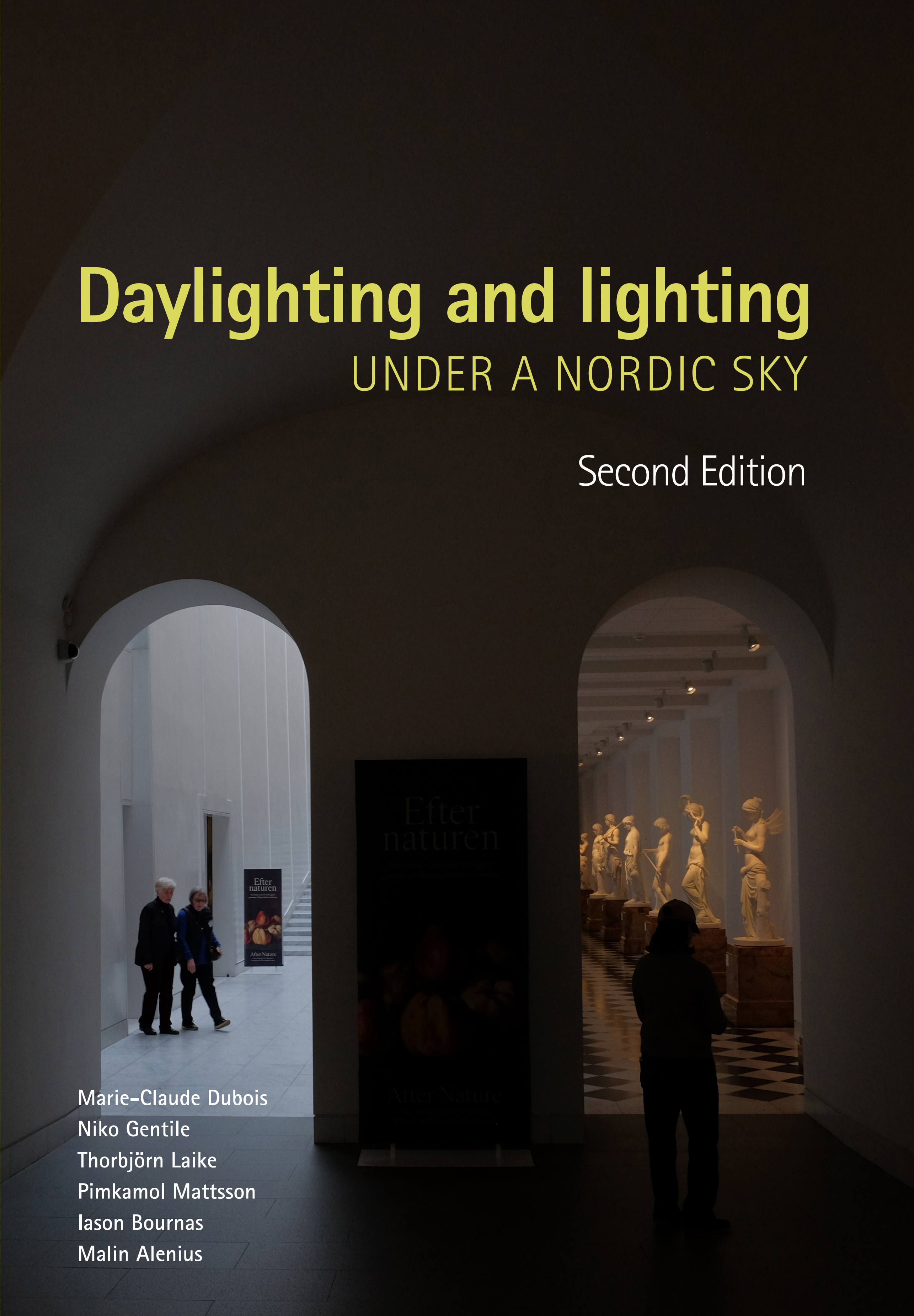
Daylighting and lighting

UNDER A NORDIC SKY

Second Edition



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ARQ is a foundation that promotes scientific research in architecture, urban planning, building planning and design. ARQ acts as a link between academic researchers and researchers in private practice through cross-border studies and projects.

Bertil & Britt Svenssons Stiftelse för Belysningsteknik

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PREFACE TO THE SECOND EDITION

After nearly a century of electric lighting dominating the design of building interiors, a return to daylight as the primary ambient light source in buildings is increasingly motivated by concerns over energy, the environment, and human health. This shift back to daylighting calls for a reconsideration of the timeless principles of building design that have shaped architecture throughout history. However, we must also account for the contemporary context: increasing urban density, evolving building regulations and certifications, advances in computer simulation tools, increased understanding of the role of light for human wellbeing, and the cutting-edge electric lighting technologies available today, such as LEDs and sophisticated control systems.

This book was originally written to provide the foundational knowledge necessary for tackling the challenge of using daylight as the primary light source in buildings, supplemented by energy-efficient electric lighting systems. Our aim in writing this book was to support our teaching of a course on daylighting and electric lighting for buildings, part of the international master's program in Energy-Efficient and Environmental Building Design at Lund University.

Following the release of the first edition, we quickly identified several areas for improvement. As scientific understanding progressed, it became evident that some sections of the book needed updating. This prompted us to seek funding to support the development of a second edition. The main updates in this revised version are described below:

In Chapter 1, we have updated the content to include the effects of outdoor factors such as ultra violet (UV) and near infrared (NIR) radiation. We have also added a new section addressing the impact of views. In Chapter 2, we removed the section on the Swedish certification system 'Miljöbyggnad' and condensed the overall text to improve clarity. Chapter 3 introduces a change in terminology, replacing 'flicker' with 'temporal light modulation' (TLM) for greater precision. Additionally, we moved the section on perception to Chapter 3 to remove redundances.

In Chapter 5, we introduced the concept of MICI (Mean Indirect

Cubic Illuminance) and included a note on luminance-based assessment methods. Chapter 6 remains largely unchanged from the first edition, with only minor revisions to improve readability and coherence. Chapter 7 has been streamlined, particularly the section on sky models, and Chapter 8 has undergone similar condensation to make the text more concise.

In Chapter 9, the part on top-lighting has been moved to Chapter 10, which has now been expanded into a standalone chapter. Chapters 11 and 12 (earlier 10 and 11) have been generally revised and enhanced to improve both depth and clarity. Finally, Chapter 14 (earlier 13) has been further developed to incorporate the latest research and trends in the field.

These updates reflect our commitment to providing the most current and accurate information, ensuring that the book remains a valuable and relevant resource for our students as well as external readers.

Light holds particular significance in the Nordic countries, where it is scarce for much of the year and overwhelmingly abundant around the summer solstice. Our lives in the North are deeply influenced by the daily variations of daylight across the seasons. The unique characteristics of Nordic daylight—weak intensity and thick cloud cover in the winter, and sharp clarity in the summer with low sun angles and prolonged sunsets—can be a great source of inspiration for architects and artists, but it demands careful study and thoughtful design, more so than in other regions. During the darker months, electric lighting becomes even more integral to our daily lives, far more so than in regions with more consistent daylight. Our dependency on electric lighting is evident when considering energy consumption figures for lighting in buildings, underscoring its critical role in the built environment.

We hope that students will find this book both inspiring and useful in their study of this vast and important subject. We also hope it will spark the interest of building professionals who wish to devote more time and attention to good daylighting design.

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- Pimkamol Mattsson, Lund University (Chapters 4 and 14)
- Johannes Lindén, Lund University (Chapters 5 and 6)
- Paul Rogers, ACC Glas och Fasadkonsult (Chapters 7 and 9)
- Malin Alenius, KTH Royal Institute of Technology (Chapters 8 and 10)
- Mandana Sarey Khanie, University College London (Chapter 13)

Thank you all for your dedication and contributions to this project!

In addition, we are deeply grateful to many friends, colleagues, and students for their direct or indirect contributions. Below is a (likely incomplete) list of those who supported us along the way:

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Lastly, we thank our friends and families for their unwavering support and for listening to our endless discussions on daylight and lighting. You heard so much about light at dinner, you could likely teach the subject by now!

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LIST OF SYMBOLS

A	Area	(m^2)
$A_{glazing}$	Net glazing area	(m^2)
A_i	Area of surface(s) in Radiosity	(m^2)
A_s	Area of surface(s)	(m^2)
A_{total}	Total area of internal surfaces including window(s)	(m^2)
A_{wall}	Wall area	(m^2)
A_z	Angular difference between solar azimuth and azimuth of sky element	(°)
C	Coefficient	(–)
C_i	Contour of surface (i) in Radiosity	(–)
D	Fractal dimension	(–)
d	Distance	(–)
d	Solar declination	(°)
dA_i	Elemental area on surface (i) in Radiosity	(m^2)
D	Daylight Matrix (in Radiance Three-Phase Method)	(–)
$DC_{\alpha\gamma}$	Daylight Coefficient for sky patch located at altitude γ and azimuth α	(–)
$d\omega$	Subtended solid angle by one element from another in Radiosity	(sr)
E	Illuminance	(lux)
$E_{average}$	Average illuminance	(lux)
Ee	Irradiance	(W/m^2)
E_g	Global illuminance	(lux)
E_h	Horizontal illuminance	(lux)
E_{in}	Initial value of horizontal illuminance (electric lighting)	(lux)
E_{indoor}	Indoor illuminance	(lux)
$\bar{E}m$	Maintained illuminance	(lux)
$E_{outdoor}$	Outdoor illuminance	(lux)
E_{rb}	Illumination reflected off the obstructing building(s)	(lux)
E_{rg}	Illumination reflected from the ground	(lux)
Es	Scalar illuminance	(lux)

$E_{s(d)}$	Direct illuminance on surface(s)	(lux)
E_t	Average horizontal illuminance at a certain time (electric lighting)	(lux)
E_v	Vertical illuminance at the eye	(lux)
E_{vert}	Vertical illuminance	(lux)
E_z	Cylindrical illuminance	(lux)
$E_{\alpha\gamma}$	Illuminance received from sky patch (of altitude γ and azimuth α)	(lux)
E_θ	Illuminance at angle θ	(lux)
F	Luminous flux	(lm)
g-value	Total solar transmittance	(%)
h	Distance	(m)
h	Atrium well height	(m)
I	Luminous intensity	(cd)
I	Result Matrix (in Radiance Three-Phase Method)	(–)
Ie	Radiant intensity	(W/sr)
K_{lum}	Luminous efficacy of luminaire	(lm/W)
L	Luminance	(cd/m^2)
l	Atrium well length	(m)
L_{70}	Lumen maintenance rating for LEDs (at 70 % of initial luminous flux)	(hours)
L_e	Emitted radiance (from a point in space)	(W/sr m^2)
L_i	Incoming radiance (onto a point in space)	(W/sr m^2)
L_o	Outgoing radiance (from a point in space)	(W/sr m^2)
L_{plate}	Luminance of the reference plate	(cd/m^2)
L_s	Luminance of the glare source	(cd/m^2)
$L_{surface}$	Luminance of the measured surface	(cd/m^2)
L_z	Zenithal luminance	(cd/m^2)
L_γ	Luminance of the sky at the elevation γ	(cd/m^2)
M	Luminous exitance	(lux or lm/m^2)
Me	Radiant exitance	(W/m^2)
MF:2	Reinhart sky dome subdivision scheme with 577 ellipsoid sky patches	(–)
MF:4	Reinhart sky dome subdivision scheme with 2 305 ellipsoid sky patches	(–)
N	Day number	(–)
n	Surface normal	(–)
n_{lum}	Luminaire efficiency	(–)
$n_{spatial}$	Spatial efficiency	(–)
P	Guth’s position index	(–)

p	Maximum grid size	(m)
P_{system}	Power of the system	(W)
r	Distance	(m)
R_{mean}	Area weighted reflectance of surfaces	(%)
R_{plate}	Reflectance of the reference plate	(%)
$R_{surface}$	Reflectance of the measured surface	(%)
R_{wall}	Wall reflectance	(–)
S	Sky Matrix (in Radiance Three-Phase Method)	(–)
S_{visual}	Sensitivity of the visual system	(–)
$S_{\alpha\gamma}$	Angular size of sky patch (of altitude γ and azimuth α)	(°)
T	Transmission Matrix (in Radiance Three-Phase Method)	(–)
tn	Transmissivity of a transparent surface	(%)
Tn	Transmittance of a transparent surface	(%)
U	Thermal conductance	(W/m^{2}K)
u,v	Coordinates in CIE 1960 UCS chromaticity diagram	(–)
u',v'	Coordinates in CIE 1976 UCS chromaticity diagram	(–)
V	View Matrix (in Radiance Three-Phase Method)	(–)
$V(\lambda)$	Spectral response of CIE standard photopic observer	(–)
$V'(\lambda)$	Spectral response of CIE standard scotopic observer	(–)
$V_M(\lambda)$	Spectral response of CIE modified photopic observer	(–)
w	Atrium well width	(m)
x,y,z	Coordinates in CIE 1931 chromaticity diagram	(–)
α	Absorptance	(%)
γ	Altitude of a sky element	(°)
γ_s	Solar altitude	(°)
θ	Sky exposure angle	(°)
θ_i	Angle of incidence	(°)
θ_r	Angle of reflection	(°)
θ_t	Angle of transmission	(°)
λ	Wavelength	(nm)
λ_{max}	Wavelength corresponding to peak response	(nm)
ρ	Reflectance	(%)
ρ_s	Reflectance of surface s	(–)
τ_{vis}	Visual transmittance of glazing	(%)
Φ	Luminous flux or luminous power	(lm)

Φe	Radiant flux	(W)
Φ_{lum}	Initial luminous flux released by the luminaire	(lm)
Φ_{lamp}	Initial luminous flux released by the lamp	(lm)
Ω	Unit hemisphere (centered around a point normal)	(sr)
ω_s	Angular size of the glare source (from eye position)	(sr)

LIST OF ABBREVIATIONS

ABDM	Aperture-Based Daylight Modelling	
AC	Alternating Current	(volts)
ADF	Average Daylight factor	(%)
AEA	Adjusted Effective Aperture	(–)
ALAN	Artificial light at night	
ANSI	American National Standards Institute	
ASE	Annual Sunlight Exposure	(%)
ASI	Aperture Skylight Index	
AU	Astronomical unit	
BBR	Boverkets Byggregler	
BF	Ballast Factor	(–)
BIM	Building Information Modelling	
BMS	Building Management System	
BRDF	Bidirectional Reflectance Distribution Function	
BRE	Building Research Establishment	
BREEAM	BRE Environmental Assessment Method	
BRS	Building Research Station	
BSDF	Bidirectional Scattering Distribution Function	
BTDF	Bidirectional Transmittance Distribution Function	
CAD	Computer-Aided Design	
CBDM	Climate-Based Daylight Modelling	
CCT	Correlated Colour Temperature	(K)
CDA	Continuous Daylight Autonomy	(%)
CDP	Caisse de Dépôt et Placements	
CFF	Critical Flicker Frequency	(Hz)
CFFF	Critical Flicker Fusion Frequency	(Hz)
CFL	Compact Fluorescent Lamp	
CFS	Complex Fenestration System	
CGI	CIE Glare Index	(–)

CIE	Commission Internationale de l'Éclairage	
CIBSE	Chartered Institution of Building Services Engineers	
CRI	Colour Rendering Index	(–)
CS	Circadian Stimulus	
DA	Daylight Autonomy	(%)
DC	Direct Current	(volts)
DDM	Dynamic Daylight Metrics	
DF	Daylight Factor	(%)
DFF	Daylight Feasibility Factor	
DF_{median}	Median Daylight Factor	(%)
DF_p	Point Daylight Factor	(%)
DF_w	Vertical Daylight Factor measured at the window	(%)
DGI	Discomfort Glare Index	
DGP	Daylight Glare Probability	(%)
DGPa	Annual Daylight Glare Probability	(%)
$DGP_{adaptive}$	Adaptive Daylight Glare Probability	(%)
DGPs	Simplified Daylight Glare Probability	(%)
DHS	Daylight Harvesting System	
DLSR	Digital Single Lens Reflex	
Duv	Delta, u,v	(–)
EA	Effective Aperture	(–)
eDGPs	Enhanced Simplified Daylight Glare Probability	(%)
EEG-alpha	Electroencephalography, alpha waves (7.5–12.5 Hz)	
EFA	Education Funding Agency	
EML	Equivalent Melanopic Illuminance	
EMR	Electromagnetic Radiation	(W)
EN	European Norms (European standards)	
EPBD	Energy Performance of Buildings Directive	
EPFL	École Polytechnique Fédérale de Lausanne	
ERC	Externally Reflected Component (of BRE split-flux Method)	
ESCo	Energy Service Companies	
EV	Exposure Value	
FR	Far-red	
FRF	Flux after first reflection	(lm)
GET	Geodata Extraction Tool	
GWR	Glazing-to-Wall Ratio	(%)

HDR	High Dynamic Range	
HVAC	Heating, Ventilation, and Air Conditioning	
IEA	International Energy Agency	
IES	Illuminating Engineering Society	
IESNA	Illuminating Engineering Society of North America	
ipRGCs	Intrinsically Photosensitive Retinal Ganglion Cells	
IR	Infrared	
IRC	Internally Reflected Component (of BRE split-flux Method)	
ISO	International Organization for Standardization	
KSS	Karolinska Sleepiness Scale	
LaaS	Light-as-a-Service	
LBNL	Lawrence Berkley National Laboratory	
LCS	Light Control System	
LD	Lighting Dependency	(%)
LDR	Low dynamic range	
LED	Light-Emitting Diode	
LEED	Leadership in Energy and Environmental Design	
LM	Light measurement	
LOR	Light Output Ratio	(%)
LPD	Lighting Power Density	(W/m^2)
LRV	Light reflectance value	(%)
LSG	Light-to-Solar Gain	(–)
LT	Light Transmittance	(%)
MDA	Maximum Daylight Autonomy	(%)
mEDI	Melanopic Equivalent Daylight Illuminance	
MF	Maintenance Factor	(%)
MICI	Mean Indirect Cubic Illuminance	
MLP	Mirrored Light Pipe	
MRSE	Mean Room Surface Exitance	(lux)
NBS	Nytt Barnsjukhus	
NIR	Near-infrared	
NIST	National Institute of Standards and Technology	
NCS	Natural Colour System	
NSL	No Sky Line	
NSM	Nya Sjukhusområdet Malmö	
OBEA	Observer-Based Environmental Assessment	

OF	Obstruction Factor	(–)
OLED	Organic Light-Emitting Diode	
OPN5	Extraocular deep brain opsins	
ORS	Optical Redirecting System	
PAI	Perceived Adequacy of Illumination	
PAR	Plan Aspect Ratio	(–)
PBMT	Photobiomodulation therapy	
PCQ	Perceived Comfort Quality	
PF	Power Factor	(–)
PILQ	Perceived Indoor Lighting Quality	
PIR	Passive Infra-Red (sensor technology)	
POEs	Post-Occupancy Evaluations	
POLQ	Perceived Outdoor Lighting Quality	
PSBD	Priority Schools Buildings Program	
PSQ	Perceived Strength Quality	
PSS	Product-Service System	
PWGSC	Public Works and Government Services Canada	
R2RD	Right-to-repair directive	
Ra	General Colour Rendering Index	(–)
RGB	Red, Green, Blue	
RVP	Relative Visual Performance	
SAC	Surface Area Coverage	
SAD	Seasonal Affective Disorder	
SAR	Section Aspect Ratio	(–)
SBS	Sick Building Syndrome	
SC	Sky Component (of BRE split-flux Method)	
SCN	Suprachiasmatic Nuclei	
sDA	Spatial Daylight Autonomy	(%)
SED	Semantic Environmental Description	
SGBC	Sweden Green Building Council	
SHC	Solar Heating and Cooling	
SHGC	Solar Heat Gain Coefficient	(%)
SI	Système International d’Unités (International System of Units)	
SPD	Spectral Power Distribution	
SS	Swedish Standard	
SSL	Solid-State Lighting	

TAIR	Target-to-Ambient Illumination Ratio	(–)
TDDs	Tubular Daylighting Devices	
TEA	Technical Environmental Assessment	
TLA	Temporal light artefact	
TLM	Temporal light modulation	
UCS	Uniform Chromaticity Space	
UDI	Useful Daylight Illuminance	(%)
UGP	Unified Glare Probability	(%)
UGR	Unified Glare Rating	
UR or U_o	Uniformity Ratio	(–)
URT	Ubiquitous Rule-of-Thumb	
US-DOE	United States Department of Energy	
USGBC	United States Green Building Council	
UV	Ultra-violet (radiation)	
VCP	Visual Discomfort Probability	(%)
VDF	Vertical Daylight Factor	(%)
VDT	Video Display Terminal	
VDU	Visual Display Unit	
VLC	Visible Light Communication	
VSC	Vertical Sky Component	(%)
WI	Well Index	(–)
WID	Well Index Depth	(–)
WWR	Window-to-Wall Ratio	(%)
YR	Yellow, Red	

CHAPTER 1

Introduction

MARIE-CLAUDE DUBOIS

> ‘Light is where we locate magic in architecture.’
>
> ANN MARIE BORYS, 2004[1]
>
> ‘Nowadays I don’t regard architecture as a building in itself; it is a means of revealing something else. For me, light is the most ecstatic architectural experience there is, and in many ways the best architecture is a preparation for the experience of light.’
>
> JUHANI PALLASMAA[2]

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Daylight, electric light, sunlight, importance of daylight, spectral composition, variability, preference for daylight, daylight and health, daylight and productivity, short-wavelength light, circadian cycle, good daylighting, visual performance, blackbody, infrared radiation, vitamin D, seasonal affective disorder (SAD), photobiomodulation therapy (PBMT), artificial light at night (ALAN), benefits and risks of daylighting, risks of electric lighting, luminous efficacy, temporal light modulation (TLM), flicker, visual and non-visual TLM, glare, daylight utilization, contrast, discomfort glare.

1.1 Importance of light and daylight

Light is important for people's health and well-being. It significantly affects the mood, emotions, and mental state of humans[3]. The two main sources of illumination in buildings are daylight and electric light, both addressed in this book. However, as expressed by Van Bommel (2009)[4], 'using lighting in the right way in buildings means principally starting by studying the possibility of daylight use'. We strongly agree with this statement. Therefore, daylighting is addressed first, followed by some chapters on electric lighting, which should always be considered as a complement to daylighting.

In contrast to illumination from electric light sources, daylight varies in level and spectral power composition with time, providing variability in building interiors[3]. The dynamic changes in daylight positively influence mood and stimulation[5], which, in turn, positively affects people's activation state, particularly in indoor work environments[6]. The changing character of daylight and sunlight provides interior spaces with 'a dynamic quality not easily achievable with an electric illuminant'[7]. Daylight illumination levels in a space are 'dynamic, constantly changing both in intensity and spatial distribution pattern as the two variable sources of daylight – the sun and the sky – interact with the geometry and physical properties of the space, the exterior context and interior conditions'[8].

In the Nordic countries, the availability and character of daylight exhibit great variability from summer to winter, particularly at higher latitudes. Above the circumsolar polar circle, the sun hardly rises above the horizon for two months around the winter solstice, while in the summer, one can easily walk in a dense forest at midnight. Even in Southern Sweden, the gloom is intense during winter as the overcast sky is predominant, and sometimes, a thick layer of clouds appears to float not far from the ground. Many days are foggy, and the sun appears only for a few hours each month. The absence of snow as a natural light reflector makes the winter gloom worse than in Northern Scandinavia, where the snow cover reflects skylight. These dark winter skies create difficult psychological conditions for the population living at high latitudes. Low levels of vitamin D are predominant in the population, and winter depression and the so-called seasonal affective disorder (SAD) affect many people. The general mood changes in summer as people enjoy abundant daylight and sunlight before and after work each day. It is no coincidence that the celebration of 'Midsommar' (Midsummer) is a strong tradition in Nordic countries as it falls around the longest day of the year.

Daylight is 'one way to provide healthy lighting in buildings; it is energy-efficient, rich in short-wavelength light, and available much of the time at high intensities' [9]. Designing buildings that make greater use of daylight and recognizing the additional benefits of natural light could greatly benefit building inhabitants because solar radiation is naturally rich in the short wavelength ('blue') radiation, which predominantly regulates the circadian system[10].

In addition, it is worth noting that in non-residential buildings, daylight availability coincides with normal work hours and, therefore, could displace a significant portion of electricity use for lighting[11]. Previous research has indicated that standard daylighting techniques can provide illumination three to 20 times cheaper than electric lighting, with the best performance reached by daylight through roof apertures[12].

1.2 Definition of good daylighting

Good daylighting has been defined as 'the conscious usage of glare-free natural light to illuminate a building's interior' [13]. There is a general acceptance that 'a space with good daylighting minimizes visual discomfort and provides high levels of visual quality under solely or predominantly daylight conditions frequently throughout the year' [8]. In 2011, Reinhart and Wienold[14] proposed a definition of (good) daylighting, which is a 'space that is primarily lit with natural light and that combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling'. According to these authors, daylighting design is, therefore, a compromise between optimizing the annual daylight availability within a space and ensuring the space is energy-efficient while providing high occupant satisfaction. Note that, in the recent years, there is more emphasis on the role of daylight (and daylighting) on effects beyond vision i.e., effects of good daylighting on health.

1.3 Preference for daylight

Daylight is invariably promoted as a 'good thing', and the literature contains numerous articles supporting the intention to provide 'good daylight' for buildings[15]. Several studies have emphasized the importance of daylight and windows, and research has demonstrated the numerous positive effects of daylighting on building inhabitants.

In work environments, daylight is generally preferred over electric lighting[16]. Canadian studies have indicated that people consider daylight the primary light source, superior for health and well-being[17]. Boubekri (1995)[7] found that workers occupying stations near windows reported significantly higher satisfaction with the lighting compared to those in core areas, which may also be attributed to access to a view. Roche, Dewey & Littlefair (2000)[18] claimed that people expect good natural lighting in their workplaces. Escuyer & Fontoynont (2001)[19] found that 44% of the respondents in a French working environment considered 'having plenty of daylight' as one very important characteristic of their office. Galasiu & Veitch (2006)[20] observed a consistent strong preference for daylight in a review of 60 peer-reviewed research studies of subjective issues related to the use of daylighting in office buildings. A Danish survey[21] indicated that 60% of office workers wish to have direct sunlight in their offices during at least one season of the year. In a more recent Egyptian study[22] on customer's perception, preference, and satisfaction in shopping malls, a preference for daylighting utilization was observed. A majority (63%) of customers agreed that daylighting is both important and attractive, while 59% preferred the entry of direct sunlight.

In residential buildings, a few studies have indicated that daylight is a key attribute in a dwelling, with around 60% ranking it as important[23]. Furthermore, a World Health Organisation (WHO) survey involving eight cities across Europe indicated that individuals reporting inadequate daylighting in their homes had a greater risk of depression and falls[24].

