often used for multiple purposes, in addition to ordinary lectures, also for debates, film shows and even theatre plays and concerts. Even if some daylight is often provided, the artificial lighting installations must be appropriate, flexible and easily managed from a central panel. Events such as a theatrical performance will require special accent lighting, that is, spotlights of various kinds. Since the halls sometimes have a sloping floor, it may be difficult to attain a glare-free environment both for the auditorium and the lecturers or performers. In addition to applying the appropriate lighting guidelines, model and full-scale studies will be needed in order to obtain an efficient and aesthetically pleasing lighting installation.

Health Care Facilities

The lighting of wards in health care facilities has to meet the requirements of both medical staff and patients. In the small cottage hospital natural daylight can be a major light source. From the patient's point of view, wards with daylight from windows and a view to the outside are to be preferred (*cp. Stress Effects*). However, protection from direct sunlight must be provided, as well as the possibility to darken the room during daytime by means of curtains or the like. The patients, confined to their beds perhaps for a considerable period of time, should have a lamp suitable for reading, etc., situated above and somewhat behind the head of the bed, with a switch within easy reach (*Figure 8*). Since a wardroom may contain several patients, some wishing to read while others need to rest or sleep, it is imperative that the bed lamps are well screened from the view of other patients (*Table 2 & 3*).

In large hospitals and medical centres, artificial light takes on an important role. The medical staff will need to examine the patients even in their beds and, for this purpose, the room should be provided with examination lighting above each bed, preferably with separate switches. This light must be fairly strong. Recommended illuminance values are around 1000 lx. In order to reveal even minor changes in the colour of skin and eyes, the colour-rendering index (R_a) of the light source should be very high, prefera-

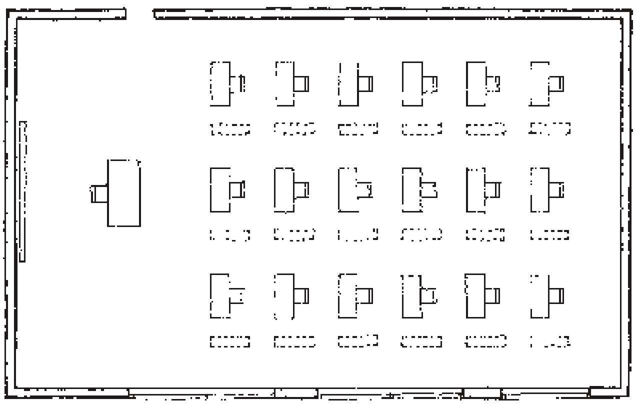

Figure 7 Arrangement of benches and luminaries in a classroom.

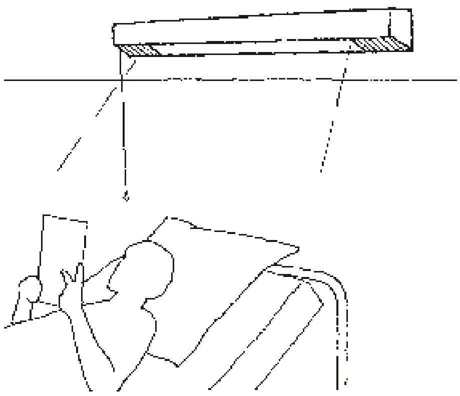

Figure 8 The reading light over a patient's bed should be well screened off from other patients.

bly above 90. Wardrooms should also be provided with general lighting for cleaning and bed making, and with adequately screened night lighting allowing both patients and nurses to find their way about during the night. A few lx on the floor will be quite sufficient.

Hospitals and health care facilities have specific requirements for the lighting of operating theatres, rooms for examination, X-ray and intensive care. Specific lamps may also be used for therapeutic purposes such as phototherapy for neonatal jaundice. Detailed guidelines are to be found in lighting manuals. The choice of installations has to be decided by specialists. Therefore, only the most general issues will be discussed here.