1.4 Benefits of daylighting

According to a recent literature review[25], there is strong evidence that natural light has a positive impact on health. Effects on health encompass both ocular and non-ocular (skin) exposure. Research has demonstrated the benefits of daylight and sunlight for the health and well-being of building inhabitants, including its necessity for regulating circadian rhythms[26] [27] [28]. Some of the benefits of daylight can only be fully realized outside buildings, as ordinary window glass allows only a portion of the total solar radiation to pass through. While the outdoor benefits of daylight are relevant to urban planning, the indoor benefits are primarily applicable to building design.

1.4.1 Benefits of daylighting outdoors

The first benefit of daylighting outdoors concerns vitamin D production through skin exposure. The healing capacity of light to cure rickets and osteomalacia was discovered around 1861-62[29]. Both conditions are cured by synthesising vitamin D in the skin through exposure to sunlight in the ultraviolet (UV) range[30]. While high vitamin D levels are essential for bone development and health, low levels are associated with a higher risk of COVID-19 infections, according to recent evidence[31]. It is important to note that since much of the UVA and UVB radiation is blocked by window glazing[32], one needs to spend time outdoors to benefit from this effect. Currently, there is concern that, due to the enormous time spent indoors in the developed countries (>87%)[33], the rickets disorder is on the rise again.

The second benefit of outdoor daylighting is linked to the ultraviolet (UV) range as well. In 1895, the Dane Finsen demonstrated that various skin infections could be treated using electromagnetic radiation in the ultraviolet (UV) range. This groundbreaking discovery earned Finsen the Nobel Prize in Medicine 1903 and directed attention to the non-visual spectrum of daylight in conventional medicine[34].

During the 1950s, a nurse, Sister Jean Ward, at Rochford General Hospital in Essex, accidentally discovered that neonatal jaundice could be successfully treated by exposure to sunlight. Subsequently, in the 1960s, research found that blue light (430–490 nm) was more effective in treating this condition.

Recent studies[35] reveal that newly identified extraocular and deep-brain opsins (OPN5), sensitive to the UVA range, may play a role in circadian and non-circadian functions, influencing eye development and endocrine regulation. Note that this research was conducted with chickens and the function of these opsins in humans is not yet fully understood. Nevertheless, results related to eye development appear consistent with other research, which associates time spent outdoors with a reduced prevalence of myopia in children[36] [37] [38] [39]. Research suggests that 'the mechanism of the protective effect of time outdoors involves light-stimulated release of dopamine from the retina, since increased dopamine release appears to inhibit increased axial elongation, the structural basis of myopia' [40]. This aspect is gaining more attention from health authorities, as myopia is a highly prevalent and potentially sight-threatening condition, affecting 80% of children in Asia and 30-50% of children in America and Europe[41]. The myopia epidemic is a global phenomenon[42] [43] [44] [45] [46] [47] projected to affect 50%

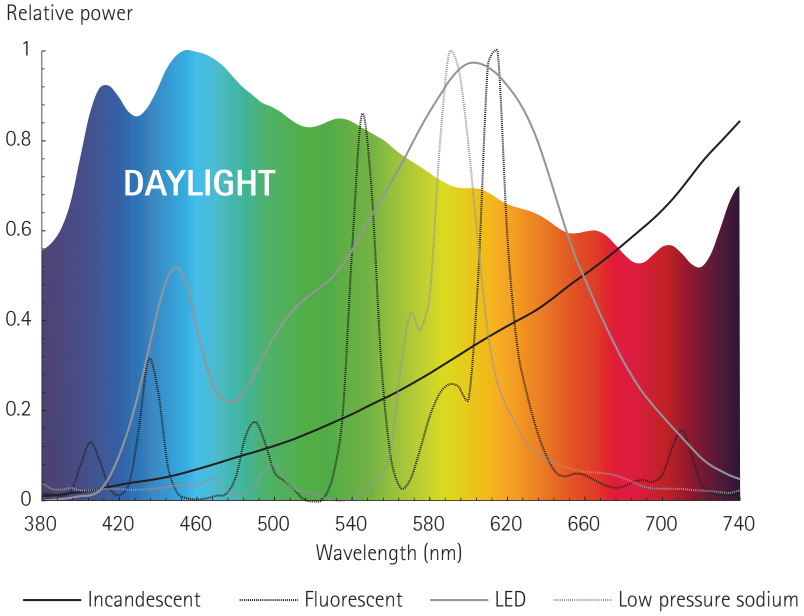

Figure 1.1
Spectral power distribution of daylight versus incandescent, compact fluorescent, fluorescent and LED light sources.

of the world's population by 2050[39]. Severe myopia can result in retinal tears and detachment, choroidal degeneration, glaucoma, cataracts, and, ultimately, blindness[48 49 50].

The third benefit of exterior daylighting relates to non-visual, near-infrared (NIR) light[51]. In Western societies, where people spend most of their waking hours indoors[33], they are exposed to virtually no NIR light due to modern glazing that removes NIR light through low-emissivity coatings[52]. This benefit of sunlight can only be experienced outdoors or under specific artificial NIR lights used in photobiomodulation therapy (PBMT). The positive effects of NIR light on health have been known empirically for centuries[53 54]. More recently, low-level light therapy in the far-red (FR) to near-infrared (NIR) range of the spectrum (~600 - 1000 nm), referred to as PBMT, has gained worldwide attention as a novel scientific approach for experimental therapeutic applications in a variety of visual and neurological conditions[51]. NIR light has been shown to induce metabolic and antioxidant beneficial effects, boost cerebral blood flow, and cognitive functions in humans without adverse effects.

In summary, outdoor daylighting provides energy in ranges well outside the visual spectrum, including ultraviolet (UV), infrared (IR), and near-infrared (NIR) light, all of which have health-related effects, such as vitamin D production, eye development, and eye-brain function. One must spend time outside buildings to benefit from these light spectra, as window glazing does not allow enough UV or IR light to pass through.

1.4.2 Benefits of daylighting indoors

The benefits of daylighting inside buildings relate to visual (performance, comfort, perception) as well as non-visual effects (circadian and seasonal effects, etc.). The following effects are discussed in this section:

1. Better visual performance
2. Better stimulation of the circadian cycle (night/day)
3. Improved mood and well-being
4. Improved hygiene and air quality
5. Increased productivity (relevant for workplaces and schools)
6. Absence of temporal light modulation (flicker)
7. High luminous efficacy (lumens/Watts) resulting in energy savings
8. Improved architectural quality and improved space perception
9. Higher building or rental value and improved building image
10. Positive effect on sales.

Numerous reports, books, and articles[16 55 56 57 58 59 60] discuss the benefits of daylight, primarily in terms of health or productivity. Some of this knowledge is briefly summarized below.

The first benefit of daylight concerns visual performance, mediated by the amount of light available[61], which is often much higher for a daylight-dominated indoor space compared to an electric lighting-dominated space during daytime. Daylight also provides a continuous spectrum of light, rich in blue light, further supporting visual performance. A continuous spectrum contains energy across the entire spectrum without any gaps or peaks, as shown in Figure 1.1. This allows all subtle colour shifts to be rendered and perceived by the eye. It is worth noting that fire, tungsten incandescent, and halogen lamps (blackbody radiators) also have a continuous light spectrum, but their dominant radiation is primarily in the red and infrared range. Daylight renders colours naturally, and since humans have evolved under daylight, their visual performance is greatest under this natural light source. On the other hand, electric lighting is a relatively recent invention. Except for LED, many artificial light sources provide an unnatural and narrower spectrum of light, where blue light may be poorly represented, leading

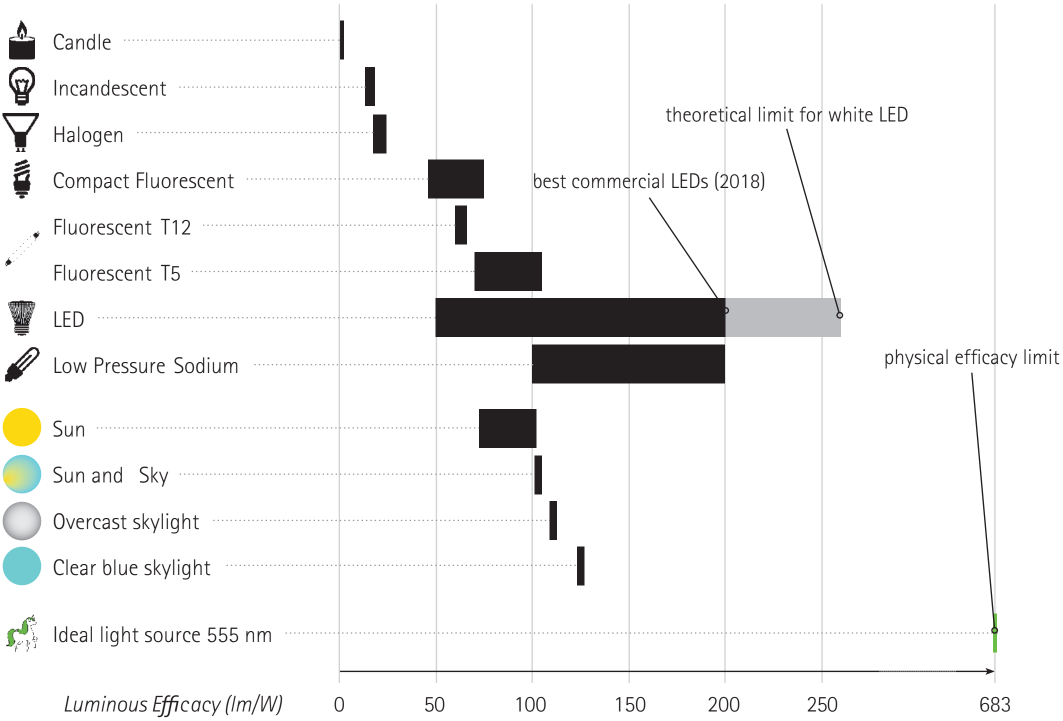

Figure 1.2 Luminous efficacy of different electric and natural light sources. Icons from www.freepik.com.

to poorer eye function[30]. The higher visual performance under daylight is related to health and safety, as individuals reporting falls are more likely to report inadequate natural lighting in their home[24]. This aspect is especially significant in the context of an aging population and warrants consideration.

The second benefit of indoor daylighting is its capacity to effectively stimulate the human circadian system, a topic which has gained considerable attention over the last two decades. Circadian rhythms have evolved to synchronize with a predictable 24-hour cycle of light and darkness, enabling organisms to align their biology with daily environmental changes. It is now understood that intrinsically photoreceptive retinal ganglion cells (ipRGCs) in the retina play a crucial role in providing signals to the human circadian clock[62 63 64 65]. Circadian rhythms influence various aspects of human physiology, including sleep patterns, alertness, memory formation, hunger, hormone release, blood pressure, body temperature, and immune response[66]. Light signals during the day are essential for maintaining overall health[67]. Light plays a key role in synchronizing the functions of the nervous and endocrine systems and the secretion of hormones, such as melatonin. Melatonin, released by the pineal gland, is one of several hormones with a circadian rhythm; it follows a 24-hour cycle in response to diurnal light patterns, helping to regulate the body's circadian rhythm. A receptor found within the ganglion cell layer of the retina called melanopsin is highly sensitive to rich blue light and signals the suppression of melatonin[68]. It is worth noting that daylight is rich in wavelengths, especially the blue spectrum, during the day[69]. In typical sleep-wake cycles, melatonin levels peak at night in darkness, promoting healthy sleep, while they are absent during the day, enhancing alertness. Disruptions to these circadian rhythms caused by inadequate daylight exposure during the day or excessive bright lights at night can lead to disrupted circadian rhythms and, in the long term, various dysfunctions or illnesses.

Seasonal daylight rhythms also affect health and well-being of humans and animals. Some individuals suffer from Seasonal Affective Disorder (SAD), which brings a cluster of symptoms every fall or early winter, including sadness, somnolence, disrupted sleep, fatigue, social withdrawal, loss of sexual interest, overeating, etc.[70] A cross-sectional study in eight European cities with 6 017 participants indicated that self-reported inadequate natural light increased the likelihood of reporting depression[24]. Other studies found a positive association between illumination and reduced self-reported depression scores[71]. In one of the studies, reduced window covering in the morning was associated with greater illumination and improved depression scores[72]. Fortunately, light therapy and exposure to daylight outdoors are effective means for mitigating SAD symptoms[73] [74].

Daylight is sufficiently intense to entrain the 24-hour cycle and maintain a state of wakefulness during the day, while decreasing light levels in the evening and a dark room promote sleep at night[68]. In absence of periodic environmental cues from light, the internal clock produces a 'subjective' day length that differs from 24 hours[71]. Recent research shows that good sleep requires exposure to high light levels, especially daylight rich in short wavelengths, during the day[75] [76] [77]. One study associated improved sleep, including duration, quality, and latency, with morning illumination[73].

Thirdly, by providing ideal conditions for the visual system and strong environmental cues to the brain related to timing and activities, daylight provides a reassuring and natural biological environment for humans, which may explain why daylighting has a positive effect on mood and a mitigating effect on stress. One study indicated that

Figure 1.3
Normal scene of a meeting showing that the windows are directly in the visual field of the occupant and create glare. Photo: Marie-Claude Dubois.

higher light doses create a positive feeling about life and that many Americans may be receiving insufficient light exposure to maintain optimal mood[78]. A Canadian study showed that exposure to above-average bright light levels (>1 000 lx) was associated with lower levels of quarrelsomeness, positive social interaction, higher agreeableness, and a better mood[79]. Daylighting is thus associated with 'improved mood, enhanced morale, reduced fatigue, and reduced eyestrain' [30]. Studies showed that office workers with less sunlight exposure have worse self-reported sleep quality and mood[76 80].

The fourth benefit of daylight relates to hygiene, as light exposure influences the viability of pathogens on surfaces[80], an aspect which has gained increased attention after the onset of the Covid-19 Pandemic[81]. For centuries, sunlight has been considered a potential buffer against the spread of pathogens in buildings[82 83 84 85] due to its potential bactericidal effects, discovered by Downes & Blunt in 1877[86]. Literature indicates that before the discovery of antibiotics, sunlight played a significant role in infection control and preventing the spread of pathogens in buildings[86 87]. The property of UV light, in particular, to sanitize the air has been demonstrated by modern science[85 88]. Even artificial lighting based on ultraviolet (UVC) light is being effectively used in hospital settings to reduce infection transmission[89 90]. Epidemiological studies have demonstrated the link between influenza transmission and season in temperate regions, while either no seasonal variability or some increase in the rainy seasons has been found for the Tropics[91 92]. Studies focusing on natural light and infectious diseases found that individuals with sunlight exposure in their homes were 94% less likely to be diagnosed with tuberculosis[93]. In India, natural light exposure has also been associated with a decreased risk for leprosy[94]. Recent research conducted in the USA[95] has confirmed that daylight exposure reduces the abundance of viable bacteria and communities in ordinary household dust. In this experiment, dust exposed to daylight contained smaller viable bacterial communities that more closely resembled outdoor air communities. The authors found that the 'bactericidal potential of ordinary window-filtered sunlight may be similar to UV wavelengths considering dosages relevant to real buildings'. In fact, the disinfectant effect of daylight has been found to persist via indirect sunlight exposure through glass[86 96]. In another study simulating sunlight (optimized in the UVA and UVB range) on influenza virus aerosols, the virus half-life was significantly reduced from 31.6 minutes in the dark control group to approximately 2.4 minutes in simulated sunlight[97]. In brief, daylighting is not only an indoor environmental quality parameter, it is an air quality parameter, and rooms with good daylighting are also healthier for breathing.

The fifth benefit of daylighting relates to the link between productivity and the presence of daylight in working and learning environments[98 99]. Daylighting research has linked increased comfort and self-reported productivity with window size and proximity, as well as with view out, control over blinds, and shielding from glare[100]. A literature review on the effects of natural light on building inhabitants concludes that 'daylighting has been associated with higher productivity, lower absenteeism, fewer errors or defects in products, positive attitudes, reduced fatigue, and reduced eyestrain' [30]. Heerwagen et al. (1998)[101] claimed that daylighting leads to higher job satisfaction, which, in turn, leads to increased work involvement, motivation, organization attachment, and lower absenteeism. Several companies have reported increased productivity ranging between 5-28% after improving daylight conditions[30]. The link between light, mood, and learning has recently been studied by experiments on mice[99]. In human studies, the effect of daylighting has been linked to better learning in schools[102]. An American study showed that students in classrooms with better daylighting obtained higher scores (7-18%) on standardized tests compared to those with poorer daylighting[103].

When considering the productivity of our healthcare system, it is worth noting that sunlighting has been shown to affect time in hospitalization, stress, use of analgesics, etc. A Canadian study showed that patients in a cardiac intensive care unit stayed a shorter time in sunny rooms compared to dull rooms, but the significant difference was confined to women, while mortality in both sexes was consistently higher in dull rooms[104]. In the USA, one study[105] showed that postoperative exposure of patients to increased amounts of natural sunlight during their hospital recovery period resulted in decreased stress, pain, analgesic medication use, and pain medication costs. Several other studies have reported similar effects on healthcare outcomes[106].

A sixth benefit of daylight is its inherent continuity in time. In nature, sunlight varies as the sun angle changes over time, clouds pass in front of the sun, and trees sway in the wind, causing intermittent light. However, most of these variations are relatively slow, irregular, organic, and likely desirable for humans. With electric lighting, temporal light modulations (TLM), commonly called 'flicker,' occur. This means that the light output exhibits rapid fluctuations of luminous flux in time, an effect which can be directly seen (visual) or sensed by the brain (non-visual) with most electric light sources. TLM produced by electric light sources has been associated with health problems in animals and humans[107], such as migraines, fatigue, etc. It is highly detrimental for highly sensitive individuals, persons with autism[108] [109] or epilepsy[110]. Fortunately, daylight is free of temporal light modulations.

Daylight, especially skylight, has a high luminous efficacy (lumens/Watts) compared to most electric light sources[111]. This is an advantage when illuminating buildings with high internal heat loads, such as offices, since relatively little heat is radiated for every lumen of light produced. As an example, the luminous efficacy of incandescent lamps is very low (around 15 lumens/W), which means that an incandescent lamp is, in fact, 'a heater that happens to also provide light' [112]. In comparison, the luminous efficacy of fluorescent lamps can be as high as 100 lumens/W, which is still low compared to that of daylight (around 105 lumens/W for global daylight and 130 lumens/W for clear blue sky[8]), as shown in Figure 1.2. Today, the best commercial LEDs have a high luminous efficacy of around 200 lm/W, which is obtained only when measuring directly at the light source. In reality, LED lamps have to be installed in lighting fixtures to avoid glare. The real luminous efficacy of LEDs is measured after the light has been reflected or absorbed in the light fixture.

Daylight, on the other hand, comes from a large light source (the sky) and can be passed through spectrally selective glazing, which removes most of the near-infrared radiation, and thus increases the overall luminous efficacy beyond the value measured outside buildings. Daylight provides an intrinsic advantage in terms of basic efficacy compared to electric light sources, and this is the reason why daylight utilization (i.e., the replacement of electric light by daylight) is generally promoted as an energy conservation measure. However, one should be careful to conclude that an all-glazed building is an appropriate architectural solution. Oversized windows may bring glare problems, large energy losses, and substantial solar heat gains leading to high cooling loads. Thus, correct window sizing is a matter of judgment and responsibility. In most applications, it is not necessary to have extremely large glazing areas to illuminate a room. As pointed out by Alberti during the Renaissance[1],

> 'each individual chamber should have windows to admit light and to allow a change of air; they should be appropriate to the requirements of the interior and should consider the thickness of the wall, so that their frequency and the light they receive are no greater or less than utility demands'.

The eighth benefit of daylight is its capacity to enhance the appearance of interior spaces. Daylight remains 'a predominant factor in how a space is revealed and perceived by its users' [113]. A recent thesis showed that daylighting design significantly impacts the aesthetic impression of a small room[114]. In general, 'daylight presence makes a significant positive contribution to light quality' [7]. Some authors[115] even claimed that daylighting 'makes an interior space look more attractive'. Compared to electric lighting, daylighting from windows creates a spatial light distribution, resulting in higher illumination of vertical surfaces[116]. Increased luminance of walls has been shown to positively affect room appearance and user satisfaction[16 117].

The ninth benefit of daylight relates to the added value that daylight provides to buildings. Since well-daylit buildings provide nicer indoor environments, their market and rental value are typically higher. Recent research[118] on commercial office spaces in Manhattan, where urban daylight simulation results were paired with a hedonic valuation model to determine the marginal value of daylight, indicated that spaces with high access to significant amounts of daylight had a 5-6% value premium over occupied spaces with low amounts of daylight. Daylighting also earns credits in most current standards and certification systems such as LEED, BREEAM, and WELL Building Standard. Environmental certifications enhance the image of the building and building owner, in addition to the added real estate value.

Lastly, daylighting indoors seems to affect profitability in the commercial sector. The link between sunny weather and credit card spending has been revealed by research[119]. Consequently, ‘shopping mall designers are interested in employing daylighting strategies and techniques, as it is now widely accepted that such practices not only save energy but also improve sales performance and increase users' satisfaction’ [22]. Many (clothes) shoppers may appreciate the presence of daylight for its good colour rendering which makes true colour determination of a product much easier. An Egyptian study revealed that illumination was ranked as the most important element in the internal environment of shopping malls[22]. In the USA, Heschong, Mahone et al. (1999)[120] studied the effect of retrofitting retail shops with skylights and found the skylight positively and significantly correlated with higher sales rates. A later study[121] obtained a strong correlation between the presence of skylights and an increase in sales.

1.5 Drawbacks of daylighting

On the negative side, daylight, and especially sunlight, has the potential to introduce glare[122], reflections, and various visual nuisances at a larger scale compared to electric lighting. This is easily explained by the fact that windows normally occupy a large portion of the visual field. They provide a higher luminous intensity than electric light sources and are located directly or indirectly, through reflection, in the visual field of building occupants. For screen users, like office workers or students, reflections on the computer screen or window can create disturbing reflections or glaring situations. Windows and diffusing curtains are located on the interior wall, which is the darkest since it receives no direct daylight. This contributes to high contrasts and discomfort glare risks, as shown in Figure 1.3. On the other hand, electric lighting systems tend to be placed close to the ceiling, away from or above the normal gaze direction.

Due to its great variability, daylighting is inherently difficult to predict and requires advanced expertise compared to electric lighting, which provides constant illumination and predictable qualities. Daylighting is also normally associated with solar heat gains and could lead to overheating in the built environment, which may be difficult to assess at the early design stage. Daylighting also typically demands studying a range of sky types, e.g., sunny, overcast, or intermediate skies, at different times of the day or annually, as the sun constantly moves across the sky vault, and weather patterns strongly affect the sky luminance distribution and the quality of interior lighting. Good daylighting design, therefore, entails studying many situations. Sometimes, a whole year of simulations and study is necessary to ensure sufficient daylight levels without the occurrence of glare or visual nuisance. In general, expertise in daylighting is scarce, as it requires many years to acquire. This knowledge, which was traditionally a compulsory part of an architect's education, has generally lost importance in the curriculum of architecture schools. The creation of this book is motivated by the need for this knowledge to resurface in the architect's and engineer's education.

1.6 Risks posed by the absence of darkness at night

Recent research indicates that there is strong evidence that exposure to artificial light at night (ALAN) has a negative impact on health. One study evaluated the link between ALAN and breast and prostate cancer risk in Spain among subjects who had never worked at night. It showed that both types of cancer were associated with high estimated exposure to exterior ALAN in the blue-enriched spectrum, which was attributed to the shift to LED technology in urban settings[123]. Note that shift work involving circadian disruption is recognized as 'probably carcinogenic to humans' [124]. A more recent systematic literature review[25] revealed that out of eleven studies investigating the relationship between electric lighting and various health outcomes, only one found no effect. A study of women under seventy-five indicated that turning on the lights more frequently during sleep time was associated with a higher risk of breast cancer[125]. Another study revealed a positive association between ALAN and carotid atherosclerosis[126]. Other studies indicated that ALAN was associated with a higher risk of dyslipidemia (a metabolic disorder), higher body mass index, and abdominal obesity[127], and ALAN exposure ≥5 lux was associated with higher nighttime blood pressure[128]. A significant association between evening light exposure (4 hours prior to bedtime) and diabetes has been reported[129], while a cross-sectional study reported a positive association between ALAN and depression[130].

Evening exposure to electric lighting or electric devices rich in blue light signals processes that affect melatonin release, negatively impacting sleep[131]. One study showed that subjects reading light-emitting devices (e.g., eBook) before sleeping took longer to fall asleep, had reduced evening sleepiness, reduced melatonin secretion, later timing of their circadian clock, and reduced next-morning alertness[132]. Another study showed that exposure to short-wavelength light colour during the hours before bedtime suppressed melatonin production[133]. As more people are exposed to this type of urban or domestic lighting, it raises concerns among health authorities, calling for a return to the appreciation of natural darkness.

1.7 Importance of a view

Daylight admittance through windows often comes with a view which fulfills the human need for contact with the outside world. In Sweden, the Swedish Work Environment Authority[134] requires that 'in areas with continuous working stations, in workrooms, and in personnel rooms where people are supposed to stay continuously, there should normally be a satisfying amount of daylight and the possibility for a visual contact with the outside'. Additionally, many environmental certification systems and standards such as LEED, the WELL Building Standard[135], and the European Union standard EN-17037 Daylight in Buildings[136] contain specific requirements for the view.

Generally, views of nature and natural elements are preferred over views dominated by buildings[137] [138] [139] [140], which is consistent with the biophilia hypothesis[141]. A view from the window provides 'a micro-restorative experience, i.e., one that provides a respite to one's directed attention' [142], which is consistent with the attention-restoration theory[143]. More recently, Wilkins (2016)[144] explained that 'the human visual system evolved to process images from nature'. His research indicates that 'visual discomfort can be caused by images in which the spatial, chromatic, or temporal features depart from those usually found in nature'. Much earlier, Lam & Ripman (1992)[145] speculated that humans have fundamental needs for information about the time and environmental conditions, as well as information about the weather as it relates to how one should dress or behave. This need extends to a connection to nature and for relaxation and the stimulation of the mind, body, and senses. Views through the window offer information about diurnal and seasonal changes, 'with the added visual interest of people, birds, and other fleeting activities, all providing cognitive stimulus and relief from the more controlled indoor environment' [146].

According to a recent literature review [67], a considerable body of evidence indicates that outdoor views of nature and ample daylight have significant positive impacts on the health and well-being of building inhabitants. Greater access to daylight and views has been advocated in school design as a means to combat the growing myopia epidemic in children[147]. Headaches and eyestrain can be prevented or avoided when the eyes are allowed to refocus on different distances. In a recent study[148], 86 test subjects were found to perform better on cognitive tests, experience more positive emotions, and have better thermal comfort when working on office-type tasks near a window with a view than the same subjects working under identical, fully controlled environmental conditions without a window view.

In healthcare environments, research on daylight and views from hospital rooms has been shown to promote recovery rates and contribute to reduced medication[149]. A seminal study by Ulrich (1984)[150] showed that gall bladder surgery patients with beds next to an outdoor view of nature recovered faster, had a better mood, took less pain medication, and had slightly lower scores for minor post-surgical complications, compared to patients with a brick wall view. A more recent Norwegian study[151] in a residential rehabilitation center, involving 278 coronary and pulmonary patients, indicated that for women, a blocked view appeared to negatively influence changes in physical health, whereas, for men, a blocked view negatively influenced changes in mental health.

The impact of daylighting has also been investigated in incarceration environments. An early study by Moore (1981)[152] indicated differences in prisoners' use of healthcare facilities as a function of view from the cell; prisoners with a view of the surrounding farmland sought healthcare least of all. In another study, inmates with windows facing a meadow or mountains had significantly lower rates of stress-related sick calls than inmates with a view of the prison courtyard and buildings[153]. Notably, inmates on the second floor had lower rates of stress-related sick calls, which can be explained by a more expansive view, but could also be due to increased illumination.

While a view of nature is preferred over a view of artificial environments, a wide and distant view is more appreciated than a narrow and near view, and a diverse and dynamic view is more interesting than a monotonous view[67]. A Norwegian study indicated that view depth (the distance from the window to the most distant visible element in the landscape) and the number of view layers had a strong positive influence on the perceived view quality[154]. Requirements for views in the European Standard for daylighting EN-17037[137] state that 'building occupants should have exterior views that are clear, unobstructed, and naturally coloured'. Building occupants should have an acceptably large, clear view of the outside, with considerations for factors such as width, distance, and features (sky, landscape, and ground)[155].

Finally, recent research indicates that 'office spaces with high access to views have a 6% net effective rent premium over spaces with low access to views' [156]. This study indicated that the financial impact of the view was independent of other value drivers like daylight. The combination of daylight *and* view was analysed, and it was found that the net effective rent premium was also 6%, leading to the conclusion that 'there is value in having both high daylight and high views; however, it is not necessarily greater than having each quality on its own'. This report reviewed several other studies linking view with property value in the residential sector[157] [158] [159] [160] [161] [162] [163] [164].

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CHAPTER 2

Historical perspective on daylighting

MARIE-CLAUDE DUBOIS

'The history of architecture is the history of the struggle for light.'

LE CORBUSIER, ARCHITECT

'Greek architecture taught me that the column is where the light is not, and the space between is where the light is. It is a matter of no–light, light, no–light, light. A column and a column bring light between them. To make a column which grows out of the wall and which makes its own rhythm of no–light, light, no–light, light: that is the marvel of the artist.'

LOUIS I. KAHN, ARCHITECT

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Vernacular architecture, mashrabiya, clerestories, roof slits, arch, barrel vault, dome, arched clerestory, window glazing, daylight rights, Pantheon, oculus, rotunda, archeoastronomy, stained glass, ogival arch, ribbed vault, flying buttresses, ribbed groin vault, chiaroscuro, penumbra, niches, aedicules, poché walls, sawtooth skylight, cylindrical blown glass, cast iron, cast plate glass, greenhouses, atrium, skylight, healing architecture, solid state lighting, fluorescent lighting, sick building syndrome (SBS), non-imaging effects of light, green architecture, sustainable architecture, building regulations, building certification.

This chapter aims to present a brief overview of the tight relation between daylighting and architecture throughout history. However, this text focuses on Western architecture and may not cover many important masterpieces from other cultural contexts. For a more comprehensive review of this topic, readers are encouraged to explore other books[1] [2] [3] [4].

Before the widespread use of fluorescent lighting after 1930, buildings were primarily illuminated by daylight. Since electric lighting was both poor and costly until that time, buildings had to rely on daylight to a great extent[5]. Although daylight served as the primary light source in all interior spaces, it was occasionally supplemented by light from candles, small gas lamps, or open fires, which also provided heat.

The history of daylighting is tightly linked to the history of architecture because one could not exist without the other. Daylighting was a fundamental element in building design, a concept cleverly expressed by Le Corbusier and Louis Kahn at the beginning of this chapter. Structural elements were used to control light, creating open spaces for daylight to illuminate. Some of the earliest examples of daylight and glare control can even be found in vernacular architecture.

2.1 Vernacular architecture

Vernacular architecture is sometimes described as 'architecture without architects'[6]. It comprises all buildings constructed by ordinary people without the involvement of architects. Vernacular buildings are still being constructed today in many countries, making it both an ancient and a contemporary building tradition.

Vernacular architecture often demonstrates excellent examples of the integration and understanding of climatic aspects, as many vernacular buildings were constructed before the era of affordable energy. One intriguing example of glare control is the mashrabiya (also known as shanshool or rushan), a feature of traditional Arabic architecture used from the Middle Ages to the mid-20th century (see Figure 2.1). The mashrabiya is a wooden lattice screen designed to diffuse natural light, especially when made of turned wood (round in section), while allowing natural ventilation and providing a view out. The privacy and view are determined by the relative intensities of light on either side of the wooden lattice. From the brighter side, one sees the screen without perceiving the darker interior. Conversely, from the darker side, the screen allows views toward the brighter public spaces[7]. Furthermore, the spacing between the wooden pieces is adjusted to minimize direct

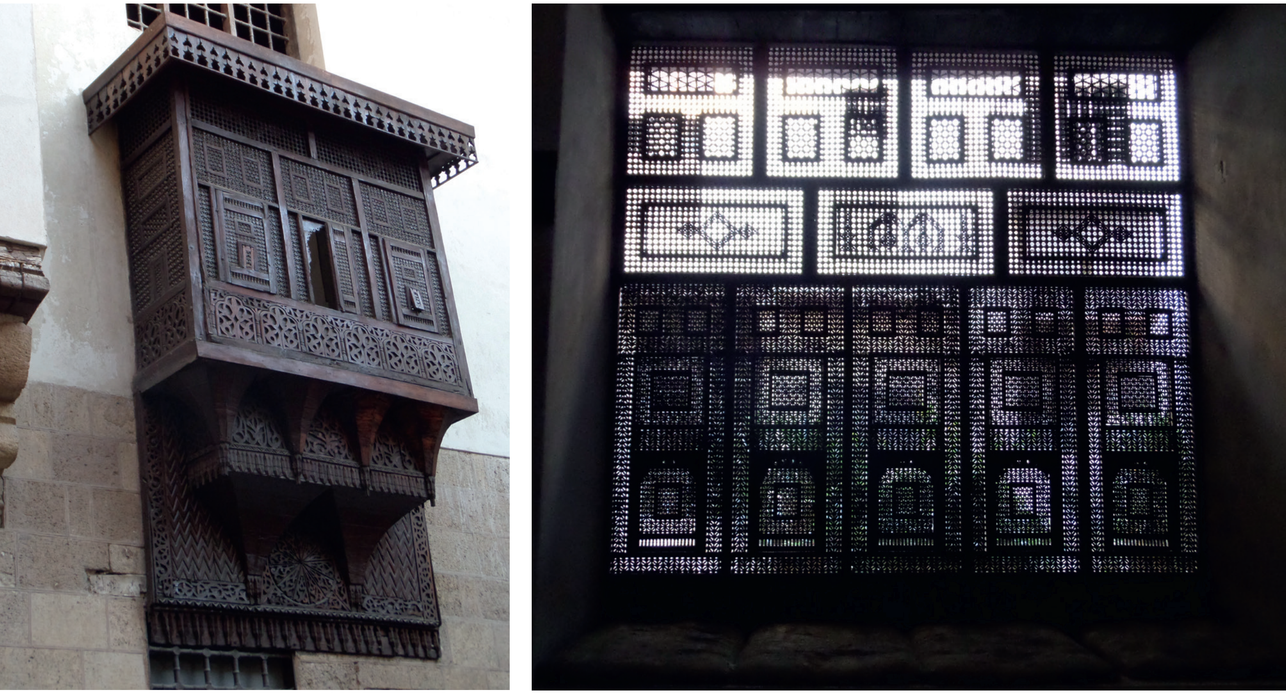

Figure 2.1
A Mashrabiya, an element of vernacular architecture showing glare control principles. Photo: Maha Shalaby.

high-angle sun penetration while transmitting diffuse reflected light perpendicular to the mashrabiya. At eye level, the spacing is minimized to prevent glare, but it increases higher up to allow deeper daylight penetration. Modern glare control systems rely on the same principles.

2.2 Ancient Mediterranean cultures

To fully appreciate the design achievements of ancient Mediterranean cultures, one must consider the quality of the natural light under which their buildings were constructed. Daylight was abundant at these latitudes, and builders responded by minimizing the size of openings and using moderate to low light levels. Buildings only allowed light where it was necessary, and thus, all openings held a special significance in the building design. The prevalence of clear skies and bright sunlight resulted in remarkable architectural masterpieces that showcased the intensity and direction of sunlight, creating striking visual effects both inside and outside. Sculptural elements and statues were unveiled by the sunlight.

2.2.1 Ancient Egypt (3100 BC–332 BC)

The Egyptians possessed a sophisticated understanding of how to incorporate sunlight and daylight into their buildings. The Pharaohs applied astronomical principles with precision and rigor when constructing temples, and likely other forms of habitation as well[8]. For instance, the grand Temple of Ammon was designed to allow sunlight penetration along the axial sequence of the main hypostyle hall. At Karnak, the layout was influenced by the sun's movement to accommodate seasonal variations[8]. The winter solstice sunrise aligns with the east side, passing through the archway of the axis.

Egyptian builders used small openings in thick walls to diffuse and soften the intense sunlight through multiple reflections. The size of these openings was constrained by the limitations of stone construction techniques. Most openings were square in shape, and they were covered with massive lintels. Clerestories had already been invented, facilitating daylight penetration into deep spaces. Additionally, daylight entered buildings through roof slits, small window openings, and entrance doors.

In summary, ancient Egyptian architecture is characterized by:

- the use of clerestories and roof slits,
- small openings and dim interior illumination,
- the application of astronomical principles for exact sunlighting effects (also motivated by religion and worldview).

2.3 Classical antiquity

2.3.1 Ancient Greek architecture (490 BC–30 BC)

Classical Greek architecture also expressed a reverence for the sun and its various powers, a characteristic evident in the design of places of worship and dwellings[8]. Greek temples displayed a deep understanding of solar geometry and its effects on light. These temples were oriented to face east, allowing the morning sunlight to cast its glow on statues of their gods through doorways and large roof openings at sunrise.

Most activities took place outdoors, and buildings were primarily objects or monuments meant to be viewed from outside rather than inhabited. The depth of the facade, with layers of closely spaced columns in front of solid stone walls, was best appreciated under the intense sunlight. On a more detailed level, the sharply fluted channels on columns emphasized their curvature, creating a rhythm of vertical lines of light and shadow when illuminated by direct sunlight. As aptly expressed by Boubekri (2008)[8], 'a dialogue between light and shadows emerges as a fundamental design element of Greek architecture'.

While sunlight in Egypt and Greece was harnessed to emphasize the exterior form and surface modelling of ancient monuments, it was rarely allowed to penetrate the interior in significant quantity. The structural limitations of the simple post-and-beam configuration hindered the construction of large openings. As a result, interior illumination was characterized by narrow shafts of light. This design was necessary to prevent excessive solar heat gains while creating a subdued, dimly lit (and cooler) interior that induced a contemplative mood. The significant structural changes that subsequently prevailed in Roman and Gothic architecture indicate a desire to enhance daylight penetration in building interiors[5]. Also, one of several aspects that motivated the development of the orthogonal town plan of ancient Greece was the need for solar access providing free daylighting and heating for residential settlements[4].

In summary, ancient Greek architecture is characterized by:

- small openings and dim interior illumination,
- exploitation of light–shadow effects under sunlight,
- building orientation in accordance with sunlight (east-facing temples),
- orthogonal town planning for solar access (for passive solar heating and daylighting).

2.3.2 Ancient Roman architecture (509 BC–4th century AD)

Ancient Roman architecture incorporated some elements from the vocabulary of classical Greek architecture. The Romans were great innovators; they introduced the arch, the barrel vault, and the dome, three technologies that allowed for more extensive, column-free space to be filled with light[7], as shown in Figure 2.2. The construction of domes became possible by using concrete, as exemplified in the Pantheon (Figure 2.3). Additionally, the Romans further developed the utilization of large arched clerestory windows to admit daylight high up in the naves of the basilicas (Figure 2.4). These structural advancements also facilitated the creation of larger spaces and openings.

Although the discovery of glass occurred around 4000 years ago in the eastern Mediterranean region[9], it is known that small panes of hand-blown glass set into bronze frames were used as infill for window

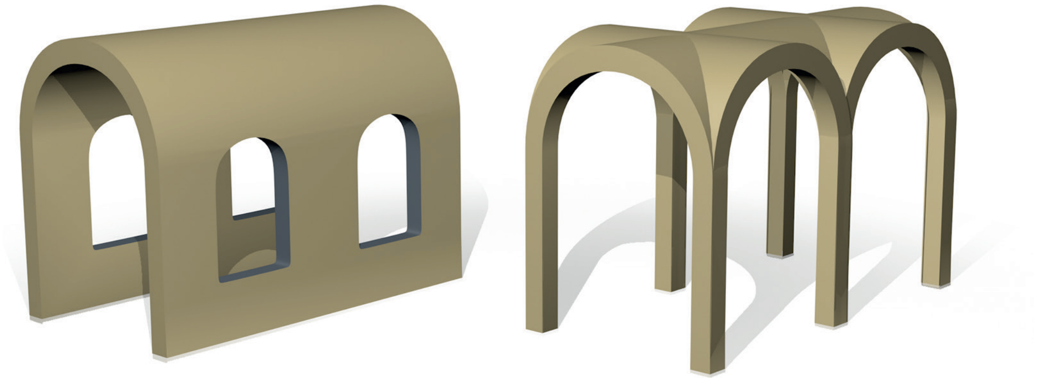

Figure 2.2
Barrel vault invented by the romans, adapted from Lechner (2014).

openings during the Roman period, i.e., around 100 AD[10 11]. The Romans are thus credited with pioneering the use of glass as window coverings, which they employed to harness passive solar heat for warming their homes, baths, and greenhouses[8]. These early applications of window glazing allowed daylighting, while keeping out cold winds and rain. They also developed rectilinear building plans elongated along the east–west axis to maximize exposure to the south, thereby harnessing passive solar gains and reducing the need for fuel (wood).

Good daylighting practices are discussed in the classical writings of Vitruvius[1], the eminent Roman architect of the first century BC, who greatly influenced architects like Palladio during the Renaissance. Vitruvius wrote about the importance of carefully considering window orientation, an aspect that remains relevant in contemporary architecture. However, light for Vitruvius was sunlight, a type of light whose mechanical properties could be harnessed and made visible[12].

The Romans were also the first to establish legal frameworks for protecting rights to daylight in existing properties against unacceptably adverse adjacent developments[1]. As urban density increased, the necessity of legislating for solar access became apparent[8]. This historical knowledge remains relevant today, especially in the global context of densifying cities.

Roman innovations are summarized below:

- development of the arch, barrel vault, and dome, enabling large spans with column-free interiors,
- enlarged wall openings,
- introduction of arched clerestories to admit daylight into the central nave,

- use of glazing materials in window openings,
- construction of elongated buildings along the east–west axis with southern exposure for passive solar heating,
- establishment of the first legal structures to protect daylight rights.

2.3.2.1 The Pantheon

The Pantheon is one of the best-preserved Roman buildings. It demonstrates a skillful use of light. Inside the Pantheon, a shaft of daylight enters high up in the spherically proportioned interior space through an oculus, which also evacuated smoke from sacrifices[13] (Figure 2.3 and 2.5). As the sun moves, the sun patch traces a path across the interior, producing strong shadows while scattering light diffusely into the vast interior.

Almost two thousand years after its construction, the Pantheon's dome remains the world's largest unreinforced concrete dome. The height to the oculus and diameter of the interior circle are the same, at 43.3 meters (142 feet). The Pantheon exemplifies the Romans' understanding of the importance of sunlight in architecture. A recent theory[14] from the field of archeoastronomy speculates that the Pantheon's facade deliberately faces north so that direct sunlight never reaches it, thus enhancing the experience of light when entering the building. It is also speculated that the monument acted as a giant sundial used to mark dates in the Roman calendar. On April 21, the date of the foundation of Rome, the oculus illuminated the arch above the entrance portal when Emperor Hadrian was entering the Pantheon.

2.4 Middle Ages

2.4.1 Romanesque architecture (6–11th century)

Romanesque architecture combined features of ancient Roman and Byzantine architecture with other local traditions to create an architectural style characterized by semi-circular arches. The characteristics of Romanesque architecture include massive building shapes, thick walls, round arches, sturdy pillars, barrel vaults, large towers, and decorative arcading. Romanesque buildings incorporate daylight principles influenced by the ancient Romans, such as the arched clerestory windows (Figure 2.7).

Figure 2.3 The Dome of the Pantheon, Rome. Photo: Marie-Claude Dubois.

Figure 2.4 Arched clerestories as refined by the romans, Basilica di Santa Maria Maggiore. Photo: Mats Hultman.

Figure 2.5 The spot of sunlight on the floor of the Pantheon, Rome, at the summer solstice 2017. Photo: Marie-Claude Dubois.

Figure 2.6 Pantheon. The only light source in this space comes from the reflected sunlight patch produced by the oculus. Photo: Marie-Claude Dubois.

2.4.2 Gothic architecture (12–16th century)

Originating in 12th century in France and lasting into the 16th century, Gothic Architecture flourished in Europe during the High and Late Middle Ages. It evolved from Romanesque architecture and was succeeded by the Renaissance. The association of God with light and the use of stained glass to create a coloured and mysterious atmosphere are central themes of the late Gothic period, producing a unique luminous experience[7], as shown in Figure 2.8.

The pointed or ogival arch, which originated in the Near East in pre-Islamic and Islamic architecture, is a hallmark of Gothic architecture

Figure 2.7
The Great Saint Martin Church, built 1150-1250, Cologne, Germany, showing the use of clerestory windows to illuminate the central nave. Photo: Marie-Claude Dubois.

(Figure 2.9). This unique arch shape simultaneously allowed for greater structural strength and increased daylight penetration. The ribbed vault (the intersection of two to three barrel vaults, Figure 2.9) and the flying buttresses (external masonry buttresses that take the lateral load of the arch, Figure 2.10), are also innovations from this period, contributing to structural strength, architectural expression, and daylighting. Gothic architecture is predominantly showcased in the magnificent cathedrals, abbeys, churches, as well as many castles, palaces, town halls, universities, dormitories, and private dwellings.

During the Gothic period, structural ingenuity enabled walls to almost vanish, leaving behind slender lines of structure, as exemplified in the King's College Chapel in Cambridge (Figure 2.11). For the first time, the wall was freed from its role as the primary roof-bearing element, enabling the creation of extensive expanses of stained glass, with the buttresses extending outwards like fins (Figure 2.10). Gothic ribbed groin vault, combined with flying buttresses, in fact, formed a skeletal construction that allowed for the use of very large windows[5].

Representative works of this period include Westminster Abbey (1045–1065) in London, King's College Chapel (1446-1515) in Cambridge, and the Chartres (1194–1220) and Reims Cathedrals in France.

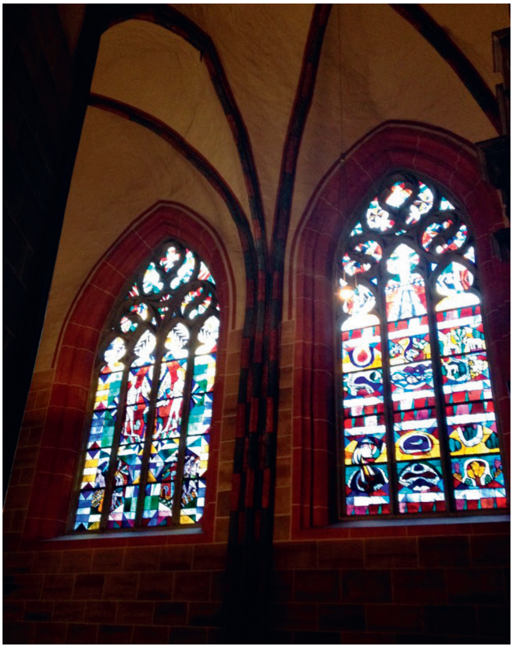

Figure 2.8
Stained colored glass in a gothic church, Bremen, Germany. Photo: Marie-Claude Dubois.

Figure 2.9
Cologne Cathedral, built 1248-1473, Cologne, Germany, showing the pointed ogival arch and the ribbed vault. Photo: Marie-Claude Dubois.

Figure 2.10
Flying buttresses at the Cologne Cathedral, Germany. Photo Marie-Claude Dubois.

Figure 2.11
King's College Chapel in Cambridge (1446–1515). Creative Commons, CC BY Lofty-SA 3.0.

Innovations of the Gothic period are summarized below:

- pointed or ogival arch,
- ribbed vault and flying buttresses, enabling a skeletal architecture and larger expanses of glass,
- stained glass with different colours, creating a mysterious atmosphere.

2.5 Renaissance (15–16th century)

The history of light in Renaissance art reveals a growing interest in the representational value of light[12]. Renaissance paintings and art theory indicate an increasing desire to achieve greater precision in painting by representing the play of light as observed in the natural world. The physics of light and its relationship to perspective received significant attention during this period[12]. Light started to be discussed more scientifically, and the terms 'lux' and 'lumen' were introduced for the first time[7], which can also be attributed to the Scientific Revolution.

One of the most renowned artists of this era, Leonardo da Vinci, integrated optical theories into his artistic investigations to explore the interplay between light and vision. He also developed a particular interest in the penumbra, which is the transitional area between light and shadow.

An influential architect of the Renaissance and in the history of Western architecture is Andrea Palladio, an Italian architect who lived from 1508 to 1580[15]. Palladio is often referred to as 'a master of light and colour'[16] who exploited abundant natural light to accentuate the divine illumination emphasizing the spirituality and connection of the interior spaces to the cosmos'[17]. He put forth mathematical principles for sizing openings, underscoring the importance of achieving a balance between the 'clarity of light' and preventing overheating[7].

Vincenzo Scamozzi (1545–1616), an assistant of Palladio, created a drawing of a villa that vividly conveys ideas about light and architecture (Figure 2.12). According to Borys (2004)[12], this drawing marks the first instance in which diffuse skylight was considered in building design. The treatment of diffuse light from a substantial light source, the sky, paved the way for further exploration, discovery, and development of theories related to light, penumbra, and shadows within interior spaces. Consequently, daylight illumination techniques became more refined and sophisticated during the Renaissance. This period witnessed the evolution of daylighting techniques, transitioning from a focus on sunlighting to the integration of direct and diffuse daylight, with special attention given to penumbra and subtle effects.

During the Renaissance, light was no longer solely considered a symbol of God, as it was in the medieval times; it was also seen as an enhancement of life[7]. The structural innovations and expressions that characterized the Gothic period were replaced by a resurgence of interest in visual harmony and proportion, with the reintroduction of classical architectural elements. The use of glass became less of a conceptual driving force, as it was during the Gothic period, and more a matter of incorporating a high-quality product into an overall architectural program[9]. During this period, the location and design of windows became more standardized, often having less direct structural relevance to the interior spaces, while the exterior elevation and appearance of the building became more important[10].

Renaissance style emphasizes symmetry, proportion, geometry, perspective, and the regularity of parts, as seen in the architecture of classical antiquity, particularly ancient Roman architecture. This period is characterized by orderly arrangements of columns, pilasters, and lintels, as well as the use of semicircular arches, hemispherical

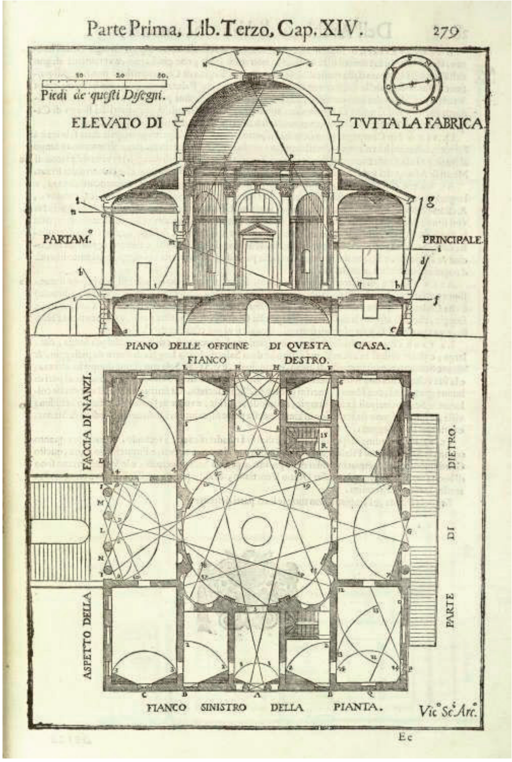

Figure 2.12
Drawing of Villa Bardellini, Vincenzo Scamozzi.

domes, niches, and aediculas. The introduction of thick poché walls, shaped on each side of openings, was a direct response to the spatial and decorative requirements of the respective rooms. The poché wall, often serving functional purposes, representing what was left over after the room spaces were hollowed out – a significant change from previous periods, especially the Gothic period, where interior space was a direct consequence of the structural system.

Key elements of architecture during the Renaissance are summarized below:

- revival of harmony and proportion from classical architecture,
- exploration of diffuse daylight and a focus on penumbra to emphasize architectural form and space,
- adoption of thick poché wall resulting from hollowed-out rooms,
- advancement in precise light representation in painting,
- development of photometric vocabulary and a growing interest in optics.

2.6 Baroque architecture (17–18th century)

During the 17-18th century, Baroque architecture spread throughout Europe and Latin America, with the Jesuits playing a significant role in its promotion. In this era, daylighting was used to create dramatic effects and evoke emotional reactions[12].

Light and shadow played a central role in Baroque architecture, characterized by sculptural exuberance and dynamic spatial qualities rooted in classical and Renaissance traditions[7]. While Gothic architects envisioned buildings as skeletons, Baroque architects regarded them as giant, three-dimensional sculptures animated by hidden, mystical light effects. The three-dimensional articulation of forms enabled a more creative use of light, introduced between overlapping layers of enclosures. Openings were no longer mere holes in plain walls, but perforated vaults behind which concealed light could indirectly illuminate other areas, creating a dramatic and mystic interior ambiance[10].