In operating theatres and examination rooms there is always a mixture of general and localised lighting. Especially in operating theatres the surgical luminaire may be extremely bright. In order to ensure visual adaptation, the general room lighting must therefore be rather bright. Illuminance values as high as 1000 lx may be required in order to keep luminance differences at a minimum. It goes without saying that all light sources must be well screened. They should be of approximately the same colour temperature, around 4000 K. Also the adjacent spaces used by the medical staff during the procedures must be bright enough to ensure easy adaptation. Undoubtedly, specific lighting problems will accompany the introduction of television-guided operations.

Units for intensive care also require a combination of general and localised lighting, however, of much lower illuminances. The general lighting should be adjustable from a few to some hundred lx by means of dimmers. The colour rendering index (R_a) should exceed 90 and the colour temperature should be approximately 4000 K. Additional bright light may be provided by portable surgical luminaries, using curtains around the bed to screen it off from the other patients. (Concerning daylight in post-operative units *cp. Stress Effects*.)

Today, the conventional X-ray technique is being partly replaced by computerised analyses with various types of visual display units (VDU). The lighting of these spaces and of hospital laboratories may give rise to specific demands, which must be referred to specialists. On the other hand, hospitals and other health care facilities contain many ordinary spaces, such as offices, lecture halls and corridors, where the regular lighting standards can be applied in a straightforward way.

Additional Sources of Information

Lighting Manuals

The present manual only aims to give a brief introduction to the field of indoor lighting. For more detailed information readers are referred to existing lighting manuals, guides and standards. A list of manuals will be found under '*Recommended Literature*' below.

Guides and Standards

There exists a large number of lighting guides and standards issued by national and international organisations. References to some of these guides and standards will be found below under '*Recommended Literature*'. Local guides and standards have also been issued by the National Committees in various countries. Addresses to National Committees in about 40 different countries will be found in the CIE Roster.

Scientific Journals

'Lighting Research and Technology' is the leading scientific journal of lighting research in the English language. Others are:

- Architectural Lighting
- Ergonomics
- International Lighting Review
- Journal of Light and Visual Environment
- Journal of the Illuminating Engineering Society
- Journal of the Optical Society of America A
- Lighting Design + Application.

There also exist a number of lighting journals in German, French, Spanish and other languages.

International Organisations

The International Commission on Illumination, CIE, is the main organ for international co-operation and exchange of information in the field of lighting. At present, the organisation is represented by national committees in about 40 countries. The CIE prepares and publishes lighting standards, technical reports and recommendations. Every fourth year, the CIE arranges a major conference hosted by one of the member countries. The CIE is organised in eight divisions covering the following topics:

1 Vision and Colour
2 Measurement of Light and Radiation
3 Interior Environment and Lighting Design
4 Lighting and Signalling for Transport
5 Exterior Lighting and Other Applications
6 Photobiology and Photochemistry
7 General Aspects of Lighting

8 Image Technology.

The main office of CIE is situated in Vienna. Information about CIE publications can be found under '*Lighting Guides and Standards*'.

Measuring Light and Visual Efficiency

Illuminance

The amount of light reaching a point on a surface is called illuminance. The light may come from any source, for instance a light bulb or a fluorescent tube, or from daylight through the window, and usually consists of both direct and indirect (reflected) components. Illuminance is measured in lx by means of a lux-meter, which is constructed in a manner that imitates the spectral sensitivity of the human eye.

The standard procedure is to measure the illuminance at noon on a horizontal surface approximately one meter above the floor. Actually, the standard height differs from one country to another, but in Scandinavia and many other European countries the standard height is 85 cm above the floor. For practical reasons, the light meter can be placed on the surface of the worktable or desk. In workstations, where the distance from the floor deviates considerably from one meter, it may be more sensible to carry out the measurement in close proximity to the work area. (For this one might employ the term 'functional lx'.) The use of horizontal lx was largely motivated by conventional office and assembly work. The introduction of VDU-work instead warrants the measurement of illuminance on vertical surfaces, so called vertical lx. This type of measurement will also be useful, for instance, in libraries, where it will be important to distinguish the titles on the back of books arranged on book cases.