Key elements of Baroque architecture are summarized below:

- the entry of concealed light through domes and vaults, hidden from direct view,
- the three-dimensional quality of volumes animated by hidden light sources,

- the use of dark paintings and frescos, along with complex ornaments.

2.7 Industrial Revolution (1760–1850)

The Industrial Revolution was a period of significant transition in manufacturing processes that occurred from 1760 to 1850. Many historians attribute the initiation of the Industrial Revolution to the improvement of the steam engine by James Watt around 1769. This transition, primarily centered in Great Britain, marked a substantial shift from manual production methods to utilization of machinery, the development of new chemical manufacturing and iron production processes, increased efficiency in hydropower, expanded use of steam power, advancements in mechanical tools, and the establishment of the factory system.

During the early years of the Industrial Revolution, Western Europe witnessed significant economic and social changes as many people migrated from rural to urban areas in the hope of securing employment in factories[8]. Urban density increased rapidly during this period, often without adequate planning, and people were forced to live in dire conditions within crowded, windowless houses. Outbreaks of diseases such as rickets, cholera, typhus, and tuberculosis created the conditions necessitating public health legislations, exemplified by

Figure 2.13
Baroque church, Santa Maria Maggiore, Rome. Photo: Mats Hultman.

the Public Health Act of 1848 in Britain. These regulations led to the creation of new town planning and urban proposals, such as 'Hygeia' by Benjamin W. Richardson in 1876, which aimed to address these issues, including regulations that prohibited the construction of tall buildings[8].

Parallel to the poor conditions witnessed in the domestic sector, the Industrial Revolution also marked a period of significant technical progress. This progress was driven by developments in materials like cast iron, wrought iron, and later, steel and reinforced concrete[18]. Rapid changes in requirements and solutions for daylighting emerged, including innovations like the sawtooth skylight arrangement, as shown in Figure 2.14. New techniques for glass production, such as cylindrical blown glass, allowed for the creation of large sheets of glass with reasonably good optical quality[1]. Glass production became more affordable and efficient, while framing technology advanced with the introduction of iron and cast iron trusses and columns.

The new glass and frame technology was not only used to illuminate large factories (Figure 2.15), but it was also applied in horticulture. Greenhouses became essential to produce fresh fruits, as refrigeration and cost-effective transportation means were unavailable. Having access to fresh peaches, bananas, and oranges became a symbol of social status, driving significant advances in greenhouse horticulture[9]. The pinnacle of this development was the Crystal Palace, a cast iron and plate glass structure originally constructed in Hyde Park, London, to house the Great Exhibition of 1851 (Figure 2.16).

The new glass and frame technology was also transferred and used in large halls, such as railway stations, libraries, and shopping arcades. Figure 2.17 shows the 'Galeries Royales Saint-Hubert' in Brussels, which preceded other famous 19th-century shopping arcades, such as the 'Galleria Vittorio Emanuele II' in Milan (Figure 2.18) and the 'Passage' in St Petersburg.

These developments make the Industrial Revolution a key period for daylighting principles, which are extremely relevant for contemporary architecture, as it was a time when indoor illumination was needed in large spaces, but electric lighting had not yet been invented. Many buildings from this period are still in use today and can teach lessons about daylighting. Two outstanding buildings from this period are the 'Bibliothèque Sainte-Geneviève' (1843–1851, Figure 2.19) and the 'Bibliothèque Nationale de France' in Paris, both designed by Henri Labrouste. 'Bibliothèque Sainte-Geneviève' beautifully illustrates some basic daylighting principles, such as a high placement of windows, a plan depth equal to about twice the floor-to-ceiling height, and the use

Figure 2.14
Sawtooth skylight illuminating factory workers during the industrial revolution. Photo: Everett Historical/Shutterstock.com.

of daylighting as the main ambient light source, supplemented with task lighting.

Right after the Industrial Revolution, the Beaux-Arts style heavily influenced architects in the United States from 1880 to 1920, before the beginning of the modern movement. The George Peabody Library, located in Baltimore, Maryland, showcases one of the first uses of the central atrium (Figure 2.20).

Figure 2.15
Typical factory building from the industrial revolution with large windows on lower floors, Cologne, Germany. Photo: Marie-Claude Dubois.

2.8 Modern architecture (1900–1980)

Modern architecture emerged partly due to new construction technologies, particularly the use of glass, steel, and reinforced concrete. It also marked the departure from the traditional neoclassical architecture and Beaux-Arts styles that thrived in the 19th century. Renown architects of the modernist movement include Frank Lloyd Wright, Ludwig Mies van der Rohe, Le Corbusier (Charles-Édouard Jeanneret), Walter Gropius, Konstantin Melnikov, Erich Mendelsohn, Richard Neutra, Louis Sullivan, Gerrit Rietveld, Bruno Taut, Oscar Niemeyer, and Louis Kahn.

Considered the most influential architect of the modern movement, Le Corbusier had a passion for light, as expressed in his famous quote: 'Architecture is the masterly, correct, and magnificent play of masses brought together in light'[19]. He thrived on the machine aesthetic and promoted a freer yet more functionalistic architecture. His sketch of the Dom-Ino House, an open floor plan structure designed in 1914–1915, opened unforeseen possibilities for 20th-century architecture. Total transparence was made possible for the first time, freeing the architect from structural constraints of load-bearing structures. Le Corbusier and his contemporaries also emphasized the therapeutic qualities of sunlight and fresh air as pivotal aspects of modern architecture.

Figure 2.16 Crystal Palace, Hyde Park, London, designed by Joseph Paxton, built 1851 and destroyed 1936 by fire. Photo: Philip Henry Delamotte (1821–1889), Smithsonian Libraries, public domain.

Figure 2.17 Royal Galleries of Saint-Hubert in Brussels. Photo: Marie-Claude Dubois.

Figure 2.18
Galleria Vittorio Emanuele II in Milan. Photo: Julija Sivolova.

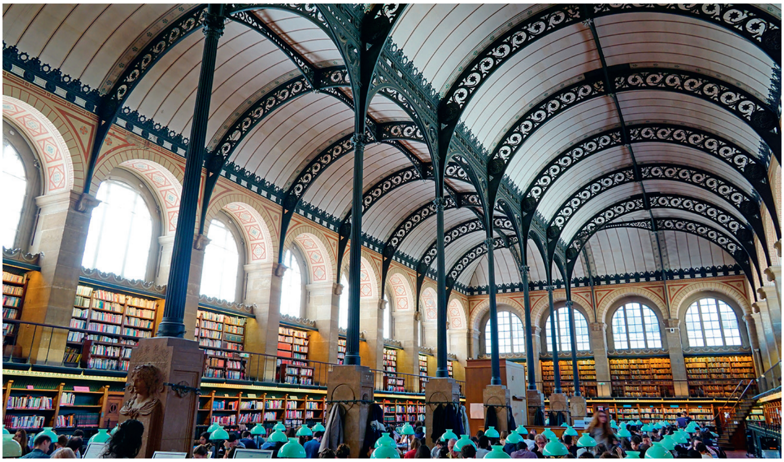

Figure 2.19
Bibliotheque Sainte-Geneviève, Paris, Architecte Henri Labrouste, built 1843–1851. Photo: EQRoy/Shutterstock.

Among his masterpieces, the Ronchamp Chapel at Notre Dame du Haut in eastern France (Figure 2.21) features articulations of openings slanting at different angles, windows of varying sizes, coloured glass, and deep recesses in thick walls to create a mysterious atmosphere. The roof of the Chapel appears to float above the walls, made possible by its support from concrete columns independent of the walls. This separation between wall and structure allows for a narrow strip of light, making the church feel more open. However, Ronchamp Chapel stands out in Le Corbusier's body of work, as it departs from his ideas of standardization and the machine aesthetic, providing instead a site-specific response. Another masterpiece where daylighting plays

Figure 2.20
The George Peabody Library completed in 1878 designed by architect Edmund. Photo: Matthew Petroff - Own work, CC BY-SA 3.0.

a central role is Sainte Marie de La Tourette. In this building, wisely placed openings, skylights, and reflections on coloured surfaces create a mystical and meditative atmosphere (Figures 2.22 and 2.23).

Ludwig Mies van der Rohe, a German American architect, is another influential figure of the modern movement. He is known for creating the International Style, characterized by extreme clarity and simplicity. His famous Farnsworth House, built in 1945–1951, is one of the first all-transparent houses and represents a radical departure from traditional domestic architecture. He also designed the German Pavilion at the 1929 International Exhibition in Barcelona. This pavilion not only showcased a simple form with a spectacular use of extravagant materials but also introduced the concepts of the 'free plan' and 'floating roof', which liberated architecture from the constraints of wall openings. These ideas aimed to express a continuous space, blurring the boundaries between the inside and outside. The design also emphasized an absolute distinction between structure and enclosure, achieved through a regular grid of cruciform steel columns innovatively interspersed with freely spaced planes. Mies van der Rohe's early works clearly reflect his special interest in glass, transparency, and the specular and translucent character of materials.

Another influential American architect of the twentieth century, Louis Isadore Kahn (1901–1974), is also known for his works and essays on light. Initially, he worked in an orthodox version of the International Style but eventually developed his own style influenced by earlier modern movements, not limited by their constraints. Some of his renowned works include the Salk Institute in Pasadena, California (1959–65), the Exeter Library in New Hampshire (1965–72), the National Assembly Building in Dhaka, Bangladesh (1962–1974), the Kimbell Art Museum, Fort Worth, Texas (1967–72), and the Yale Center for British Art at Yale University (1969–74, see Figure 2.24). The Kimbell Art Museum features repeated bays of cycloid-shaped barrel vaults with light slits along the apex, bathing the artwork in an ever-changing diffuse light. In February 1969, Kahn gave a lecture at the School of Architecture of the Swiss Federal Institute of Technology in Zürich, entitled 'Silence and Light'. This lecture, now available in printed form, explains his spiritual understanding of architecture, which went beyond simply constructing buildings. He also provided a remarkable account of his belief in sustainable architecture, foreseeing the birth of the green architecture movement.

Figure 2.21
Notre Dame du Haut, Ronchamp Chapel, 1954, Le Corbusier. Photo: Jouri Kanters.

Figure 2.22
Sainte Marie de La Tourette, Le Corbusier. Photo: Malin Alenius.

Figure 2.23 Sainte Marie de La Tourette, Le Corbusier. Photo: Malin Alenius.

2.8.1 Modern architecture in the Nordic countries

Evolving beyond the formal and machine aesthetic of modern architecture, Nordic architects developed a freer, more flexible version of modernism, emphasizing the celebration of daylight and natural materials. In the twentieth century, Nordic architects sought to make simple volumes appear natural by enhancing the subtle qualities of Nordic light and employing curved shapes, as well as organic forms and surfaces abstracted from nature. Renowned architects of this period include Gunnar Asplund, Sigurd Lewerentz, Peter Celsing, and Klas Anshelm in Sweden; Arne Jacobsen and Jørn Utzon in Denmark; Erik Bryggman, Alvar Aalto, Reima Pietilä in Finland; and Sverre Fehn in Norway. For further reading on this subject, the reader is referred to Plummer (2014)[20].

Finnish architect Alvar Aalto is undoubtedly recognized as one of the central figures of daylighting in architecture. He is known for his meticulous study of daylight and his emphasis on the relationship between form, materials, nature, and Nordic light. Aalto had a fascination for layers of poles and sinuous surfaces, which alluded to flickering sunlight in a dense forest. He used walls coated with rippling tiles to evoke the play of light on the surface of a lake[20]. The poetry of Aalto's architecture is not found in imitation but rather in his use of abstract forms and modern materials to create light effects resembling phenomena observed in nature. Some of his famous works include Villa Mairea (1941), the Rovaniemi Library (1963–68), the Viipuri Municipal

Figure 2.24 Yale Center for British Art at Yale University (1969–74), architect Louis I Kahn. Photo: Malin Alenius.

Library (1935) in Vyborg, Russia, Nordens hus in Reykjavik, the Nordjyllands Art Museum (1972), and the Säynätsalo Town Hall (1952).

At the Rovaniemi Library, the most remarkable features include the use of a large canopy at the entrance, which lowers the adaptation level of the eye before penetrating the dark interior. Large skylights and reflectors directed at the bookshelves along the perimeter walls evoke an infinite snowy landscape, while sunken reading sections allow for deeper daylight penetration (a design element also observed in Nordens hus and other projects). These features suggest that Aalto not only harnessed light poetically but also possessed an understanding of light, on a technical level, as a resource to efficiently illuminate building interiors.

In Nordens hus, as shown in Figure 2.25, Aalto not only applies the same principle of intimate sunken reading spaces but also demonstrates his understanding of daylighting techniques by placing windows high up to maximize light penetration. Larger windows are carved out where daylighting should be more abundant, while smaller ones are positioned above the entrance, creating a natural gradation in light intensity. A skylight in the center of the roof provides uniform ambient daylighting conditions.

The Paimio Sanatorium (1933) in Southwest Finland is dedicated to maximizing sunshine and fresh air as a means of treating tuberculosis patients. In the early years of combating this disease, the only known cure was complete rest in clean air and sunlight. Consequently, on each floor, at the end of the patient bedroom wing, sunning balconies were designed to allow patients to be pulled directly outside in their own beds. Healthier patients who could walk had the option to relax on the top floor's sun deck. This project can be seen as an early attempt at what is now referred to as 'healing architecture'. Authorities at the time aimed to humanize the hospital environment by creating 'a cushioned whiteness that conveyed empathy'[21]. Smoothly rounded white volumes are highlighted with the use of luminous colours, guiding visitors with a colour code. Daffodil yellow linoleum floor in the reception area (Figure 2.26) and up the staircase creates an impression of sunshine to uplift the patients' spirits. Another notable feature is the ceiling in the patients' rooms, which was painted a soothing grayish green to prevent glare for those laying down. Aalto was clearly ahead of his time, foreseeing the importance of visual comfort and health aspects, which are now central themes in healthcare design.

Jørn Utzon's Bagsvaerd Church (1976, Figure 2.27) is another significant project in daylighting design. Inspired by clouds of Danish skies, he employed the principle of a double envelope, with an inner curved surface that modulates daylight entering through a small opening. The resulting sensuous and well-lit interior evokes surprise and even astonishment, especially when contrasted with the industrial appearance of the building from outside.

The Swedish architect Gunnar Asplund created sublime works such as the Woodland Chapel (1920) in Stockholm, the Stockholm City Library (1927), and Gothenburg Law Courts (1937). In Stockholm City Library, as shown in Figure 2.28, Asplund strategically uses light to capture visitors' attention and stimulate their movement. The entrance to the building begins through a narrow vestibule with polished black stucco walls. From this dim passage, shadowy stairs branch off on either side, leading to the upper level, where light guides the visitors' focus forward. Symbolically emerging from darkness, visitors arrive at a grand, luminous cylinder or rotunda. The journey continues as they move around the cylindrical base and ascend rounded stairs. The experience of this ascent is shaped not only by the circular design of

Figure 2.25
Nordens hus in Reykjavik, Iceland, architect Alvar Aalto. Photo: Marie-Claude Dubois.

Figure 2.26 Skylight above the reception at the Paimio Sanatorium by Alvar Aalto. Photo: Marie-Claude Dubois.

the rotunda but also by the contrast between the dark entrance and the bright ceiling of the rotunda[20].

2.9 Transition to sustainable architecture

Daylight remained the primary means of illuminating building interiors until the early twentieth century. However, for various reasons, including structural changes and technological developments, the central role of daylight began to be questioned after the invention of fluorescent lighting around 1930 and its widespread adoption during the 1950s and 1960s. The growth of the workplace in the nineteenth century laid the foundation for the development of the 'burolandschaft' (landscape office), a period that can be considered a low point for daylighting, as buildings were designed with great floor depths primarily illuminated by electric light[10]. During this time, some schools and factories were even designed without windows[21], based on the misguided belief that this would reduce costs and create an environment of concentration for workers and students.

Reflecting the architectural trends of his time, Mies van der Rohe played a role in this endeavor by designing deep-plan, tinted glass towers, such as 860–880 Lake Shore Drive in Chicago (1949–50), the Seagram building (1958) in New York (see Figure 2.29), and Westmount Square (1964) in Montreal. While these buildings featured finely detailed facades and sophisticated urban spaces at ground level, they clearly

Figure 2.27
Bagsveard church, Bagsvaerd, Denmark, Jørn Utzon architect. Photo: Tomas Tägil.

distanced themselves from the natural environment (and daylight) with their deep floor plans and highly tinted glazed facades, which were identical on all sides of the building. This architectural style contributed to the development of skyscraper designs in the 1960s, 70s and 90s that heavily relied on cooling systems and electric lighting.

The economic pressure to reduce floor-to-floor height and increase light levels came from utility companies seeking to sell electricity and manufacturers selling lamps and fixtures. By the 1960s, the concept had gained such prominence that some believed that: 'It is inevitable that artificial light must become the primary light source where efficiency of vision is combined with an economic analysis of building function. Natural light is becoming a luxury'[10]. In the USA, authorities in the state of Florida passed a law requiring all schools in the state to be air-conditioned and windowless.

It was even suggested that these windowless buildings could save on heating costs, as they would rely on secondary heat from electric light sources. This led to the construction of buildings where electric lights were used throughout the day and year, even when heating

Figure 2.28
Stockholm Public Library, architect Hans Asplund. Photo: Paul Rogers.

was unnecessary. The affordability of electricity justified cooling the secondary heat generated by the lights during warmer periods[21]. The fact that this concept was not considered absurd at the time reflects the growing disconnect between humans and nature during that era. The faith in modernity and progress, driven by machines and technology, was more powerful than the ancient human connection to natural light.

In summary, the convergence of technologies such as air conditioning and fluorescent lighting in the 1930s significantly impacted architectural possibilities. According to Baker & Steemers (2013)[7], the introduction of powerful and cost-effective electric lighting enabled uninspired architectural designs to prosper, leading to the creation of 'dark boxes where the largest, cleanest, and highest-quality source of light – daylight – often cannot reach' [22].

The energy crisis of the early 1970s brought an abrupt end to this trend. The heavy reliance on fossil fuels within the deep floor plan architecture of the 1960s and 1970s was questioned, coinciding with the emergence of the so-called 'sick building syndrome' (SBS) prevalent in these office towers. This set the stage for the birth of the sustainable or green architecture movement, which not only incorporates concepts of daylighting but also addresses building resource and energy design more broadly.

Sustainable architecture has become a prominent force in contemporary architecture, driven by the mounting pressures of climate change and the risks associated with resource depletion and ecosystem collapse. The utilization of renewable energy sources, such as passive solar energy and daylighting, is now an integral part of 'normal' building design. Additionally, the recent focus on the photobiological effects of light in relation to health and well-being provides further rationale for returning to natural methods of illumination in building interiors.

2.10 Contemporary architecture

Today's architecture is freer than ever, with almost infinite possibilities regarding form and expression, transparence and opacity, materials, and structural choices. Many different architectural styles can coexist simultaneously. The only significant constraints of contemporary architects are those imposed by the environmental crisis, urban densification, pollution, and housing shortages. Climate change, collapsing ecosystems, and vanishing resources have provided fertile ground for the resurgence of a more contextual, climatic architecture. In parallel, new techniques of computer-aided design and environmental simulations allow buildings to be modeled precisely on computers in three dimensions and constructed more rapidly. Advanced daylight and energy simulations make it possible to predict daylighting levels and distribution in buildings, as well as their energy use and indoor climate.

The landmarks of contemporary architecture are the works of a small group of architects who operate on an international scale. Contemporary architects who emphasized daylighting include, to name just a few, Tadao Ando, Peter Zumthor, Sanjai Mohe, Steven Holl, and Hiroshi Sambuichi.

The Kolumba Museum (2003–07) in Cologne by Peter Zumthor, shown in Figure 2.30, is a sophisticated building where small openings in the brick facade create striking light effects on the ceiling. However, beyond the poetic aspects of light, several international architects work with daylighting as a key indoor environmental quality (IEQ) aspect in buildings. They employ various well-proven strategies that exploit daylight's intrinsic visual, health, and energy-conserving attributes. These architects integrate daylighting techniques as part of a broader sustainable or green architecture. Some renowned names in the sustainable architecture movement include Fosters & Partners, Henning Larsen, UNStudio, Sauerbruch Hutton, Snøhetta, White arkitekter, Perkins and Will, etc. Many of these firms have their own research and development teams of specialists focusing on daylighting. They produce information, reports, and attend international conferences, connecting with the scientific community and positively contributing to developments in this field.

Figure 2.29 Seagram building, New-York. Photo: Jouri Kanters.

2.10.1 Building regulations

The green architecture movement has certainly contributed to the emergence of regulations and environmental certification systems regarding minimum daylight levels in continuously inhabited rooms. It is worth noting that these regulations and certifications primarily focus on the quantity of daylight rather than its quality or the creation of interesting daylight effects discussed throughout this chapter.

In Sweden, for instance, daylighting is regulated in the Building Regulations (BBR) by the National Board of Housing, Building, and Planning, known in Swedish as 'Boverket'. BBR includes both mandatory provisions ('föreskrifter') and general recommendations ('allmänna råd'). The requirements connected to daylight in BBR encompass three aspects: daylighting, sunlighting, and a view out.

According to mandatory provisions, any room 'used more than occasionally' should be designed and oriented to provide good access to direct daylight, where direct daylight refers to daylight through windows[23]. In collective rooms, indirect daylight is accepted. This mandatory provision is followed by a general recommendation suggesting a window-to-floor area ratio of 10%. This simplified rule is based on an outdated standard SS 91 42 01[24], which specifies conditions for validity, including room size, window glazing, window geometry and position, and sky exposure angle.

Alternatively, compliance can be demonstrated through computer simulation, achieving a minimum point daylight factor (DFp) of 1% at a point located at 0,8 m from the floor, 1 m from the darkest lateral wall, halfway along the room's depth. In cases where simulations are unavailable, a manual, time-consuming calculation method is also proposed, leading most consultants to select computer simulations instead[25].

A general recommendation is also presented for the view out, with a minimum of one window in any room used more than occasionally. The window should be positioned to enable observation of the daily and seasonal changes. Skylights are not considered suitable to fulfill this requirement. Regulations also cover access to direct sunlight in housing, mandating that at least one room or separable part of a room used more than occasionally must have access to direct sunlight. In practical terms, this means that apartments with only north-facing rooms cannot obtain a building permit. Student apartments smaller than 35 m^2 are exempt from this sunlight requirement.

2.10.2 Standards and environmental certification systems

Building standards and environmental certification systems, such as LEED, BREEAM, and Miljöbyggnad, currently serve as strong drivers in the global building sector, including the Nordic context. These systems motivate architects, engineers, and developers to envision, plan, and verify all aspects of building design for enhanced performance across various environmental sustainability parameters. Considering daylight as a free and essential energy source crucial for health, well-being, productivity, energy-efficiency, and building value, environmental certification systems often allocate credits earned by demonstrating that the building meets the minimum indoor daylight level, typically expressed as a minimum daylight factor or daylight autonomy level. Additional requirements may include access to a view, direct sunlight, glare prevention, and adherence to certain uniformity criteria.

In the Swedish building sector, three environmental certification systems—Miljöbyggnad, LEED, and BREEAM —are utilized and managed by the 'Sweden Green Building Council' (SGBC). While other certification systems such as NollCO2, GreenBuilding, etc., are also gaining popularity (see www.sgbc.se), these systems do not specifically

Figure 2.30
Kolumba Museum, Cologne, Germany, architect Peter Zumthor. Photo: Marie-Claude Dubois.

incorporate daylight requirements. It is worth noting that while the daylight requirement is optional in both LEED and BREEAM, it was recently removed from the Swedish Miljöbyggnad system version 4.0, which is an unfortunate development. Interestingly, the WELL Building Standard launched in 2014 does include daylight and light requirements. Notably, the daylight requirements are grounded on climate-based daylight modelling (CBDM) and recommended daylight levels outlined in the new European Standard EN 17037 (discussed below) as an option for compliance[26].

2.10.2.1 BREEAM

BREEAM (Building Research Establishment Environmental Assessment Method) is a certification system from the United Kingdom, developed and administrated by BRE (Building Research Establishment). It has been on the market in various versions since 1990 and is the most widely adopted environmental certification system in Europe. Adapted to Swedish conditions by the SGBC, the version used in Sweden since 2013, is called BREEAM-SE[27]. The system covers significantly more aspects than Miljöbyggnad.

When it comes to daylighting, in addition to requirements for view, glare prevention, exposure to sunlight, and TLM (flicker) in electric lighting, BREEAM-SE offers two options for meeting the daylight requirement. One option involves using target illuminance levels of 100-300 lux in parts of the room for 50% of annual daylight hours, depending on building and room category. The second option is to achieve a target daylight factors in parts of the room, depending on the certification level, orientation of openings (horizontal or vertical), or building type. The reader is referred to the SGBC website for further information on this system.

2.10.2.2 LEED

The LEED Green Building Rating System was developed in the USA by a non-profit organization called U.S. Green Building Council. Since its inception in 1999, this system has been available in various versions and is the most widely adopted internationally, covering more aspects than any other environmental certification system.

Fulfilling daylight requirements is one way to earn credits in LEED, but the daylight credit is not mandatory. The requirements for daylighting have varied significantly between different versions of

LEED[28]. In version 4, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) are utilized, which are dynamic daylight metrics (DDM). Two other options are available: one involves simulating illuminance levels to meet a specific range for a certain number of hours on two specific calendar days, and the other requires physical measurements of illuminance levels, also for a specific number of hours on two different occasions[29].

2.10.2.3 New European Standard 'Daylight in Buildings'

Apart from the voluntary certification systems listed above, the new European Standard EN-17037[30], released in 2018, is the first standard to exclusively focus on daylighting, covering both the quantity and quality of daylight. It emphasizes four key areas:

1. daylight provision,
2. assessment of the view out through windows,
3. access to sunlight,
4. glare prevention.

To provide flexibility while ensuring usability, EN 17037 sets a minimum level of performance for each of the four areas. In addition to the minimum recommendation, two further performance levels may be achieved —medium or high. The daylighting provision requires that adequate natural lighting, i.e., 300 lux, should be present over 50% of the space for more than half of annual daylight hours without electric lighting[31]. This standard marks a departure as it is the first major standard based on absolute illumination levels (e.g., 300 lux) rather than relative values such as the daylight factor. Due to Sweden's high latitude and the method and requirements presented in the standard, higher target daylight factors are needed to achieve the same amount of natural illumination as in countries in southern Europe. Therefore, compliance with this standard is more challenging compared to the requirements in the environmental certification systems discussed above. Note that the standard has faced criticism[32], and researchers have observed that it tends to result in the selection of much larger window areas, leading to higher energy use, especially in Nordic countries[33].

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CHAPTER 3

Visual effects of light

MARIE-CLAUDE DUBOIS

'People only see what they are prepared to see.'

RALPH WALDO EMERSON

'Millions of items of the outward order are present to my senses which never properly enter into my experience. Why? Because they have no interest for me. My experience is what I agree to attend to. Only those items which I notice shape my mind – without selective interest, experience is an utter chaos. Interest alone gives accent and emphasis, light and shade, background and foreground – intelligible perspective, in a word. It varies in every creature, but without it the consciousness of every creature would be grey chaotic indiscriminateness, impossible for us to conceive.'

WILLIAM JAMES, 1890

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Visual perception, attention, expectations, optical illusions, constancies, lightness constancy, colour constancy, size constancy, shape constancy, visual system, visual cortex, retina, cornea, pupil, crystalline lens, optic nerve, blind spot, iris, sclera, ciliary muscles, vitreous humor, vision, photopigments, cones, rods, select ganglion cells, intrinsically photosensitive retinal ganglion cells, photobiological response, macula, fovea, accommodation, near triad, dioptric, cataract, adaptation, transient adaptation, dark adaptation, light adaptation, photopic adaptation, mesopic adaptation, scotopic adaptation, Purkinje shift, trichromatic, standard observer, field of view, visual field, peripheral vision, ergorama, panorama, binocular vision, stereoscopic vision, fixation, tremors, saccades, discomfort glare, disability glare, glare index, Unified Glare Rating (UGR), Daylight Glare Probability (DGP), veiling reflections, temporal light modulation (TLM), flicker, critical flicker frequency (CFF).

Daylight affects almost every aspect of human physiology via three main pathways:

1. visual,
2. direct skin absorbance,
3. non-visual* ocular actions on the circadian clock in the brain and on other neuronal pathways[1].

3.1 Visual perception

Although visual perception remains to some extent a mystery and has been the subject of various theories since ancient Greece[2], there is little doubt that the process of seeing involves both the eyes and the brain working together[3 4]. As stated by Lam (1977)[5], 'Seeing involves the brain as well as the eye, and through prior experience, the brain plays a major role in determining which characteristics of objects make them worthy of attention'. The role of attention in visual perception is fundamental; vision is both a passive inward process (light enters the eye and the person sees) and an outward process (i.e. an active information seeking process; the person determines what to look for)[2].

Tregenza & Wilson (2011)[6] explained that perception is 'the process of linking immediate sensory information with remembered experience'. This means that the brain already has a preconception of what the different objects in the world look like and simply links the internally stored visual impressions to the ones presented at any moment in front of the eyes. The result of the perceptual process is therefore not like a bit-mapped digital image from a camera. One does not see an array of millions of luminous points: one recognizes things that have meaning (a 'room', a 'window', a 'chair', a 'person', 'my dog', etc.). Patterns of light and colour have meaning; experiences are grouped into categories based on what the memory has stored through experiences. Attributing meaning to things or experiences is thus the method used by the brain to organize and remember the massive amount of information presented to the visual field at any moment. Without this process, the brain would simply be overloaded with information, and it would be impossible to concentrate on a task or simply survive in the natural environment.

This is also why expectations are so important in lighting design[7]. First, we see a bedroom through our visual system, and then we recognize it as a bedroom because we have a previous experience of

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* Sometimes called 'non-image forming'.

'bedroom'. Perception is thus closely related to memory, which in turn creates expectations of what a bedroom should look like. This is perhaps why Emerson stated that 'people only see what they are prepared to see'. Note that expectations as well as perceptions are different for people coming from different cultures since they are based on memory and on what they have been used to. For example, a person coming from a hot arid climate will perceive a room with a small window as pleasantly cool while the same room will be perceived as gloomy and unpleasant by a person coming from a temperate climate[6].

In familiar situations, where everything that is subconsciously sensed is expected, one is likely not to notice the surroundings at all[6]. The attention can then be put on a task, a conversation or something else. Imagine you had a meeting with your teacher for the first time and upon entering the teacher's room, the decor and lighting would be that of a disco bar with a rotating mirror sphere casting moving light spots around the room. How hard would it be to concentrate on academic subjects with your teacher? Your attention would be focused on analyzing the environment and trying to resolve the conflict between your memory (and expectation) of a teacher's room and what is presented to your visual system.

Much of the art of good daylighting and lighting design consists of providing the lighting conditions that are expected unless the opposite effect (surprise or attention) is what one strives for. This also involves trying to replicate the way daylight normally renders the natural environment. A classic example to illustrate this principle is the human innate expectation of light coming from above and not below, as exemplified by Figure 3.1. In this figure, dents and dings are created by light and shadow. When the figure is inverted, the dents become dings and vice versa. This is because humans unconsciously assume that the light casting shadows come from above (as in nature with sky above head).

The fact that perception is so tightly linked to memory and expectations might explain why the brain can easily be fooled by so-called optical illusions like the one shown in Figure 3.2. In this optical illusion, the brain has already stored a concept of an elephant and is unable to see the image as it is in reality. The brain is confused between what it is prepared to see, and what the image presented to the eyes really looks like. Visual illusions are considered as highly fascinating by most people and can be explored further in many other books[8].

Apart from optical illusions, many visual phenomena provide the human visual system with incredible capacities to more efficiently make

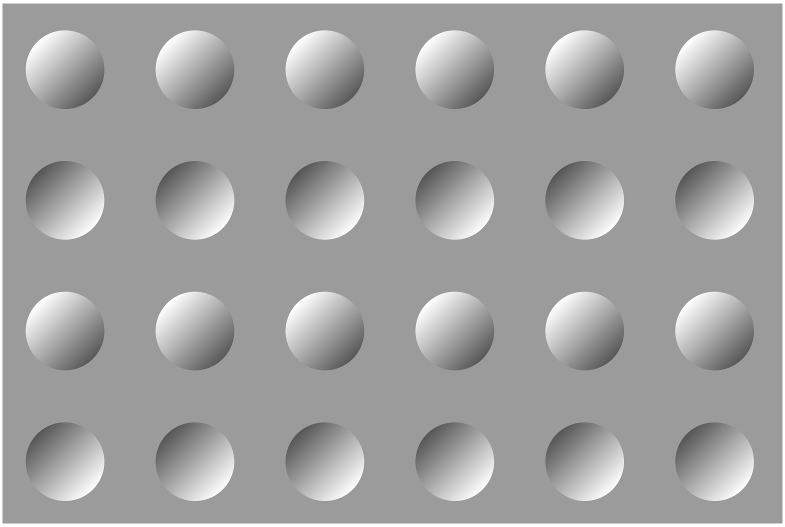

Figure 3.1
Indent illusion.

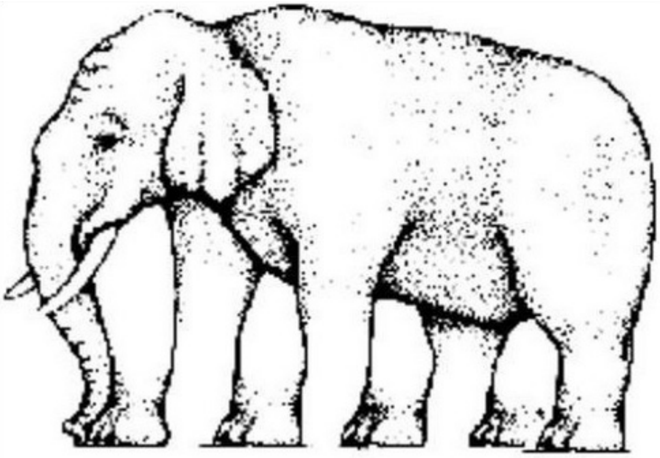

Figure 3.2
Elephant legs optical illusion.

sense of the exterior environment. Some of these phenomena are called ‘constancies’ because they refer to attributes of objects that are perceived as constant over different lighting conditions. These constancies are briefly described below:

1. *Lightness constancy* is the ability of the human brain to distinguish between illuminance on a surface and its reflectance. The brain can distinguish the difference between a low reflectance surface receiving high illuminance and a high reflectance surface receiving low illuminance even when both surfaces have the same objective luminance[4]. For example, a

dark grey book near the window is seen as dark grey while a white sheet of paper away from the window is seen as white.

2. *Colour constancy* is like lightness constancy but it applies to coloured surfaces and coloured light. The brain can distinguish the difference between incident and reflected light colour. This is illustrated in Figure 3.3, which shows that despite the obvious pink tone of the back wall, the brain knows that the surface is white and receives coloured light instead.
3. *Size constancy* is the brain's ability to use cues such as texture and masking to get an understanding of real size. The famous Ames room designed to distort the perception of perspective provides an example of this phenomenon, see Figure 3.4. Despite the forced perspective distortion, the brain knows that the child on the left side of the image cannot possibly be almost twice as large as the child on the right side.
4. *Shape constancy* is the ability of the brain to know the shape of objects despite distortions created by perspective. For example, the wheel of a car is understood as round even when seen in perspective where it is elliptical.

In general, constancy is likely to disappear when the target object is devoid of context. For example, looking at a small sample of the wall in Figure 3.3 would make it impossible to know that it is the light which is coloured and not the surface. In the next sections, the human visual system is further discussed independently of interpretations by the brain.

3.2 Visual system

Since lighting and daylighting systems are usually designed for human beings, it is essential to understand how the human visual system responds to light in order to create appropriate and satisfying light conditions for this system. The human visual system is one of the most important and sophisticated systems in the human body, while the ability to see is certainly one of the great wonders of nature.

The visual system is responsible for receiving visual stimuli and passing them to the brain. The visual stimuli are essentially processed in the visual cortex, which is the part of the cerebral cortex responsible for vision. The visual cortex, which takes up about one third of the whole brain, is in the occipital lobe at the back of the brain, normally distributed equally between each hemisphere. The relative size of the

Figure 3.3
Huddinge hospital, Sweden. Two adjacent rooms with the same (white) colour for walls and ceiling but different colours for the floor. Photo: Malin Alenius.

Figure 3.4
Size constancy in the Ames room. Despite the distorted perspective, one knows that the child on the left side cannot possibly be twice the height of the child on the right side. Photo: Marie-Claude Dubois.

visual cortex with respect to brain probably contributes to the general recognition that 'vision is the primary sense that humans use to process their surroundings'[9].

The visual cortex of the left hemisphere receives signals from the right field of view and the right visual cortex from the left field of view, see Figure 3.5. A person losing the visual cortex on the right side loses information (vision) on the left side of the visual field or the other way around.

It is also well known that the image impinged on the retina is upside down, just like in an optical camera. How come the world is not perceived as upside down? The reason is simply that through proprioception, the experience of touch and sound and previous encounters by moving through the physical world, the brain has learned that a visual stimulus which is in the upper part of the retina is located downwards and vice versa, as proposed by Gibson[10]. This process is automatic, and it is impossible to unlearn it and see things as they really appear on the retina (i.e. upside-down).

3.2.1 Human eye

One of the important components of the visual system is obviously the eye, which is a sophisticated optical device, see Figure 3.6. The eye measures about 24 mm in diameter and contains the cornea, pupil and crystalline lens that transmit the external light stimuli into patterns of nerve impulses, which are then transmitted to the brain via the optic nerve. Some of the most important parts of the eye are the cornea, which is the transparent part of the eye's outmost layer (the sclera) allowing light to enter. Inside the cornea, the iris contains a circular opening, the pupil, which is basically a hole admitting light into the eye. The pupil changes size through the action of two sets of muscles, where one is for contracting and the other for extending. Pupil size varies as a function of light level, but it is also influenced by distance to objects, age of observer and emotional factors[11]. After passing through the pupil, light reaches the crystalline lens, which varies in focal length by adjusting its shape using the ciliary muscles. For close objects, the lens

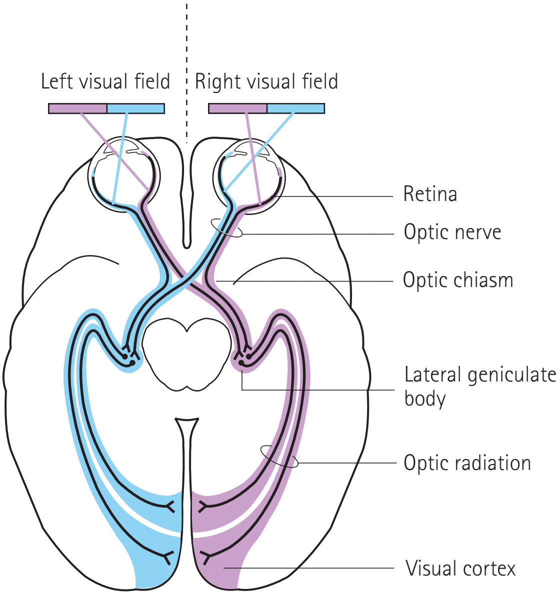

Figure 3.5 The right eye sends signals to the left hemisphere and vice versa. Illustration: Lena Lyons.

thickens (accommodation), the pupil constricts, and the eyes converge to the focus point, which is referred to as the near triad[12]. With age, the lens stiffens causing problems to all three areas, which is why we need reading glasses and more light when reading when we have presbyopia.

After passing the lens, light travels through a jellylike transparent material called vitreous humor and reaches the retina, where it is absorbed and converted into electric light signals. These signals are passed to the optic nerve at a precise point called the blind spot where all the nerve endings from the retina bundle and exit the eye. Since there is no photoreceptor cell at this specific spot, there is no vision. However, humans do not perceive the blind spot since the brain compensates for it by filling the hole in the perceived picture with information. Even in cases where diseases of the retina impair vision of parts of the visual field, the brain will artificially construct a coherent image of the whole and fill missing information with patterns, textures and colours that 'should' be there. A vivid account of this phenomenon is given in Sacks (1998)[13].

3.2.1.1 Retina

All ocular effects of light result from photons impinging on the retina[1], which is located at the back of the eye. The retina, is considered as 'an extension of the brain' and like the brain, damaged cells are not being replaced[4]. The retina is a highly sophisticated light sensitive layer containing roughly 125 million photosensitive cells called rods and cones, which are spread nonuniformly over its surface. Photosensitive cells are in fact neurons specialized to detect light[14]. These photoreceptors contain proteins with light sensitive photopigments (pigments that undergo a chemical change when absorbing light) called opsins. Photopigments absorb light and start the electrophysiological

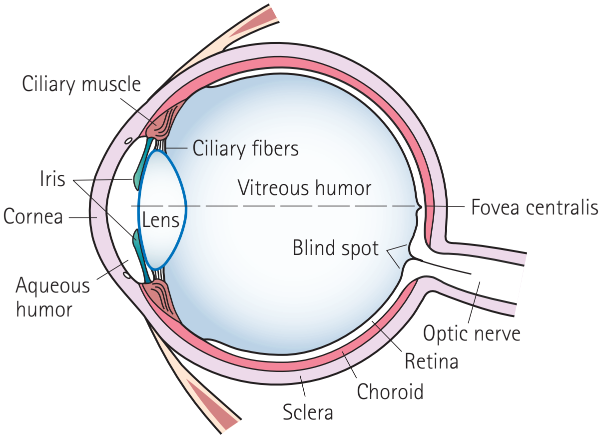

Figure 3.6
Section of the human eye showing the retina, fovea centralis, blind spot and optic nerve. Illustration: Lena Lyons.

chain of events that result in seeing. When the photopigments absorb light, they bleach after which they cannot absorb more light until the photopigment regenerates[8].

As mentioned before, these photosensitive cells convert incident light energy into electrical signals that are processed to the brain through the optic nerve and create visual impressions. A third type of cells (the so-called *third receptor* or *select ganglion cells* or *intrinsically photosensitive retinal ganglion cells*, i.e. *ipRGCs*) has been discovered in the 1990s and is responsible for the photobiological response to light, which is discussed in the next chapter. However, there is growing evidence that select ganglion cells also contribute to vision by discriminating between brightness and light–dark transitions[15]. Figure 3.7 shows a cross section of the retinal tissue with the different photoreceptors.

3.2.1.2 Cones

In the middle of the retina, the macula (or 'yellow spot') exhibits a small dimple called fovea or fovea centralis, which contains highly packed cone cells. The fovea centralis contains about 5 million cones (each about 0.006 mm in diameter), which are less sensitive than rods but are fast and can adapt to the brightest lights, being almost impossible to saturate. Cones undoubtedly evolved before rods, in areas of strong sunlight where vision was a great advantage[14].

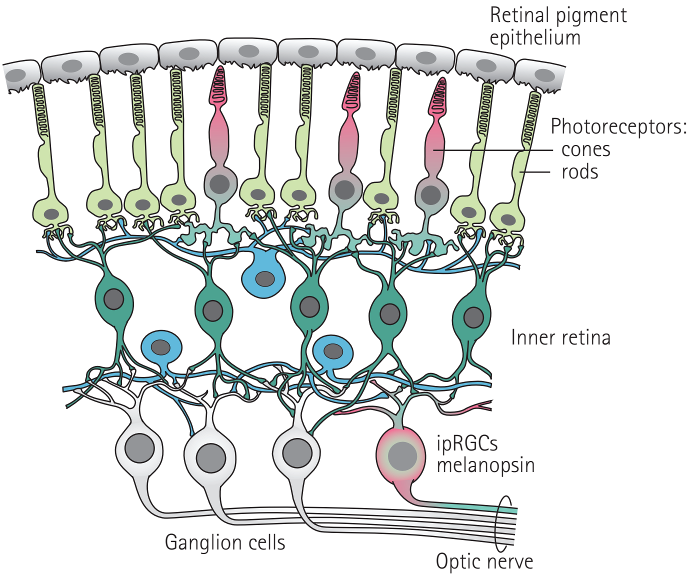

Figure 3.7
Photoreceptor cells in the retina. Illustration: Lena Lyons.

Cones perform very well in bright light conditions, providing detailed coloured views, but they are relatively insensitive at low light levels, i.e. below about 3 cd/m^2[3]. There are three types of cone cells: red, green and blue each containing different photopigments. Each photopigment has a specific response according to wavelengths of light, with peaks in different parts of the electromagnetic spectrum, see Figure 3.8:

- red (denoted L for long with peak at 564 nm),
- green (denoted M for medium with peak at 534 nm),
- blue (denoted S for short with peak at 420 nm).

The three cone types are distributed differently across the retina. The L- and M-cones are concentrated in the fovea while the S-cones are largely absent from the fovea, reaching a maximum concentration just outside the fovea and declining gradually with increasing eccentricity from the fovea[4]. L-cones are the most numerous followed by M-cones, while the S-cones are rather rare.

3.2.1.3 Rods

Rods (each about 0.002 mm in diameter), which are more numerous than cones (120 million rods versus 8 million cones), are slow in reaction time but much more sensitive to light than cones. They perform in light too dim for the cones to respond to (i.e. below 0.001 cd/m^2). There is no rod photoreceptor in the centre of the fovea. Rods are in fact defined by

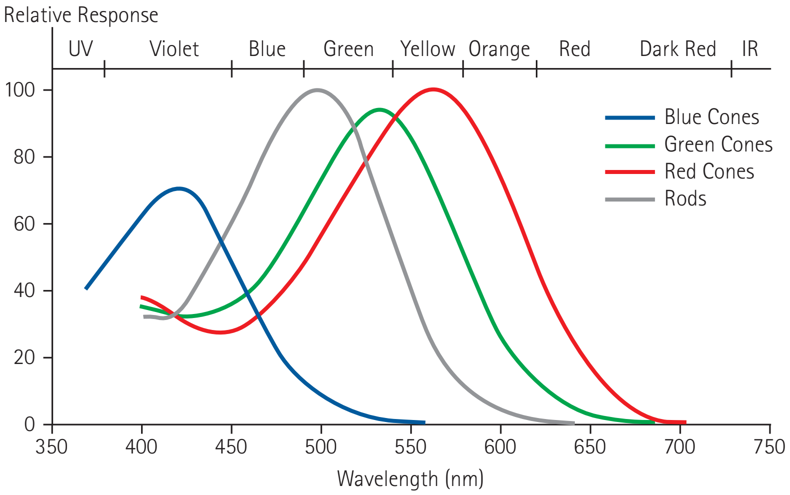

Figure 3.8
Relative response of blue, red and green cones in relation to rod response. Adapted from Molnar & Gair (2015)[69].

the Commission Internationale de l'Éclairage (CIE) as photoreceptors containing a light-sensitive pigment capable of initiating the process of scotopic vision[16]. Scotopic vision refers to night vision, discussed further down in the text. Rods are unable to distinguish colour, and the images created by the rods are not well defined. Therefore, the world looks gray at night.

In general, the rods predominate in the periphery of the visual field and provide the ability to perceive shape and motion. In other words, reaction to movement in the visual field is more acute when movement occurs in the peripheral visual field, which is probably the result of evolution as this provides obvious advantages for an animal out in nature. Rods are not used much in modern society where electric illumination adequate for cone vision is dominant[14]. In fact, they are important to provide a general perception of space and room, environment, and context, which can be further explored by the foveal, cone-dominated vision.

3.2.2 Colour vision

The photoreceptors in the retina allow colour vision. Colour vision is an illusion created by the interactions of billions of neurons in the human brain. There is no colour in the external world; colour is created by neural programs inside the brain, projected onto the outer world[14]. Different animals see the world in different colours (dogs do not perceive the red car of their owner as red), which is a proof that colour in the external world is an illusion.

Colour is created by the brain based on two properties of light: energy and frequency of vibration or wavelength[14]. Colour is learned at a young age. When a child grabs a green block, his parents tell him immediately that this frequency of vibration is called 'green' and the child's brain establishes a link between the sounds of the word green and the visual impression of this specific frequency of vibration.

Human colour vision is called trichromatic because it is based on three different cone photoreceptors (the red-L, green-M and blue-S receptors). As mentioned before, photoreceptors are characterized by different peak sensivity responses at different wavelengths, with an overlapping bellshaped response curve, see Figure 3.8. The colour perception is made possible by the relative response of these red-green-blue (RGB) photocells. To detect objects by differences in spectral reflectance, two or more different types of cones are required[14]. Therefore, it is impossible to perceive colour with a single receptor

Figure 3.9
Colored picture and black and white version of the same picture showing the clear advantage of colour vision. Photo: Marie-Claude Dubois.

cell, as is the case for rods in the peripheral vision at night (scotopic sensitivity).

In primates, high resolution vision and trichromatic colour vision evolved to enhance survival[14], which probably allowed a perception of different objects with similar energy but different spectral reflectance. As an example, Figure 3.9 shows that it is much more difficult to locate apples when the image is black and white than when the colour information is present. Even though colour vision is extremely important for visual performance and survival, it is seldom considered in lighting regulations and practice. Unless specifically stated, lighting requirements are expressed as minimum photometric units devoid of colour information; colours are represented by a single sensitivity response curve, which is even integrated into a single number, e.g. a certain amount of lux or cd/m^2. In the future, as our capacity increases to handle colour information in calculations, we can expect that colour information will be part of design regulations and practice.

3.2.3 Visual field

The terms ‘visual field’ and ‘field of view’ are used interchangeably but they mean slightly different things. ‘Visual field’ refers to the spatial array of visual impressions as introspectively experienced by humans or animals while ‘field of view’ refers to the physical objects and/or light sources in the external world perceived by humans or animals.

Humans have two eyes placed frontally, which is typical for predators. This configuration provides binocular or stereoscopic vision, i.e. the perception of a single three-dimensional image produced by an overlap between two fields of view. Binocular vision accounts not only for the fact that the visual field is wider than high; it also provides three-dimensional vision and depth perception. It is the slight differences between the two images produced by each eye that provides a cue to the brain about where the objects are located in space. Binocular vision and depth perception are useful when stalking and capturing a prey or when one needs to rapidly grab a tree branch in the jungle. However, note that even when one closes one eye, depth perception is not completely lost as other mechanisms like shadows, shape, and colour play a role into depth perception. In contrast to predators, preys normally have eyes mounted laterally to be able to see the environment all around them and react rapidly when attacked by a predator[4].

The human visual field normally extends to approximately 60 degrees nasally (towards the nose, or inwards) from the vertical meridian in each eye, to 100 degrees temporally (away from the nose, or outwards) from the vertical meridian, and approximately 60 degrees above and 75 degrees below the horizontal meridian, see Figure 3.10. With both eyes open, the visual field thus has a horizontal dimension of about 200 degrees, composed of approximately 60 degrees of binocular overlap with a monocular temporal crescent on each side[17]. The shape of the visual field varies from person to person as it is determined by the shape of the face, jaw, cheeks, nose, and forehead. People with big noses have a more limited visual field towards the nose. Figure 3.11 shows the approximate extent of the visual field of the two eyes in humans and the overlap between them. Given the limited visual field resulting from frontally placed eyes, humans and other predators can move both eyes and head to look at special areas of interest in the visual field.

As explained in the previous sections, the cones are concentrated in the fovea although there is a low density of cones across the remaining part of the retina. The cones in the fovea provide colour vision and sharpness (in a narrow angle of about 2 degrees) under daytime or photopic adaptation. The visual system devotes most of its resources to analyzing the central area of the retina, particularly the fovea[4]. About 80 percent of the cortical cells (in the brain) are devoted to the central

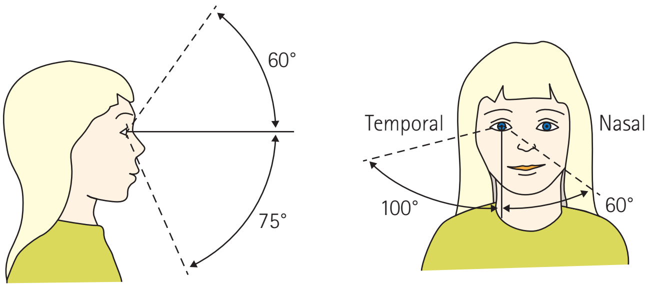

Figure 3.10
Visual field. Adapted from Moore (1985)[70].

10 degrees of the visual field[18], of which the centre is the fovea. Note that most research on vision has concentrated on this small central part of the visual field[19] but there are indications that the peripheral visual field plays a central role in the general and immediate perception of space.

The peripheral vision, which has been the subject of fewer research, is mainly devoted to identifying something that should be examined in detail by turning the head and eyes, so the detail of interest falls on the fovea for further inspection. As mentioned before, rods are predominant in the periphery of the visual field and provide the ability to perceive shape and motion. Liljefors & Ejhed (1987)[20], Pallasmaa (2014)[21] and Wänström Lindh (2012)[22] claim that peripheral vison has generally been largely underestimated, as it is of great importance for our perception of space and immediate spatial atmosphere. Pallasmaa (2014)[21] explains that 'the real experience of architectural reality depends fundamentally on peripheral and anticipated vision; the mere experience of interiority implies peripheral vision'. According to this author, the left (brain) hemisphere is specialized in processing detailed observation and information whereas the right hemisphere is dominantly engaged in peripheral experiences and the perception of entities. There is evidence that 'peripheral and unconscious perception is more important for our perceptual and mental system than focused perception'[23]. Recent research also suggests that humans are significantly better at discriminating shapes throughout the lower (peripheral) visual field compared to elsewhere[24]. This is explained by the fact that humans manipulate objects chiefly within their lower visual field, a consequence of upright posture and the anatomical position of hands and arms.