For practical purposes it can be necessary to measure the amount of light at several times of the day and year. Whenever illuminance is measured, the time, type and location of the measurement must be carefully specified. Also, the types and locations of the various light sources should be described. However, to measure illuminance beneath a movable desktop lamp is seldom meaningful since the slightest movement of the lamp may cause a considerable change in the lx value. The person making the measurements might shade the lux-meter, thereby reducing the illuminance readings. In order to avoid this, some meters are provided with a separate light cell on a wire, which will enable the person to stand at some distance from the measurement point. Other meters have a button, which allows the reading to be stored for later inspection, while the person can remain submerged below the reference surface during the actual measurement. Often it may be more realistic to let the person remain in the normal working position while the measurement is taken, since this will reflect the functional lx value.

Measuring illuminance outdoors, or indoors close to a window, should normally be made under light overcast conditions, and, whenever there is sunlight, the standard procedure requires that the light meter is screened off from direct sunlight, for instance, by a small piece of cardboard held on a metal string. In locations with many hours of sunlight, measurements involving clear sky conditions should also be carried out. In order to calculate the daylight factor, the illuminance should be measured simultaneously indoors and outdoors in an open space, making certain that the lux-meter is not affected by direct sunlight. The daylight factor is usually expressed as the percentage of indoor illuminance in relation to the illuminance outdoors. Measurements should be carried out in different areas of the room, centrally, as well as close to, and far from the window.

Luminance

The amount of light reflected from a surface in any given direction is called luminance. Again, the light may originally come from any light source, artificial as well as natural. Luminance is measured in candela per square meter (cd/m^2) by means of a luminance meter, which, just as the lux-meter, imitates the spectral sensitivity of the human eye. Since luminance represents the brightness seen by the eye, it is nowadays often regarded as a more useful measurement in lighting design than the illuminance.

Luminances are regularly measured in various directions from the point of view of the observer, usually at eye level on the front, side and rear walls. If the different parts of the walls are distinctly different in brightness, due to their distance to a light source or their reflectance, many measurements should be made. Additional measurements should include the desk area and the screen of the visual display unit (VDU). In order to calculate a glare index, measurements are also taken at various angles upwards in the visual field, where the ceiling luminaries are situated. Specifications of these measurements and calculations are to be found in guidelines and lighting manuals (*cp. Calculations and Computer Aided Design*).

The luminance values in a room can vary much more than the illuminance values. Obviously, a luminaire will be much brighter than the surrounding ceiling. A dark board will reflect only a fraction compared to the white wall surrounding it. Even the various parts of a patterned wallpaper will reflect different amounts of light. This unevenness in brightness may cause considerable problems during the measurement procedure. Normally the luminance is measured at a visual angle of 1°. When the visual field contains large homogeneous areas of distinctly different brightness, measurements for each area should be carried out. If, instead, the visual field contains many small fields varying in brightness, it will be better to measure the average luminance within a larger visual angle. Therefore, some luminance meters are provided with this option, for instance 36°. Others contain a diffusion lens, by means of which the luminance is averaged over a wide field.

Glare and Flicker

Glare estimations are usually based on numerous measurements of luminances at various angles in the visual field (*cp. Luminance*.) Several different systems for glare evaluation have been developed, amongst others by the CIE (*cp. Calculations and Computer Aided Design*). A simple method to discover glare caused by reflexes involves placing a fair-sized mirror directly onto the work surface, for instance, the desktop or the VDU-screen. Provided the lighting design has been successful, no naked light source or part of the sky should appear in the mirror.

The light from conventional light bulbs and other incandescent lamps is produced through heating a metal wire or other element by means of an electric current. This light is fairly stable even with an alternating current. The light emitted from fluorescent lamps, on the other hand, is based on electric discharges and is therefore modulated by the power supply. An alternating current of 50 Hz will cause flicker of mostly 100 periods per second, which will not be seen by the naked eye but still may reach the brain (cp. Stress Effects). One convenient way of assessing the flicker is to use an advanced luminance meter aimed at the light source in combination with a calibrated oscilloscope.