The central part of the visual field in a cone of 30–40 degrees has also been found to have more importance in visual comfort studies. Loe, Mansfield & Rowlands (1994)[25] claimed that even if the visual field is almost 200° horizontally and 120° vertically, the part which has a significance for visual comfort evaluations is a band of 40° centered at normal eye height. Carter et al. (1994)[26] demonstrated the importance of the surfaces in front of the subject, compared with surfaces to either side when assessing the room brightness. The most important factors appeared to be the luminance of the walls, particularly those forming the background to the tasks as perceived by the subjects, which determined the relative brightness of the tasks. In general, ratings of brightness increased as the average luminance within a 40 degree-wide horizontal band centered about the eye increased but there is some evidence that surfaces in front of the subject had a greater influence than surfaces to the side, and also that dark room surfaces, notably ceilings, outside the

40 degree band adversely influenced the assessment of brightness. In a publication about shading screens, Fontoynont (2000)[27] considered that a central cone of vision of 30 degrees was significant for visual comfort. Other authors[28] consider that the visual field consists of two main parts: the ergorama and the panorama. The ergorama is a cone of 60 degrees, while the panorama is a cone of 120-140 degrees centered about the main line of sight.

Humans generally have the impression that the whole visual field is sharp. Apart from underestimated abilities of the peripheral visual field, this is explained by the fact that the eye constantly moves about the object on which it is focused, creating perceptual fragments upon which the brain constructs a sharp image. As explained by Pallasmaa (2014)[21]:

> This fragmented perception of the world is actually our normal reality, although we believe that we perceive everything with precision. Our image of the perceptual fragments is held together by constant active scanning by the senses, movement and creative fusion and interpretation of these inherently dissociated percepts through memory.

If one stops moving the eye by focusing on a point, it becomes obvious that it is a very limited area (about 1–2 degrees) of the visual field that is sharp. When staring directly at a target without moving the eyes, a process called fixation, different types of eye movements occur: tremors and saccades. Tremors are small oscillations in the eye position that are always present and in the absence of which vision rapidly fails[29]. Saccades are the rapid jump movements back to an object of interest which counter the tendency of the eye to drift slowly away from the fixation point. The eyes can also follow a target by smooth pursuits, where the saccadic movements cease.

In summary, although the eye receives information from a field of about 200 degrees, the acuity over most of that range is rather poor. To form high resolution images, the light must fall on the fovea, which limits the acute vision to about 15 degrees. Under low illumination, the fovea becomes like a second blind spot since cones have low light sensitivity and cannot pick up light signals when they are too weak. Therefore, stars in the night sky seem to disappear if one stares at them – the rods are much more sensitive to low light levels and they are concentrated off axis about 20 degrees. Astronomers aware of this phenomenon often suggest looking slightly beside the star thus using peripheral visual field's low light sensitivity.

3.2.4 Adaptation

Adaptation is the process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminance values, spectral distributions and angular subtenses[30]. In other words, it is the regulation by partly the pupil and retina of the quantity of light entering the eye, which allows vision under different lighting conditions or large contrasts. The human visual system operates over an enormous range of light levels[8]. This range enables processing light signals over about 12 orders of magnitude[4] from starlight at 0.000001 cd/m² to over 100000 cd/m² on a sunlit day[3]. Being able to process this large brightness range was an evolutionary necessity which probably contributed to survival under very different light conditions.

However, Reinhart (2014)[3] emphasized that humans can only adapt to a brightness range of about two orders of magnitude at any given time by varying the aperture size of the pupil, a process which takes less than one second. Other neural and photochemical processes are also involved in the adaptation process, see Boyce (2014)[4].

When the visual system is adapted to a given luminance, much higher luminances will appear as glaring while much lower luminances are perceived as black shadows[4], Figure 3.12. This explains why one can barely sustain the direct gaze of a flashlight in a dark room while the same flashlight will be barely noticed under daytime light conditions.

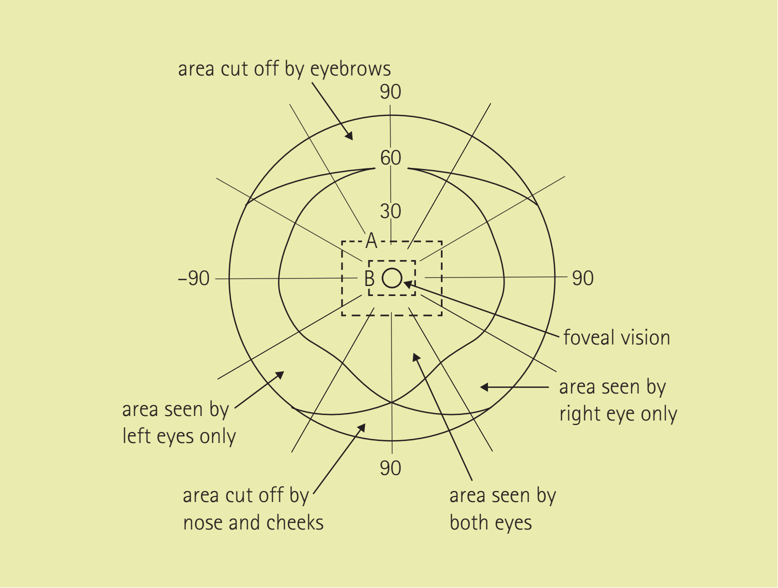

Figure 3.11 Approximate extent of the visual field of the two eyes in humans and the overlap between them. Adapted from Moore (1985)[70].

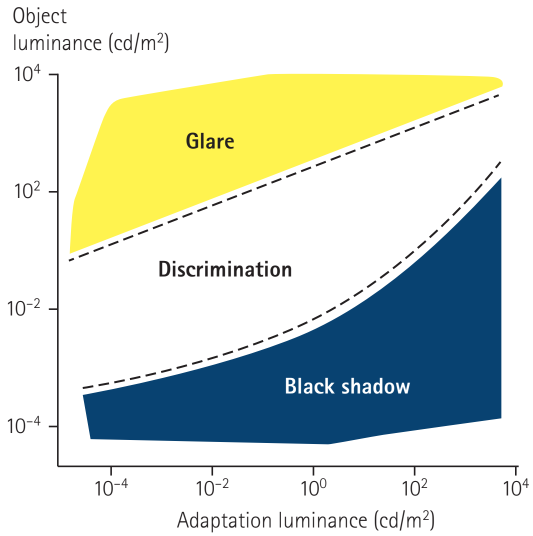

Figure 3.12 Relation between target and adaptations luminance. Adapted from Hopkinson & Collins (1970)[71].

The large adaptation range of humans is not necessary inside buildings, where the brightness ranges from around 10–20 cd/m² when reading a book at night, to about 300 cd/m² when looking at a modern flat screen, to a few thousand cd/m² when looking at an electric light source or sunlight reflected off a wall[3].

3.2.4.1 Adaptation states

The cones located in the fovea operate during the day under normal light conditions and allow the vision of colours and details. This situation is called daytime or photopic adaptation. As expressed by Reinhart (2014)[3], photopic adaptation is the main adaptation state that matters for interior lighting, daylighting or electric lighting. Photopic adaptation is thus the main adaptation state considered in this book.

As the light level drops, cones become less useful and rods, which are more sensitive under dim light conditions, come in more useful. At this point, the eye is in a state called mesopic adaptation. The overall impression is a much less brightly coloured scene. Mesopic adaptation is relevant for outdoor lighting after dark.

At even lower levels, like under moonlight, the eyes totally lose their ability to see in colour and the rods take over completely. At this point, the scene looks completely black and white. This is called nighttime or scotopic adaptation, an adaptation level which is relevant to areas without electric lighting after dark.

Under photopic adaptation, the eyes sensitivity response peaks at 555 nm, in the green region of the spectrum, with a bell-shaped distribution around the peak represented in Figure 3.13. This means that the human eye is best at detecting light in the green region of the spectrum during the day, such as light reflected off plants, an aspect which would certainly be an evolutionary advantage when humans had to forage for food in the forest, see Figure 3.14.

For rod vision, the maximum sensitivity is shifted towards blue light at 507 nm[1]. This change in peak spectral sensitivity from longer to shorter

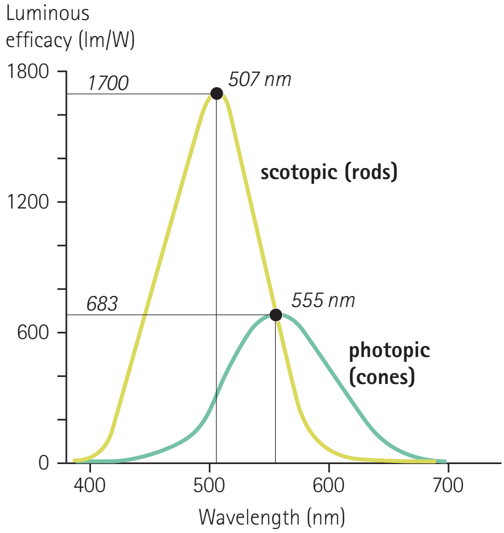

Figure 3.13
Photopic and scotopic adaptation. Adapted from Williamson & Cummins (1983)[72].

Figure 3.14
In the photopic adaptation state, green is the colour best seen by the eyes. Photo: Marie-Claude Dubois.

wavelengths as illumination decreases is called the Purkinje shift. This explains why in darkness, the vision of colours is lost, especially the warm colours. It is interesting to note that in Scandinavian languages and in French, the term blue hour ('blåtimmen' in Swedish, 'l'heure bleue' in French) corresponds to the time of the day when the sun has set and only some weak skylight remains. It is the time between day and night called dusk in English. At that moment, objects are weakly daylit by the remaining skylight, but they have lost their colour, only bluish glow remains, to which the human eye is more sensitive at lower light levels, see Figure 3.15. The human eye's spectral sensitivity thus completely matches the diminishing light conditions between day and night.

In addition, the sensitivity of rods and cones is not linear but logarithmic, meaning that it takes about ten times the amount of light falling on the eye at any moment to produce the perception that there is twice as much light[3], see Figure 3.16. A consequence of this is that humans normally do not perceive slight changes in light levels. This is why dimming systems that slowly adjust illumination as a function of daylight can go unnoticed by building inhabitants. This aspect can even be exploited for energy savings, as suggested by a research[31], where

Figure 3.15
From mesopic to scotopic sensitivity, the blue hour. Photo: Marie-Claude Dubois.

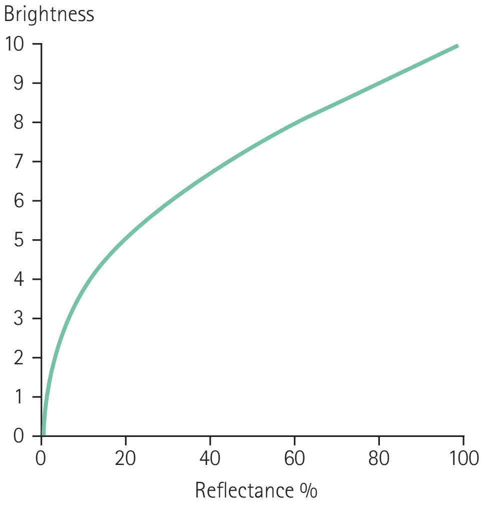

Figure 3.16
Perceived brightness of light diffusely reflected from a surface is not linear but logarithmic. Adapted from Munsell, Sloan & Godlove (1933)[73].

electric lights were slowly dimmed down to about 40–50% of their initial flux, an unnoticed effect by the participants in the experiment.

3.2.4.2 Standard luminous response curves

Just as each person has a unique brain and body, each person has a unique sensitivity to colours under different adaptation states. Some people can even perceive slight differences in the perception of colours between their two eyes! However, to simplify things and allow common grounds for calculations, measurements, definitions, and development, the CIE has described what is called a 'standard observer' through experiments[32 33 34].

The CIE has also recognized three different spectral sensitivities known as:

- the CIE Standard Photopic Observer (denoted CIE $V(\lambda)$),
- the CIE Modified Photopic Observer (denoted CIE $V_M(\lambda)$),
- the CIE Standard Scotopic Observer (denoted CIE $V'(\lambda)$).[4]

The first spectral curve was adopted in 1924 based on the work of Gibson & Tyndall (1923)[32]. Their experiment used a small test field usually less than 2 degrees in diameter with an amount of light sufficient to put the visual system in the photopic state. The second curve was based on subsequent work by Judd (1951)[35], who showed that the CIE standard photopic observer was too insensitive at shorter wavelength, which led to the international agreement about the modified observer. The third curve was adopted in 1951 based on measurements by Wald (1945)[33] and

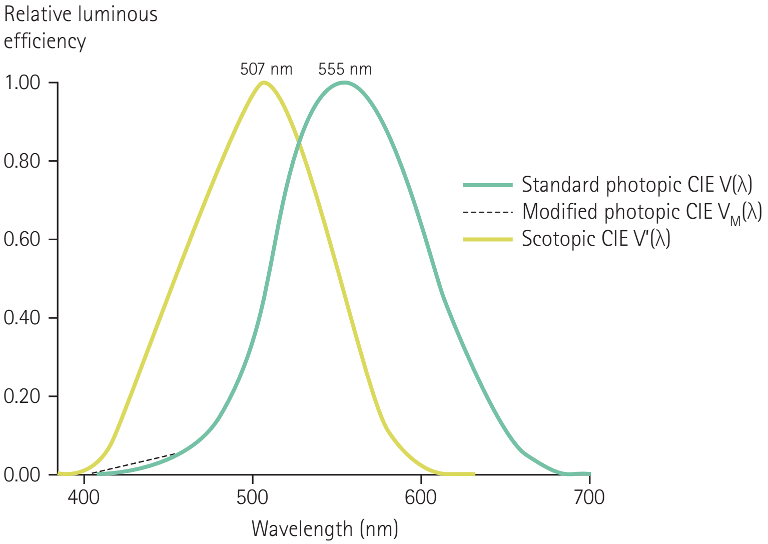

Figure 3.17 Relative luminous efficiency functions for the CIE Standard photopic observer, the CIE modified photopic observer, the CIE standard scotopic observer, and the relative luminous function for a 10 degree field of view in photopic conditions. Adapted from Boyce (2014).

Crawford (1949)[34] using an area covering the central 20 degrees of the visual field with a photopic luminance of about 0.00003 cd/m². These experiments have resulted in the production of standardized response curves shown in Figure 3.17. These curves are important as they are the basis for the conversion from radiometric to photometric quantities.

3.2.4.3 Transient adaptation

Transient adaptation refers to the period during which the visual system is not completely adapted to the prevailing retinal illuminance. During this period, the visual capabilities are limited, and it is therefore an important aspect to consider when the situation requires a rapid reaction e.g., driving into a road tunnel, evacuating a building after a power break, etc. Adaptation from light to dark (called dark adaptation) is normally more problematic since it takes more time than adapting from dark to light as discussed below.

Dark adaptation

Decreasing the amount of light from daylight to darkness takes the visual system through three distinct adaptation states, the photopic, the mesotopic and the scotopic[4]. The time needed for dark adaptation is well known. It is a two-branched function; one for the cone receptors and the other for the rods, see Figure 3.18. The point at which the rods become more sensitive is called the rod-cone break. Cones take

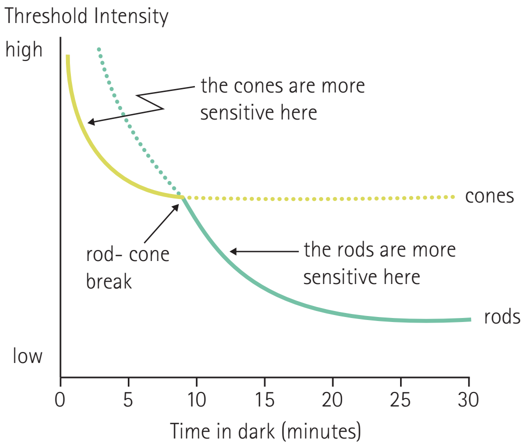

Figure 3.18
Dark adaptation. Adapted from Kaiser (2009)[8].

approximately 9–10 minutes to adapt to the dark while the rods can require 60 minutes or more[3].

Dark adaptation is an important aspect to consider in building design, as one might experience lost vision during the first 15–30 minutes after entering the building. A good way to prevent dark adaptation problems is to provide passive design features such as building entrances with long exterior protection or canopy above head. This not only protects the occupant against rain and climatic elements, it contributes to lower the adaptation level of the eye before entering the building. Using high reflectance indoors and plenty of daylighting in the building hall is another way to reduce dark adaptation problems. In offices, Reinhart (2014)[3] suggested using borrowed daylight from glazed doors or transoms to illuminate the circulation spaces. This is a good idea since building inhabitants typically switch electric lights on immediately upon entering their workspace. By providing various passive design features to mitigate dark adaptation, electric lights are less likely to be switched on directly and remain on all day.

Light adaptation

One of the major differences between dark adaptation and light adaptation is their time course. Whereas dark adaptation takes about 30 minutes to be complete, light adaptation happens very quickly, usually in less than a minute. Another difference between these two types of adaptation is that light adaptation does not impair visibility as much as dark adaptation. When going from a darker area to a very bright one, there is no temporary blindness as with dark adaptation.

3.2.5 Accommodation

Accommodation is the process of adjusting the focal distance of an optical instrument to the object which is to be viewed with precision. The CIE (2014) definition is 'adjustment of the dioptric* power of the crystalline lens by which the image of an object, at a given distance, is focused on the retina'[36]. Alternately, accommodation can be thought of as the automatic and natural adjustment of the eye to obtain maximal sharpness of the retinal image for an object at which one is looking. This process is made possible through the contraction of the ciliary muscle around the lens.

Accommodation from distant to close objects is achieved by rounding out the lens to shorten its focal length, since the image distance to the retina is essentially fixed. Reversely, accommodation on distant objects is made by flattening out the lens.

As mentioned earlier, with age, the lens in the eye becomes stiffer, which makes accommodation and the near triad a more difficult process. Above the age of about 45, the lens' ability to change in shape is considerably reduced and people over the age of 45 almost always require glasses to read or see distant objects. It is not unusual for people in their fifties and older to wear bifocal or even trifocal lenses[8]. As one gets older, the lens can also become cloudy, which causes veiling glare, a condition called cataract. When cataracts become too severe the lens must be removed and replaced with an artificial lens, which is not capable of accommodation. However, by the time most people are afflicted with cataracts, they have naturally lost most of their capacity for accommodation and already depend on reading glasses to perform this operation[8]. Note also that as one ages, the lens becomes yellower, meaning that people normally experience lower spectral sensitivities for the shorter wavelength part of the spectrum. In other words, they are not as sensitive to radiation in the blue part of the spectrum as before, which has consequences for the visual as well as the non-visual response to light.

3.2.6 Glare

The CIE (2014) defines glare as 'a condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme

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* Dioptrics is the study of the refraction of light, especially by lenses.

contrasts'[37]. An alternative definition of glare is 'a subjective human sensation that describes light within the visual field that is brighter than the brightness to which the eyes are adapted'[38]. An example of this is the perception of car headlights at night or during the day. The same headlights can be perceived as glaring at night and non-glaring during daytime, which is mainly caused by the fact the eye's adaptation level is raised during daytime.

3.2.6.1 Disability and discomfort glare

Glare is normally characterized as either disability or discomfort glare. Disability glare is glare that impairs the vision of objects without necessarily causing discomfort[39] (see Figure 3.19) while discomfort glare is the premature tiring of the eyes due to large contrasts in the visual field[40]. People normally act to correct a disability glare situation, for example by pulling down blinds, changing their sitting position, or adjusting the computer screen.

Discomfort glare does not create a loss of visibility[41], which is why it is more a source of concern in buildings since building occupants do not necessarily correct the glare situation immediately as they are not aware of it. Discomfort glare is normally noticed after the glare situation has occurred for a certain time, such as in the evening or after a long period of work. Generally, if discomfort glare limits are met, disability glare is usually not a major concern in buildings[42]. Discomfort glare

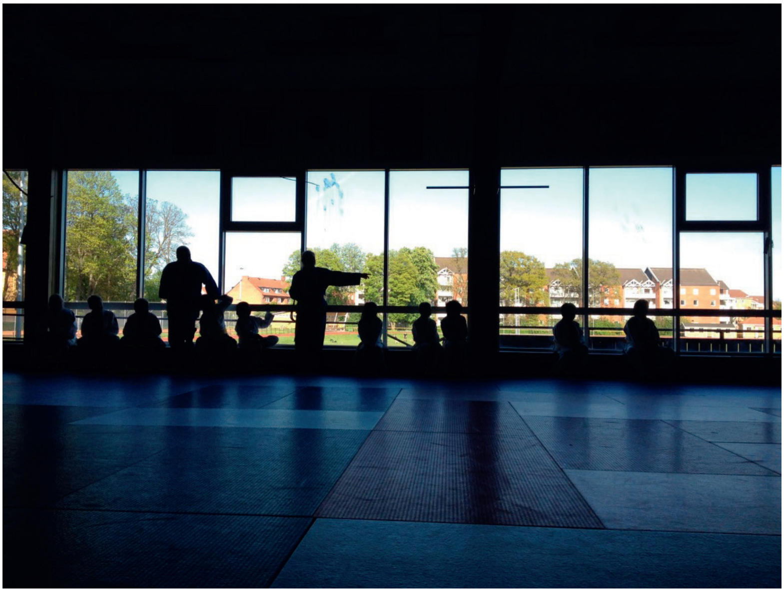

Figure 3.19
Disability glare where the brightness of the light source (in this case the window) is so high that it is no longer possible to distinguish faces of people taking the judo class. Photo: Marie-Claude Dubois.

is the worst type of glare, because people are not aware of it. However, the eyes will strain more and the muscles in the upper back and neck have to work more, sometimes resulting in neck and upper back pain. Headache is also common with discomfort glare, especially the light sensitive individuals and those with photophobia.

Discomfort glare from windows is 'one of the fundamental barriers to the effective use of natural lighting in buildings'[43]. Glare from windows may occur when direct sunlight enters the room and shines into the eyes of occupants or reflects off visual tasks, lateral walls, and surrounding surfaces. Glare may also be caused by high window luminance originating from sunlight reflections off exterior surfaces, for example the glazed facade of a neighboring building, or by a direct view of the sky[44].

Care needs to be taken to control the glaring effects of high luminances associated with the view of the sky. Previous studies have shown that glare is tolerated much more from a daylight source than from its artificial equivalent[45]. Cowling et al. (1990)[46] found that there were significantly less incidents of eyestrain reported by people whose workstations received large portions of natural light. In addition, previous studies[47] [48] [49] indicate that the tolerance for discomfort glare increases when the glare source contains interesting information. Previous research[50] [51] [52] [53] also suggests that views of natural environments have a more positive effect on both psychological and physical human responses. More recent research[43] found a higher tolerance for discomfort glare of distant views including skyline than for near views, concluding that the mean luminance of a window, the type of window view, and the distance of the viewed objects should also be considered in the evaluation of the subjective discomfort glare from a window.

Glare levels in buildings can be determined using the so-called glare indices. A glare index is a numerical evaluation of high dynamic range images using a mathematical formula that has been derived from human subject studies[40]. Although there are many glare indices, two are widely used in practice: the CIE Unified Glare Rating for electric lighting sources and the Daylight Glare Probability (DGP) for glare from side windows. These are further discussed in chapter 7.

3.2.7 Veiling reflections

Veiling reflections are 'specular reflections that appear on the object viewed and that partially or totally obscure the details by reducing

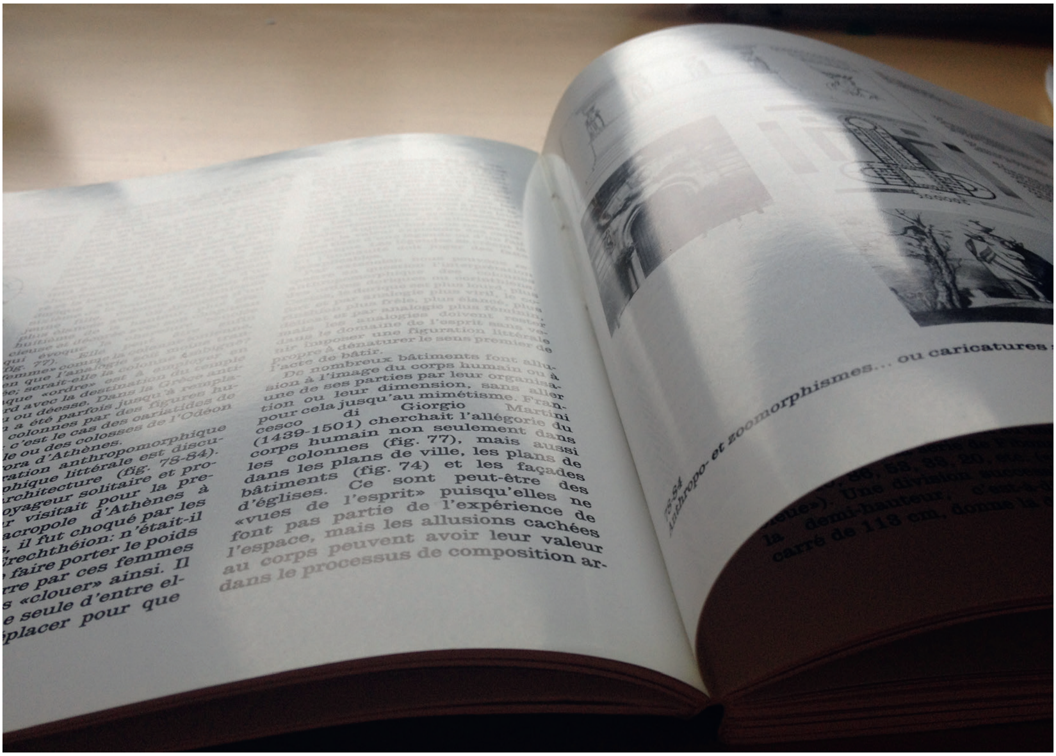

Figure 3.20
Veiling reflections occur on the magazine. Photo: Marie-Claude Dubois.

contrast’[4] [54]. An example of veiling reflections is one trying to read a glossy magazine but the electric light source or the window is placed in such a way that it creates a veil of light on the glossy paper, see Figure 3.20. In other words, the contrast in the image is completely lost and it is impossible to read unless one tries to view it from a different angle. According to Boyce (2014)[4], veiling reflections and disability glare are similar in that both change the contrast of the retinal image, but they differ in that veiling reflections change the luminance contrast of the task itself, while disability glare changes the contrast of the retinal image of the task.

3.2.8 Temporal light modulation (TLM)

Temporal Light Modulation (TLM) is a cyclic variation in light output from a light source or lighting system[55], occurring mainly with electric lighting. Most electric light sources are powered by alternating current (AC), which oscillates at 60 Hz in America, i.e. 60 times per second, while in Europe, Asia, Africa, and Australia, the AC operates at 50 Hz. Incandescent lamps produce TLM of 100 Hz (or 120 Hz in

America) since the filament heats up as the voltage increases in the positive or negative directions and cools as the voltage approaches zero. Fluorescent, compact fluorescent (CFLs), high-pressure sodium, and LED lamps produce TLM at 100 (or 120) Hz. However, LEDs powered by direct current (DC) do not produced TLM. Research has shown that LED products exhibit a broad range of variability in TLM[56 57].

The rapid and regular TLM produced by electric light sources may cause so-called Temporal Light Artefacts (TLA)[58] such as:

- flicker (when the light source itself appears to vary temporally, which is visible to a frequency of about 80 Hz[58]);
- stroboscopic effects (when a moving object appears to have interrupted movement)[59];
- phantom array (when the movements of the eyes produce the appearance of a spatial pattern in the objects being viewed) [57 60].

TLM has an effect on human visual perception, neurobiology, and performance[57]. It can generate mild to severe health problems, such as headache, eyestrain, migraine, epilepsy, etc.[62] Low-frequency (100-150 Hz) TLM can cause adverse consequences for humans, e.g. visual perceptions, cognitive performance effects, disrupted eye movements, neural activity changes, discomfort, and headache[61]. There are wide individual differences in sensitivity to TLM[62]. People with autism[63] or epilepsy may experience severe problems. Flickering light is, in fact, a diagnostic tool used to provoke epileptic seizures in humans[64].

Flicker is the term incorrectly used to describe TLM[62]. According to the International Commission on Illumination (2020) flicker is the 'perception of visual unsteadiness induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a static observer in a static environment'[65]. When these fluctuations are visible, they are commonly called 'visual flicker' but sometimes they can be detected in the retina without being perceived visually, which is referred to as 'non-visual or subliminal flicker' [64]. As the frequency speeds up, flicker becomes imperceptible, which is called the Critical Fusion Frequency or Critical Flicker Frequency (CFF), i.e. the frequency of alternation of stimuli above which flicker is not perceptible for a given set of conditions[66]. Depending on the species or individual, the CFF can be anywhere between 50 and 100 Hz, but around 80 Hz is considered as the most common CFF in humans[67]. It is well known that young adults are normally more sensitive to TLM[68]. Küller &

Laike (1998)[64] found that individuals with high CFF (corresponding to younger, healthier brains) responded with a pronounced attenuation of electroencephalogram (EEG) α waves, and an increase in speed and decrease in accuracy of performance, which was attributed to a heightened arousal of the central nervous system.

The human eye is most sensitive to TLM at the edges of the visual field, and least sensitive at the centre of gaze (the area being focused on). Therefore, one can be highly disturbed by electric lights when looking away from them but as soon as one turns the gaze towards the lights, the effect seems to vanish.

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CHAPTER 4

Non–visual effects of light

THORBJÖRN LAIKE AND PIMKAMOL MATTSSON

> 3 'And God said, "Let there be light," and there was light. 4 God saw that the light was good, and he separated the light from the darkness. 5 God called the light "day", and the darkness he called "night". And there was evening, and there was morning—the first day.'
>
> GENESIS 1:3–5

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Alertness, biological rhythm, body's internal clock, circadian rhythm, cortisol, critical flicker fusion frequency (CFF), electroencephalogram (EEG), intrinsically photosensitive retinal ganglion cells - ipRGCs, light exposure, melanopsin, melatonin, monochromatic light, polychromatic light, seasonal affective disorder (SAD), sub-SAD, suprachiasmatic nuclei.

This chapter covers various aspects related to the non-visual effects of light and introduces the fundamentals of how light is biologically linked to humans, guiding our sleep-wake patterns and affecting our alertness and mental health.

4.1 Background

Our knowledge of the non-visual impact of light on humans has a relatively short history. It was not until the 1950s that German ophthalmologist Fritz Hollwich (1979)[1] described how patients suffering from cataracts, which lead to a blurred lens in the eye, displayed significantly lower levels of the stress hormone cortisol compared to individuals with normal vision. Cortisol is a steroid hormone that helps us manage stress, regulate blood sugar levels, and fight infections. Normally, cortisol levels are highest in the morning upon waking and lowest at night. After surgery to replace the lens, the cortisol levels returned to normal. This indicated that visible light entering the eye and reaching the retina impacts biological rhythms in the human body. These rhythms include sleep and wakefulness, body temperature, metabolism, and hormone production (Arendt & Pévet, 1991)[2]. Most of these rhythms operate on a 24-hour cycle, known as the circadian rhythm, and are tied to the suprachiasmatic nuclei (SCN) located in the hypothalamic area of the brain.

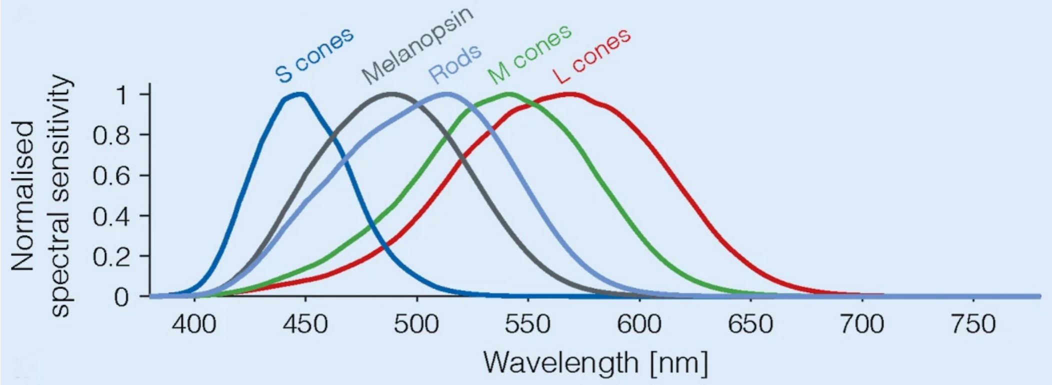
In addition to its effects on biological and circadian rhythms, light influences alertness, mood, mental health, and behaviour. Together, these effects are generally referred to as the non-visual effects of light. One early study was conducted in classrooms with nine-year-old children in Southern Sweden (Küller & Lindsten, 1992)[3]. At that time, there were classrooms with and without windows. The study found that children with access to daylight in their classrooms experienced a decline in morning cortisol from autumn to winter, with levels rising again in February. In contrast, the cortisol levels for children in windowless classrooms continued to decline in February and did not rise until April, when daylight became more abundant. The higher cortisol levels in the morning were positively associated with social and group-oriented activities, indicating the importance of the non-visual effects of daylight. Additionally, a study of below-ground and above-ground work environments found that daylight played a crucial role in regulating the balance between the sleep hormone melatonin and the stress hormone cortisol (Küller & Wettenberg, 1996)[4].

The attention to non-visual effects of light has significantly increased due to the recognition of intrinsically photosensitive retinal ganglion cells (ipRGCs) in the early 2000s. Berson and his colleagues (2002)[5] suggested that neither rods nor cones were needed to modulate human circadian rhythms; instead, retinal ganglion cells with a photopigment called melanopsin, which innervate the SCN, were intrinsically photosensitive. Since then, several studies have shown that these ipRGCs, also called the 'third receptors,' mediate the effects of light on circadian rhythms (Hannibal et al., 2004; Melyan et al., 2005; Qiu et al., 2006)[6 7 8]. The ipRGCs receive inputs from rods and cones and act as 'integrators of information' across wavelengths and light levels (Blume et al., 2019)[9].

It has long been understood that rods and cones are responsible for vision (seeing colours, motion, and details), while melanopsin plays the most important role in mediating the non-visual effects of light. However, there is now evidence suggesting that melanopsin may also play a role in our visual perception (Cao et al., 2018; Zele et al., 2014)[10 11]. Figure 4.1 shows the relative spectral sensitivities of the photoreceptors in the human retina.

Factors triggering non-visual effects of light include timing (time of day), light intensity, wavelength, spectrum (spectral power distribution), colour temperature, quantity, directionality, duration of light exposure, and light history. Understanding the non-visual effects of light has involved interdisciplinary research, drawing knowledge from several fields such as life sciences, ergonomics, psychology, and behavioural and cognitive neuroscience. This research contributes to improvements in our light exposure and lighting environments in architectural design, building regulations, and standards, promoting positive effects and preventing negative ones.

Figure 4.1
Relative spectral sensitivities of human's photoreceptors. Source: Blume, Garbazza & Sptischan (2019)[41].



4.2 Circadian rhythms

Circadian rhythms are part of the body's internal clock, which is naturally aligned with the day-night cycle. These rhythms can vary from person to person due to genetic variation. An individual's circadian rhythm may be slightly shorter or longer than 24 hours. To stay synchronized with the 24-hour cycle, we need an external 'zeitgeber' (time giver), and the SCN helps us by using cues from the strongest zeitgeber, which is ambient light. This is why we need light to entrain our internal clock every morning to benefit from hormone production and sleep quality.

The timing (time of day) of light exposure is considered to have a strong impact on circadian rhythms, primarily through melatonin suppression. Exposure to light, especially daylight with enriched short wavelengths (or 'blue light') in the early morning, advances the 24-hour internal clock, while light exposure in the late evening and at night delays the clock and, therefore, sleep (Blume et al., 2019)[9]. Moreover, exposure to daylight during the day has been found to affect our sleep by advancing sleep timing (Boubekri et al., 2014)[12]. Approximately 15 to 30 minutes of daylight exposure, particularly in the morning, is suggested to be sufficient. So, roughly speaking, short durations of daylight exposure at high intensities are beneficial for sleep.

As we are exposed to artificial light during the day and after the day in everyday life, studies have been conducted to investigate how light properties affect circadian rhythms. Using monochromatic light, Brainard et al. (2001)[13] found that the peak sensitivity for melatonin suppression was between 446–477 nm (λ_{max} = 464 nm), while Thapan et al. (2001)[14] found it between 457–462 nm (λ_{max} = 459 nm), and Hankins & Lucas (2002)[15] reported a peak (λ_{max}) at 483 nm. This knowledge is crucial for understanding how the circadian system works. However, in real-life situations, we do not use monochromatic light. As Brainard & Hanifin (2005)[16] pointed out, it is essential to understand the impact of polychromatic light to elucidate how organisms respond to light in practical applications.

Further studies have exposed humans to different light intensities, colour temperatures, and wavelengths to investigate the effects of these light factors. Experiments conducted at night or in the evening showed positive associations between the amount of light and stronger melatonin suppression (Revell et al., 2007; Adamsson et al., 2016; Knaier et al., 2017)[17] [18] [19]. However, some results indicated no significant impacts of light intensity on melatonin suppression when experiments were conducted in the early morning (Leichtfried et al., 2014)[20]. Furthermore, the effects of colour temperature (CCT) and wavelength on melatonin suppression have also been identified, with findings showing that melatonin suppression increases with higher CCT (Chellappa et al., 2011; Lu et al., 2016)[21] [22] and with increased 'blue light' as part of the spectrum (Revell et al., 2007; Danilenko & Sergeeva, 2015)[23] [24]. While blue light has been found to affect our circadian rhythms by delaying our bedtime and wake-up time (Münch et al., 2006)[25], the effect of CCT remains unclear (Lu et al., 2016)[22].

To summarize, there is evidence that light has non-visual impacts on human circadian rhythms and that hormone suppression is controlled by light stimuli reaching the retinal ganglion cells with melanopsin, which are sensitive to certain wavelengths of light. However, it should be noted that clear results regarding the impact of polychromatic light from existing light sources have been found only under the specific conditions of the aforementioned studies.

4.3 Alertness

Effects of light on alertness have been investigated using tools such as the Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990)[26], which is a self-report measure of sleepiness at a specific time of day, as well as electroencephalogram (EEG) tests that measure brain waves. Unlike its effects on circadian rhythms, the impact of light exposure timing and duration on alertness is still unclear, particularly when relying solely on self-reports of alertness (Xiao et al., 2021)[27]. However, effects of light intensity, CCT, wavelengths, and directionality have been identified.

Exposure to bright light increases alertness. Compared to lighting conditions of 100–400 lux, brighter lighting conditions (≥ 1 000 lux) at eye level have a positive effect on alertness during the day, as reported by research participants (Smolders et al., 2012; Leichtfried et al., 2015; Huiberts et al., 2017)[28] [20] [29] and on task performance, particularly in the morning (Smolders et al., 2012; Huiberts et al., 2017)[28] [29]. However, some studies (Huiberts et al., 2017; de Vries et al., 2018)[29] [30] found no effect of higher intensity on performance. Furthermore, participants reported that exposure to cooler light at 6 500 Kelvin enhanced alertness in the evening compared to warmer light at 2 500–3 000 Kelvin (Chellappa et al., 2011)[21], but not during normal office hours (Ru et al., 2019)[31]. Together, these findings suggest that the effects of CCT depend on the timing of exposure. Similarly, better performance in the evening was found among participants who were exposed to higher CCT, shorter wavelengths, and more blue light (Chellappa et al., 2011; Knaier et al., 2017; Rahman et al., 2017)[19 21 32].

In junior school classrooms, it was found that the direction of artificial light reflected from the walls and reaching the eye played an important role in affecting the children's school performance when daylight levels decreased (Govén et al., 2011)[33]. In high school classrooms with a daylight factor of 5% and the same CCT of 4 000 Kelvin for electric light sources, no difference in the students' performance was found between LED luminaires with no direct light on the work surface and fluorescent T5 luminaires with direct/indirect lighting, both having the same CCT (Gentile et al., 2018)[34]. Thus, we may assume that electric light sources have less impact when daylight conditions are good.

4.4 Mental health

The effect of light, particularly daylight, on mental health is well recognized through the differences in emotional status over the year in countries far from the equator, where the variations in day length are significant across different seasons. The short days of winter can lead to a clinical depression known as Seasonal Affective Disorder (SAD), which occurs at the same time every year. SAD is a serious psychiatric disorder that requires assistance from a qualified mental health professional. A milder form, called sub-syndromal SAD (sub-SAD), is a type of fatigue that also appears at the same time each year and occurs more frequently at latitudes farther from the equator. The symptoms include low activation levels, low well-being, low sociability, and, in some cases, sleep problems.

In an international study involving office workers from Sweden, the UK, Saudi Arabia, and Argentina (Küller et al., 2006)[35], self-reports indicated that there were no significant differences in SAD indicators (i.e., activation level, well-being, and sociability) over the year among those close to the equator. In contrast, in Sweden and the UK, these indicators declined from September until February and started to increase in April, with levels in June higher than those in Saudi Arabia and Argentina. Interestingly, participants far from the equator (Sweden and the UK) displayed better emotional status when experiencing a brighter work environment compared to their counterparts in less bright work environments. It should be noted that we do not have a physiological explanation for this. Currently, there is no accepted model for the interaction between light and emotional status, despite several studies showing similar patterns of differences in emotional status, chronobiologic markers, and sleep throughout the year in countries far from the equator (Adamsson et al., 2017; 2018)[36 37]. Circadian and seasonal rhythms of various hormones have also been studied in healthy and depressed individuals to investigate the possibility that abnormal circadian rhythms may cause seasonal variations in mood. There is some evidence supporting this idea, but the knowledge is not coherent enough to provide a clear biological explanation.

In a study conducted in a junior school (Govén et al., 2011)[33], it was found that daylight had an impact on mood among children aged 9 to 10 years. The children in the first-floor classrooms, which had a higher daylight factor (5%), reported more positive moods throughout the year compared to those in the ground-floor classrooms, which had a lower daylight factor (2%). Additionally, in highschool classrooms with a 5% daylight factor, the students' positive emotions were generally higher than their negative emotions during the day, while negative emotions peaked in the dark winter months and decreased in the spring (Gentile et al., 2018)[34]. The timing of light exposure appeared to impact moods as well. Exposure to bright light was found to increase positive emotions in the morning (Leichtfried et al., 2015)[20] and decrease them in the afternoon (Borisuit et al., 2015)[38]. While exposure to higher CCT light was found to enhance mood during daytime, warm light at low CCT is often considered to promote positive moods or emotions such as relaxation, calmness, and comfort (Xiao, Cai & Li, 2021)[27]. In relation to this, it can be assumed that individuals will become more relaxed when exposed to lower light levels. However, more studies are needed to obtain clearer results (Barkman et al., 2012; Sleggers et al., 2013)[39 40].

4.5 Conclusions

Today, we know more about the non-visual effects of light on humans. Specifically, our organisms are adapted to daylight, which differs from electric lighting in terms of intensity, spectral power distribution, and timing. These properties are important when installing electric lighting, and we need to be informed about all the details of electric light sources as well as issues related to temporal light modulation to create the best possible lighting environment. However, daylight has qualities that best suit humans, and we must prioritize using natural light as much as possible. Therefore, the availability of daylight in daily work and living environments, along with its benefits to our health and well-being, should always be considered.

Having enough daylight at the right time of the day is the easiest way to maintain healthy sleep-wake patterns, which may also influence our mental health. Studies have attempted to mimic daylight and have suggested positive effects on sleep quality, for example, by using higher lighting levels in the morning along with more light in the short-wavelength area, and lower lighting levels in the afternoon with longer wavelengths. There is also a suggestion that lower lighting levels can help us feel less tense and more relaxed. However, more studies are needed to provide clear evidence.

Last but not least, we should be especially careful when working in environments far from the equator, as people spend a lot of time indoors and face challenges regarding daylight exposure. There is a significant need for light to meet human needs during the dark winter months, as well as a need for darkness for sleeping during the bright summer months. Despite daylight being our primary light source, we also require electric lighting at certain times. The development of the new light source, LED, has provided greater opportunities to control light in terms of illuminance levels, colour temperatures, and spectral distribution. Achieving a good balance between the use of daylight and electric lighting, and viewing lighting as a complementary tool, is important for creating the most beneficial environment.

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CHAPTER 5

Photometry

NIKO GENTILE

'There are two ways of spreading light:
to be the candle or the mirror that reflects it.'
EDITH WHARTON

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Luminous flux (lumens), luminous intensity (candelas), solid angle (steradians), illuminance (lux), luminance (candelas per square meter), exitance or luminous emittance (lux), brightness, inverse square law, Lambert's cosine law, specular and diffuse reflection, transmission, mean room surface exitance (MRSE), mean indirect cubic illuminance (MICI).

5.1 Definitions and units

The word light usually refers to visible light, i.e. radiant energy visible to the human eye and responsible for sight or seeing. In physics, light is defined as electromagnetic radiation (EMR) within a certain part of the electromagnetic spectrum, i.e. between 380 and 780 nanometers (nm) according to CIE, and to which the human eye responds. In simpler terms, light is the part of the electromagnetic spectrum to which the human eye is sensitive. Light is just a tiny bit of the electromagnetic spectrum (Figure 5.1).

Measurements considering radiation emitted over the whole EMR spectrum is called *radiometry*. Radiometry is used, for example, in the study of solar energy. *Photometry*, instead, is concerned with the measurement of radiation as perceived by the human eye. The science of photometry takes root in the Renaissance, a period of great inquiry into the light phenomenon, but photometric definitions are newer. Photometry considers wavelengths from 380 to 780 nm – although other sources use the 380-740 nm or the 300-800 nm intervals. Within this range, the radiant power at each wavelength is weighted by a luminosity function that corresponds to the human brightness sensitivity at the different adaptation states (photopic, mesopic, or scotopic, see chapter 3). The relative spectral sensitivity curve of the human eye for a standard observer in photopic conditions is defined by the CIE in 1924 and it is commonly named CIE V(λ) curve[1] [2]. According to the CIE V(λ) curve, the relative luminous efficacy of the human eye is very low

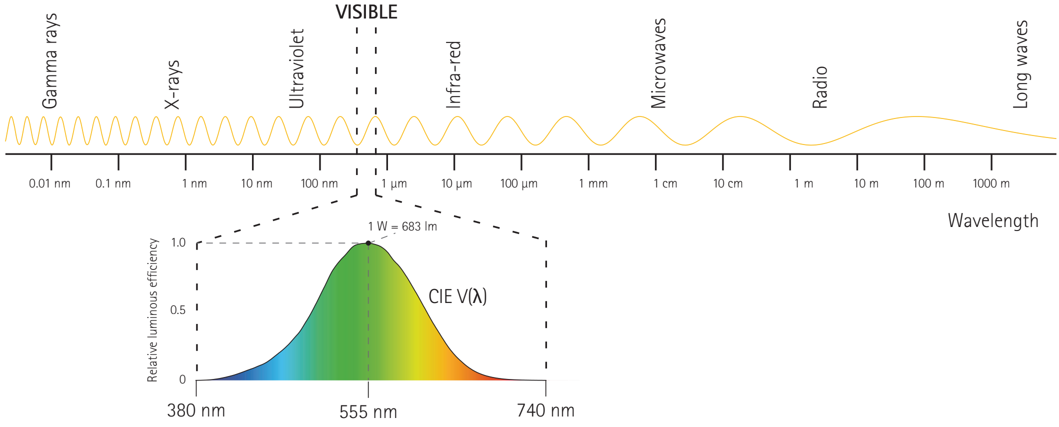

Figure 5.1 Light as part of the electromagnetic spectrum. Illustration: Niko Gentile.

for wavelengths below 380 nm or above 740 nm, which explains why different sources uses different ranges to define light.

Note that photometric theory does not address how humans *perceive* colours. The measured light can be monochromatic or a combination or continuum of *wavelengths*. As radiometry and photometry address similar questions, even their describing quantities are similar (Table 5.1).

5.1.1 Luminous flux

The luminous flux, or luminous power (Φ) measures the amount of light emitted in all directions and it is measured in lumens (lm) (Figure 5.2). It is analogous to the radiometric quantity called radiant flux (Φ_e), measured in Watts (W), (see Table 5.1), but it includes only the power emitted in the visible portion of the EMR, the latter being weighted for the relative spectral sensitivity of the human eye defined by the V(λ) curve. One (1) W of radiant flux at 555 nm corresponds to 683 lm of luminous flux (in photopic conditions). At this wavelength, the relative spectral sensitivity of the eye is maximum. In mathematical terms, this could be written as

$$\Phi_e = 683 \int_{380}^{780} \Phi_e(\lambda) V(\lambda) d\lambda \tag{5.1}$$

where $\Phi_e(\lambda)$ is the spectral radiant flux (measured in W/nm), while the other terms have been previously introduced. The luminous flux is commonly indicated, for example, in lamp packaging to describe the

Figure 5.2
Photometric quantities at a glance. Illustration: Niko Gentile. Adapted from Autodesk Knowledge Network.

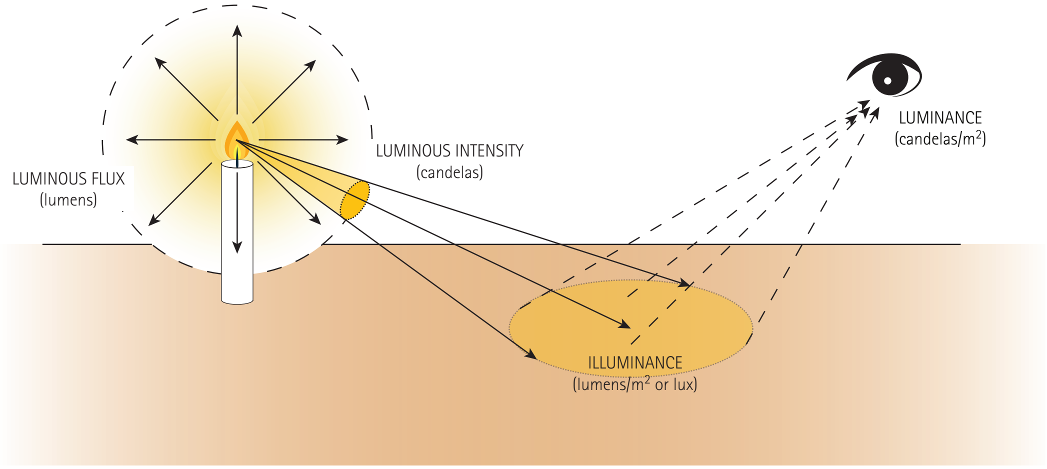

Table 5.1 Fundamental radiometric quantities and their photometric equivalents.

Radiometric Quantity			**Photometric Quantity**		
Quantity	**Symbol**	**Unit**	**Quantity**	**Symbol**	**Unit**
Radiant Flux	Φ_e	W	Luminous Flux	Φ	lm
Radiant Intensity	I_e	W/sr	Luminous Intensity	I	cd (lm/sr)
Irradiance	E_e	W/m^2	Illuminance (lux)	E	lux (lm/m^2)
Radiance	L_e	W/sr · m^2	Luminance	L	cd/m^2
Radiant Exitance	M_e	W/m^2	Luminous Exitance	M	lm/m^2

total luminous power emitted by a bulb. Common home light bulbs provide from 200 to 1 000 lumens. While the luminous flux is useful to compare the total luminous output of a light source, this quantity does not provide information about the directionality of light.

5.1.2 Luminous intensity

The luminous intensity (*I*) is the luminous flux emitted by a point source in a given direction. The direction is expressed by a solid angle, measured in steradian (sr)*. Therefore, the luminous intensity is measured in lumens per solid angle, also called candelas (cd = lm/sr). The candela is the fundamental unit for photometry and one of the seven base units in the SI system.

Historically, the name 'candela' derives from the word 'candle'. Indeed, an ordinary wax candle emits light with an intensity of approximately 1 cd in a given direction. Such a definition is, of course, too ambiguous for scientific purposes. Therefore, the candela has been provided with an operational definition:

> '*The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.*'[3]

However, a different formulation for SI units has been introduced in 2019. For an isotropic light source, which is a source emitting light

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* Steradian: the steradian (sr) is the SI unit of solid angles. Given a unit sphere with radius *r*, a surface portion of area A = r^2 will subtend one steradian. A sphere subtends 4π steradians.