Calculations and Computer Aided Design

Lighting design generally requires careful calculations at an early stage of the planning and building process. Once the building has been erected, there will be no possibility to influence the shape and location of the building itself, or the size and orientation of the windows. At this early stage the problems of daylighting will be at the centre of interest. Various methods for the calculation of daylight factors, etc., have been developed both for manual and computer aided design and new or updated programs appear all the time. Once the building has been erected, or when re-designing an existing building, decisions will have to be made concerning room colours, types and placement of luminaries for general and local lighting, etc. For this purpose, there exist methods both for manual and computer aided calculations.

Some of the most useful methods for manual calculation are:

- BRS Daylight Protractors
- The NB-method
- The CIE Collection on Glare 2000.

Among recent computer programs may be mentioned:

- Adeline – Advanced Daylighting and Electric Lighting Integrated New Environment.
- Calculux – Lighting Design Program for Personal Computers
- Daysim – Dynamic Daylight Simulations
- DIAL-EuropeE – European Integrated Daylighting Design Tool
- DIALux – Lighting Software
- Genelux – Daylighting and Lighting Design Tool
- Leso-DIAL – Daylighting Design Software
- Lightscape Viewset – Visualization System
- Lumen Micro – Lighting Design, Analysis and Specification
- Radiance – Synthetic Imaging System
- Radiosity – Visualisation Program
- ReLux – Computer Software
- Superlite – Lighting Analysis Program.

References to these methods and programs are given in the list of *Recommended Literature*. The readers are also referred to the various lighting guides and manuals.

Visual Performance and Discomfort

One way of measuring visual performance of one or more persons is to use a simple visual task, such as a reading test consisting of texts varying in size from 4 to 20 points placed perpendicular to the line of sight at a fixed reading distance. (Such a test has been developed by the American Optical Company.) Visual performance in terms of 'readability' can be rated by the persons themselves by means of a graded scale ranging from 'very poor' to 'very good'. The quality and speed of visual performance may also be assessed by, for instance, verbal or numerical proof reading tests or mechanical tests involving the compilation of minute industrial components.

The overall lighting quality may be assessed by rating scales covering aspects such as pleasantness, softness, warmth, naturalness, mildness, variation, brightness, clearness, etc. In order to measure user satisfaction and the overall pleasantness of the indoor space, subjective methods developed within the field of Environmental Psychology may be used. Visual discomfort may be assessed by means of rating scales or check lists with items such as visual fatigue, eye pain, dryness, itching, ache, tears and blurred vision. The scores of these items may be averaged in order to form an index of visual discomfort. The administration of these tests and the interpretation of the outcome is better left to professionals from the fields of Ergonomics or Applied Psychology.

Visual and Colour Deficiency

The diagnosis of visual and colour deficiencies requires the skilful investigation and advanced equipment of an optician or even an ophthalmologist. However, an approximate estimation of a person's visual acuity may be obtained by using, for instance, Monoyer's Chart and, of colour vision, by applying the Ishihara test.

Glossary

accent lighting – lighting aimed at particular objects or features of a room

accommodation – focal adjustment of the eye at various distances

adaptation – adjustment of the eye to the prevailing lighting situation

artificial lighting – lighting emanating from artificial light sources

ballast – device used to stabilise e.g. *fluorescent lamps*

brightness – visual sensation of more or less light in an area

ceiling-recessed luminaire – *luminaire* mounted into the ceiling

colour deficiency – disability to discriminate between certain colours

colour rendering – capacity of light source to reproduce colours naturally, indexed as R_a

colour temperature – dominant spectral character of the light, indexed as K (Kelvin)

colour vision – ability of the eye to differentiate between various colours in the visual field

compact fluorescent lamp – small size *fluorescent lamp* meant to replace the *light bulb*

cone – receptor in the retina of the eye required for daytime and colour vision

contrast – relative *luminance* of two parts of the visual field, physically or subjectively

cool-white light – bluish white light with a *colour temperature* > 5 300 K

daylight – natural light emanating from solar radiation

daylight factor – ratio between *illuminance* indoors and outdoors under a clear sky

daylighting – designing buildings for maximal use of natural *daylight*

daytime vision – see *photopic vision*

decorative lamp – lamp used mainly for aesthetic purposes

desktop lamp – a kind of *localised lighting* for temporary use placed on desk or table

dimming control – device for manual or automatic regulation of artificial light

disability glare – light, reaching the eye, which impairs the *visual performance*

discomfort glare – light, reaching the eye, causing a sense of discomfort

downlighting – *luminaire* in the ceiling concentrating the light downwards

electronic ballast – see *high-frequency ballast*

emergency lighting – lighting that works when normal lighting fails

escape lighting – part of *emergency lighting* indicating escape route

examination lighting – high quality *general* and *local lighting* for visual inspection of patients

flicker – impression of fluctuating lighting *fluorescent lamp* – discharge lamp where most of the light is emitted through fluorescence

general lighting – overall uniform lighting of an indoor or outdoor space

glare – visual discomfort or reduced performance caused by bright light

halogen lamp – gas-filled lamp with a tungsten filament

high-frequency ballast – electronic device converting 50 à 60 Hz to 20 à 100 kHz

illuminance – amount of light reaching a point on a surface, usually measured in lx

incandescent lamp – lamp with light produced by a heated filament

infrared radiation – optical radiation with wavelengths > *visible radiation*

Kelvin – correlated *colour temperature*, indexed as K

light bulb – traditional lamp where the light is produced through incandescence

lightness – visual sensation of the an object being light or dark

local(ised) lighting – lighting aimed at illuminating a specific area e.g. of a work space

louver – translucent, opaque or lamellae screen of a *luminaire*

luminaire – device containing lamp(s) and distributing light

luminance – amount of light reflected from a surface in a given direction, measured in cd/m^2

lx – (lux) unit for *illuminance*, indexed as lx

maintenance – exchange of lamps, cleaning of *luminaries* and windows, repainting of room

mercury lamp – lamp where light is produced by mercury vapour and fluorescence

mesopic vision – vision intermediate to *photopic* and *scotopic vision*

metal halide lamp – lamp where light is produced by metallic vapour and halides

natural lighting – see *daylight*

night lighting – dim light for way finding in an otherwise dark space

night vision – see *scotopic vision*

non-visual effects of light – psychological or physiological effects not directly related to vision

output depreciation – reduced lighting due to ageing or dirty lamps, or lack of maintenance

pendent luminaire – *luminaire* suspended from the ceiling by means of a cord, etc.

photopic vision – colour vision in medium or bright light mainly by means of *cones*

R_a*-index* – see *colour rendering*

recessed luminaire – *luminaire* mounted in the ceiling or wall

reflectance – proportion of light reflected from a surface, e.g. a wall or a floor

rod – receptor in the retina of the eye required mainly for *night vision*

SAD – see *seasonal affective disorder*

scotopic vision – black-and-white vision during very dark conditions mainly by means of *rods*

seasonal affective disorder – fatigue or sadness due to variations in day length

shading device – exterior and interior devices to screen off *sunlight* or excessive *daylight*

sodium lamp – light produced by low- or high-pressure sodium discharge

spotlight – device projecting the light from a lamp onto a small field

sunlight – see *daylight*

sun screen – see *shading device*

surgical luminaire – lamp with bright, highly focused light for surgical operations

survival time – the effective or total lifetime of a lamp

transmittance – proportion of light transmitted through a window, etc.

ultraviolet radiation – optical radiation with wavelengths < *visible radiation*

uplighting – light from a *luminaire* directed onto the ceiling and then reflected downwards

VDU – see *visual display unit*

visible radiation – radiation causing visual sensation

visual acuity – capacity for seing minor objects sharply and distinctly

visual adaptation – the tuning of the visual system to the external lighting conditions

visual cataract – partial or total opacity of the lens of the eye, common in elderly persons

visual comfort – sense of satisfaction with the visual environment, lack of *discomfort glare*

visual deficiency – impaired *colour vision* or *visual acuity*

visual display unit – picture screen of a computer work station or a television set

visual performance – ability to distinguish small items accurately and quickly

warm light – reddish white light with a *colour temperature* < 3 300 K

white light – white light with a *colour temperature* 3 300 – 5 300 K

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