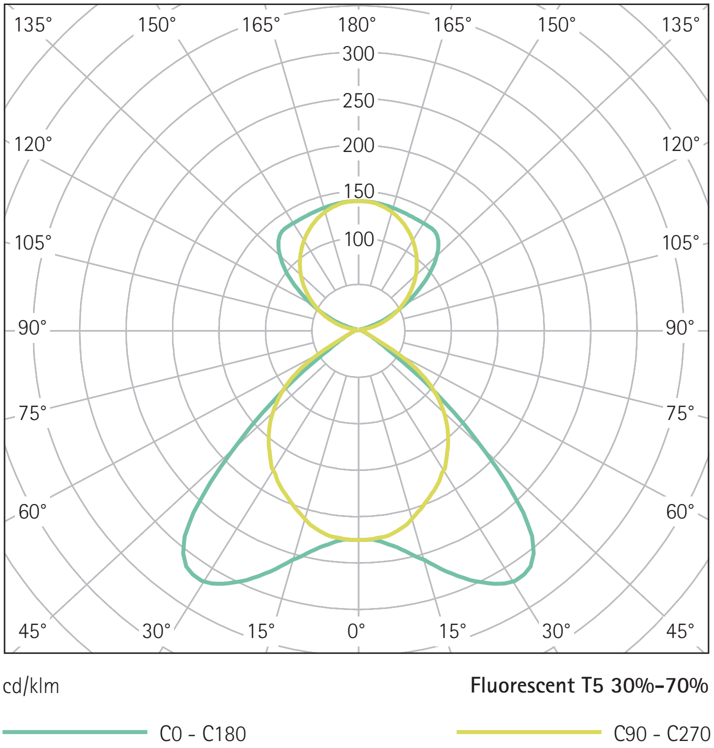


Figure 5.3
Polar diagram of a fluorescent T5 light fixture with light flux directed 30% upwards and 70% downwards. Note that the luminous intensity is normalized (cd/klm). Illustration: Niko Gentile.

equally in all directions, the luminous flux (in lumens) is related to the luminous intensity (in candelas) by the following formula:

$$\Phi = I \cdot 4\pi \tag{5.2}$$

where Φ is the total luminous flux in lumens, I is the luminous intensity in candelas, and 4π represents the solid angle (in steradians) of a full sphere, because an isotropic source emits light uniformly in all directions, covering a solid angle of 4π steradians. If this source uniformly radiates 1 candela in all directions, its total luminous flux will be $1 \text{ cd} \times 4\pi \text{ sr} = 4\pi \text{ cd} \cdot \text{sr} \approx 12.57$ lumens.

The luminous intensity provides information about light directionality of light sources. For example, light fixtures are provided with light distribution curves (or polar diagrams), which are luminous intensity distribution curves (Figure 5.3).

5.1.3 Illuminance

Both luminous flux and luminous intensity refer to light sources, and they have associated units which refer to units of surface. The luminous flux is associated with illuminance, which is the amount of luminous flux falling on a unit of surface. Illuminance (E) is measured in lux where:

$$1\ \text{lux} = 1\ \text{lm/m}^2 \tag{5.3}$$

Illuminance depends on the luminous flux of the light source and its reciprocal position with the investigated surface. Imagine holding a torch and projecting its circular light perpendicularly on a wall; it will provide a certain density of luminous flux falling on a definite unit of surface. If the distance between the torch and the wall is increased, or if the torch is tilted, the density of light on the same unit of surface will be lower, therefore the illuminance will be lower.

Illuminance is one of the fundamental units in lighting design, as it expresses whether an area is well illuminated for performing a certain activity. For example, it is a general recommendation to provide 500 lux horizontally on an office desk, 300 lux in the whole office, and 150 lux in corridors[4].

Typical values of outdoor illuminance vary from decimals of lux for nights with full moon, to about 120 000 lux for bright clear sky days.

Illuminance does not provide much information about the perception of surfaces, since it focuses on light delivered to the surfaces but not on the light reflected from that surface. For example, the same light source kept in the same position will deliver the same illuminance on the same desk, independently from the desk being painted white or black.

5.1.4 Luminance

Luminance (L) measures the luminous intensity emitted, transmitted, or reflected by a unit of projected surfaces, and it is measured in cd/m^2. Therefore, luminance is associated with luminous intensity.

While illuminance measures the light falling on a surface from all directions, luminance measures the light leaving a surface towards a specific direction. This implies that luminance better describes how the human eye perceives the brightness of surfaces, although brightness cannot be simply related to luminance[5].

The reflectance of surface (ρ) affects the relation between illuminance and luminance, and such relation can be very complex. However, for a perfectly diffusive (or *Lambertian*) surface – that is a surface emitting equal luminance in all directions of the half sphere over the surface – the relation is simple:

$$L = \frac{E \cdot \rho}{\pi} \tag{5.4}$$

The luminance values in a room can vary much more than the illuminance values. For example, a luminaire is much brighter than the surrounding ceiling; various parts of a patterned wallpaper will reflect different amounts of light, etc.[6]. Luminance patterns should make sense in relation to the architectural, interior and lighting design of a space, i.e. they should reinforce the visual information in a scene. Osterhaus (2009)[7] emphasized that '*confusing light patterns can result in loss of visual and mental harmony and lead to problems with spatial orientation*'.

For years, existing lighting codes and standards have relied mainly on illuminance levels on horizontal surfaces, probably because it is easier to measure. At the same time, research in lighting design moved towards luminance-based metrics. Luminance is today included in standards, despite illuminance still being much more used in common practice. The advent of cheap devices for luminance-based techniques, e.g. High-Dynamic Range imaging, may pave the way to new luminance-based lighting recommendations.

5.1.5 Luminous exitance

Luminous exitance (M), previously named emittance, is the total luminous flux leaving a surface in all directions, and it is measured in lux or lm/m^2.

The exitance of a diffuse Lambertian surface is related to the luminance of the same surface:

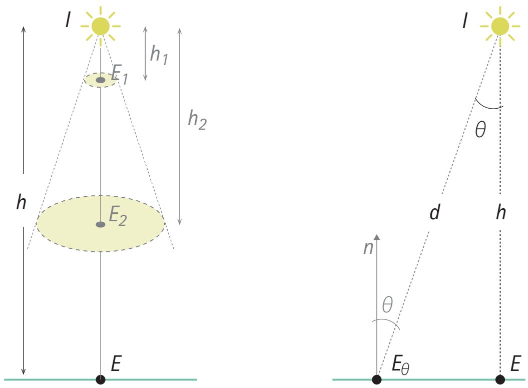
$$M = L \cdot \rho \tag{5.5}$$

Exitance is analogous to illuminance, although it measures the luminous flux *leaving* a surface, rather than *falling* on it. In comparison to luminance, the information about light directionality is lost. It is nevertheless undisputable that even exitance could provide a general understanding about the perceived brightness or perceived adequacy of illumination in a room[8][9].

Exitance is recently gaining a bigger role in the lighting design world and lighting specialists are trying to introduce it in lighting standards. The idea is to change the paradigm from which a luminous environment can be described by the light incident on a surface (illuminance-based), by rather considering the light reaching the eye (exitance-based)[9]. For example, Cuttle (2010)[9] proposed to use the concept of exitance to define the Mean Room Surface Exitance (MSRE). One of the advantages of using MSRE is that the metric is room based and independent of a defined visual task[10], a common situation in real spaces. However, MSRE can be difficult to measure in geometrically complex environments, where not all surfaces are visible from the measuring point[11]. Raynham et al. (2019)[12] introduced the concept of Mean Indirect Cubic Illuminance (MICI), that is the average of the six indirect illuminances falling on the six faces of a cube placed at the measuring point. Both MSRE and MICI correlate well with the perceived adequacy of illumination, with MICI having the advantage of being easier to measure even for complex real geometries. While current lighting standards are still heavily based on maintained horizontal illuminance for a visual task, lighting design is expected to shift towards an increased use of room-based metrics independent of a visual task, such as MSRE and MICI.

5.1.6 Brightness

Brightness is described as the subjective perception of luminance, which depends largely on the adaptation state of the viewer. Being



Inverse square law

Lambert's cosine law

Figure 5.4 Fundamental laws of illumination for a point light source. Illustration: Niko Gentile.

subjective, brightness does not have an exact mathematical definition. Studies attempted to propose robust brightness equations based on existing photometric quantities, but there is no consensus. It seems that background luminance is one of the most important predictors of brightness[13]. Although luminance is a major determinant of perceived brightness, it is not the only factor affecting brightness. For example, research has shown that different perceived brightness levels may be linked to different light spectra[14], or to different ambient lighting distributions[15].

5.2 Laws of illumination

5.2.1 Inverse square law

There exists a relation between the distance of an isotropic point source of luminous intensity I and the illuminance E falling on a surface, known with the name of *inverse square law*. The inverse square law states that the illuminance E varies in inverse proportion to the square of the distance h from the isotropic point light source delivering an intensity I (Figure 5.4).

$$E = \frac{I}{h^2} \tag{5.6}$$

For example, an isotropic point light source emitting 160 cd will provide 40 lux on a plane positioned at 2 m. If the illuminance on a generic plane is known, the inverse square law can be written as

$$E_1 h_1^2 = E_2 h_2^2 \tag{5.7}$$

where the subscripts indicate the two points where the illuminance is measured (Figure 5.4). If a point source delivers $E1$ = 1 000 lux at $h1$ = 1 m distance, it will deliver 40 lux at 5 m distance. This means that the illumination is reduced to a quarter when the distance is doubled.

For practical applications, a rule-of-thumb – which has however been recently criticized[16] - suggests that the inverse square law could be applied to real light sources if the largest dimension of the real light source is five times smaller than the distance of observation.

Although illuminance will always decrease with the distance from the light source, the inverse square law does not apply to focused light sources – like a laser beam –, sources parallel to one direction – like

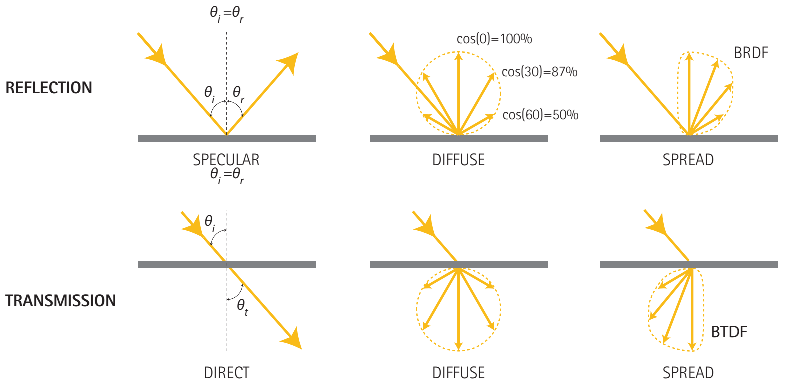


Figure 5.5
Specular, diffuse and spread reflection/transmission of a light beam. Illustration: Niko Gentile.

continuous row of fluorescent tubes – or spread source – like LED ceiling panels.

5.2.2 Lambert's cosine law

The illuminance will also vary with the incidence angle of light beam with respect to surface (Figure 5.4). The Lambert's cosine law states that the illuminance delivered on a surface by the isotropic light source varies with a factor of $cos(\theta)$, where θ is the angle between the direction of the incident light and the normal to the surface.

$$E_\theta = E \cdot \cos\theta \tag{5.8}$$

The Lambert's cosine law can also be written as a function of isotropic point light source intensity and the distance d from the light source (Figure 5.4).

$$E_\theta = \frac{I}{d^2} \cdot \cos\theta \tag{5.9}$$

Geometrically, the distance $d = h / cos(\theta)$ (Figure 5.4), therefore:

$$E_\theta = \frac{I}{h^2} \cdot \cos^3\theta \tag{5.10}$$

5.3 Reflection and transmission

Light interacts with surfaces. The interactions concerned in lighting design are reflection, for opaque surfaces, and transmission, for clear surfaces. Transparent and translucent surfaces like shading devices, but also glazing, may both reflect and transmit light.

Depending on the surface characteristics, the reflection or transmission can generally be specular, diffuse or spread (Figure 5.5).

In specular reflection, the angle of incidence θ_i and the angle of reflection θ_r of the light beam are identical. The relation $\theta_i = \theta_r$ takes the name of law of reflection. Mirrors are specular reflectors. The equivalent transmission mechanism is called direct transmission.

In diffuse reflection and transmission, the reflected (or transmitted) light beam is perfectly diffused and thus follows the Lambertian cosine law. In a diffuse surface, there is no direct component of reflected light beam.

A situation in between is represented by spread reflection and transmission. In this case, the light distribution is complex. Bidirectional Scattering Distribution Functions (BSDF) are used to describe the behaviour of the surface. BSDF is the overarching name for Bidirectional Reflectance Distribution Functions (BRDF) and Bidirectional Transmittance Distribution Functions (BTDF). BSDF potential is not yet fully exploited. BSDF are, for example, critical for assessing glare through shadings. Currently, efforts are being made to standardize BSDFs, eventually prompting their use in ordinary daylighting and lighting design.

Finally, not all wavelengths are equally reflected or transmitted by a surface. The spectral behaviour of surfaces in the visible spectrum is gaining importance in recent years with the increasing interest in circadian lighting design.

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CHAPTER 6

Colour

NIKO GENTILE

‘A painter should begin every canvas with a wash of black, because all things in nature are dark except where exposed by the light.’

LEONARDO DA VINCI

‘It seems obvious that colours vary according to lights, because when any colour is placed in the shade, it appears to be different from the same colour which is located in light. Shade makes colour dark, whereas light makes colour bright where it strikes.’

LEON BATTISTA ALBERTI

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Colour matching functions, CIE chromaticity diagrams, black-body, Planckian locus, Correlated Colour Temperature (CCT), Duv, Colour Rendering Index (CRI Ra), Colour ordering systems, hue, chroma, value, Munsell, Natural Colour System (NCS).

6.1 Colour perception

Two light sources delivering the same luminance may provide very different light spectrums, yet they will be identical in a strict photometric sense. Photometry does not account for colours, and the science measuring colours is called *colorimetry*[1].

Surfaces are not inherently coloured. The colour perception is indeed a complex phenomenon involving three main actors:

1. a light source emitting light at different wavelengths,
2. an object reflecting some of the incident wavelengths emitted by the light source, and
3. an observer, whose eyes and brain process the reflected wavelengths.

The spectral components of the light emitted by the light source contribute to the colour appearance of the light source. The chart in Figure 6.1 shows the relative Spectral Power Distribution (SPD) of two light sources: the CIE standard illuminant D65[2], i.e. a standardized daylight spectrum, and a hypothetical green-yellow narrow band light. The spectral radiant flux of the daylight is emitted at any wavelength (λ) of the visible range and the resulting light appears whitish. The spectral radiant flux of the hypothetical light source in Figure 6.1 is emitted only at the wavelengths corresponding to the green-yellow part of the visible spectrum, and the resulting light appears greenish-yellowish.

As second step, when hitting an object, part of the incident light is absorbed, and part is reflected. The reflective characteristics of the object, combined with the type of incident light, determines the colour of the object. An object illuminated by daylight as in Figure 6.1 shows all its reflected colours, while it would rather appear greenish-yellowish if illuminated by the hypothetical light source. If the incident light does not comprise any of the wavelengths that are reflected by the object, the object will appear greyish. For example, an object that appears pure blue under daylight, will rather appear greyish when illuminated by the hypothetical light source in Figure 6.1.

However, it is not completely correct to say that the object will certainly appear greenish-yellowish or greyish to everybody. The colour perception, indeed, is not deterministic and it depends on the observer's visual system and cognition. This last step is the most complex to deal with.

This chapter discusses the CIE colorimetry system and other colour ordering systems. The CIE colorimetry system tries to quantify colours

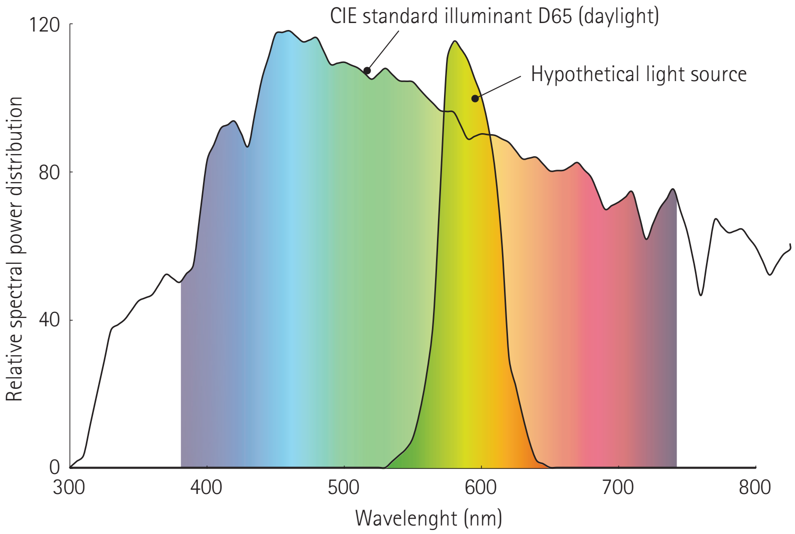

Figure 6.1
Relative spectral power distribution for two light sources. Source of illustration and underlying data: Niko Gentile.

and it is mainly used to standardize the colour appearance of light sources. Other colour ordering systems are based on more subjective and qualitative clues, and they are easier to communicate. Among other applications, they are widely used to identify surface colours in architecture and construction.

6.2 CIE Colorimetry system

The CIE colorimetry system is a colour matching system. The experimental methodology of colour matching is based on Grassman's law of colour science[3]. In the original colour matching experiments, individuals were exposed to three narrow band light sources coloured in red (R), green (G), and blue (B), which produced a certain colour impression. A fourth light source generated a fourth colour impression. The RGB sources were tuned until the observer found that the colour impression from the RGB combination was matching that from the fourth light source. The experiments, which was carried out on a large number of observers[4 5], led to the modelling of three colour matching functions (Figure 6.2). The three functions represent the human eye sensitivity of a standard observer in photometric conditions to three primary colours for a 2° visual field.

The functions peak in the blue, green and red wavelengths ranges. However, the CIE colour matching functions do not strictly represent the actual physiological response of the cones to different wavelengths. Indeed, the functions were derived from the reported response of the individuals taking part in the experiments, implying that the colour stimulus was mediated by cognitive processes.

The three colour matching functions are used as weighting factors for the spectral radiant flux of a light source. The integration of the spectral radiant flux $\Phi_e(\lambda)$ (in W/nm) for the colour matching functions in the visible range determines the tristimulus values X, Y and Z, which represent the degree of stimulation required to match the colour of the spectral radiant flux.

$$X = \int_{380}^{740} \Phi_e\,(\lambda)\bar{x}(\lambda)\;d\lambda \tag{6.1}$$

$$Y = \int_{380}^{740} \Phi_e\,(\lambda)\bar{y}(\lambda)\;d\lambda \tag{6.2}$$

$$Z = \int_{380}^{740} \Phi_e\,(\lambda)\bar{z}(\lambda)\;d\lambda \tag{6.3}$$

The shown integration procedure is an analogue to the conversion from radiant flux to luminous flux shown in the photometry chapter. In this case, however, there are three different weighting functions of the human eye sensitivity, rather than the singular monochromatic response described by CIE V(λ).

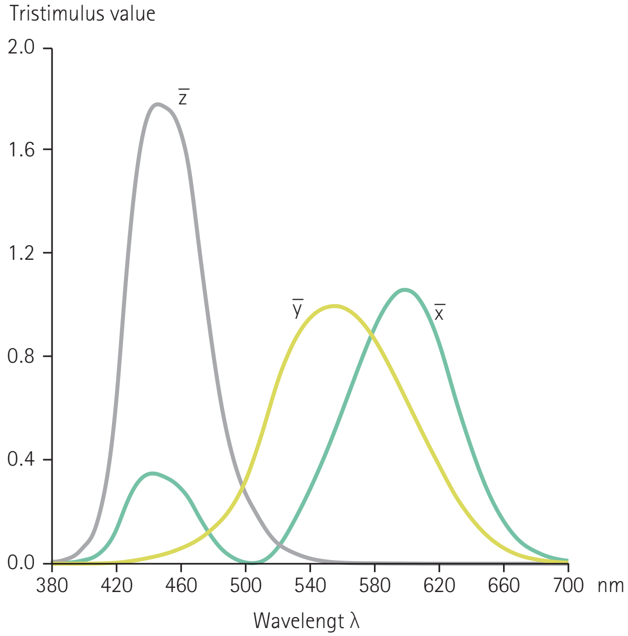

Figure 6.2 Colour matching functions for the CIE 1931 standard observer (2°). Illustration by Niko Gentile, underlying data from CIE.

The tristimulus values X, Y and Z can be normalized, according to

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} \tag{6.4}$$

giving the *chromaticity coordinates* x, y and z. Just two of these coordinates are enough to describe the chromaticity of the light, since their sum is $x + y + z = 1$ (the information being lost is the luminance, or brightness, of the light). A two-dimensional chart is drawn by using the coordinates x and y. This is an arbitrary decision made by the CIE, and it leads to the CIE 1931 chromaticity diagram[6], Figure 6.3. All colours can be characterized in terms of their location in the chromaticity diagram.

The CIE 1931 chromaticity diagram can be read as follows. The curved boundary of the diagram, called 'spectrum locus', features the pure wavelengths. These are the coordinates of monochromatic light sources, like lasers. The straight part in the bottom of the diagram is called 'line of purples', as it contains the most saturated purples. In the central-lower part of the diagram, the 'equal energy point', or colourless point, is found. Here $(x, y, z) = (1/3, 1/3, 1/3)$ and corresponds to a constant

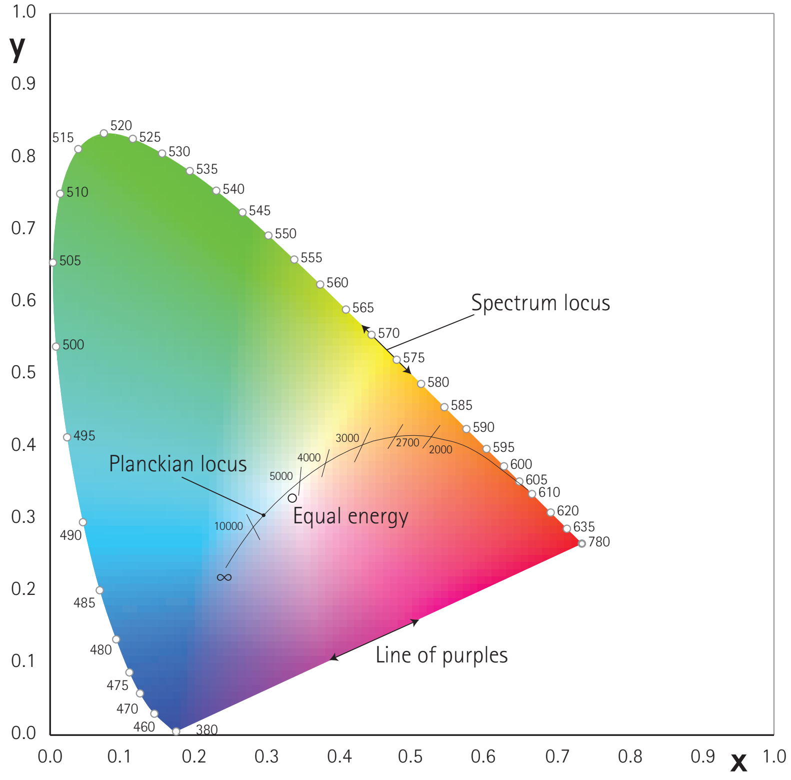

Figure 6.3
CIE 1931 chromaticity diagram, based on CIE (1931) data. Illustration: Niko Gentile, underlying data CIE.

spectral distribution across the visible spectrum, hence the name. The curved black line right above the equal energy point is called 'Planckian locus'. The Planckian locus represents the colours assumed by a black body at different temperatures. A certain colour can be produced by a combination of different wavelengths. Any point in the curve represents a single colour, but there are many combinations of wavelengths producing that colour.

The CIE 1931 chromaticity diagram has some limitations. One is that the chart is not perceptually uniform, namely some colours, like greens, occupy a bigger area of the chart. This limitation was overcome in the following years, with the introduction of newer colour spaces based on CIE 1931. The perceptual non-uniformity of CIE 1931 was partially solved by linear transformation of the x and y coordinates. This resulted in two Uniform Chromaticity Scales (UCS): the CIE 1960 UCS and the CIE 1976 UCS diagrams, both based on original intuition by MacAdam[7]. The transformed *x* and *y* coordinates take the name of *u* and *v* in the CIE 1960 UCS, and *u'* and *v'* in the CIE 1976 UCS. They are related to *x* and *y* in CIE 1931 as follow:

$$\text{CIE 1960 UCS} > \qquad u = \frac{4x}{12y - 2x + 3}; \qquad v = \frac{6y}{12y - 2x + 3} \tag{6.5}$$

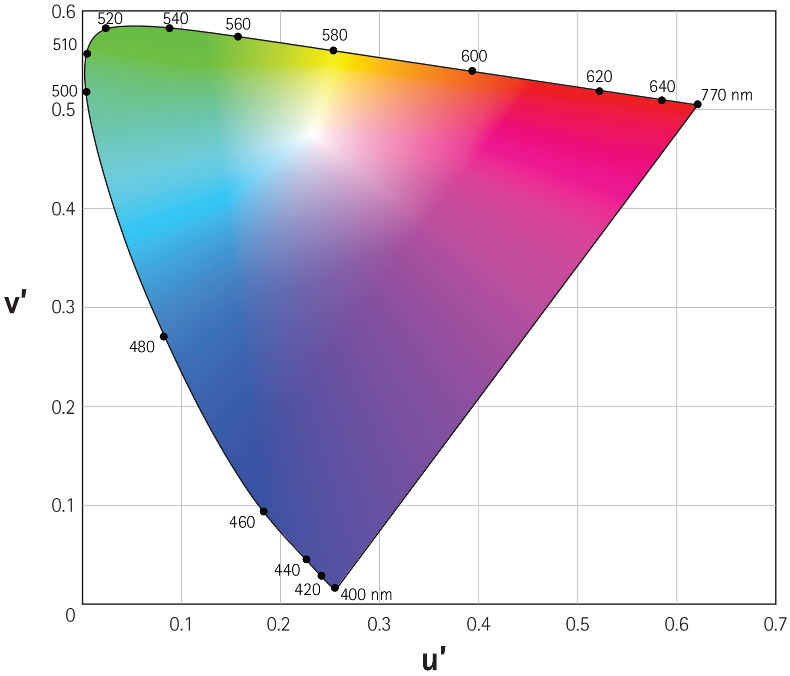

Figure 6.4
CIE 1976 Uniform Chromaticity Space, based on CIE 1976 data. Illustration: Niko Gentile, underlying data CIE.

$$\text{CIE 1976 UCS >} \qquad u' = \frac{4x}{-2x + 12y + 3}; \quad v' = \frac{9y}{-2x + 12y + 3} \tag{6.6}$$

Another important limitation of CIE 1931 and of both CIE UCS spaces is that two coordinates determine the hue colour and its saturation, but nothing is said about brightness, since this is the information lost in the normalization. While this is enough to describe the colour of a light source, a third dimension specifying brightness is needed when evaluating colour of surfaces.

This was introduced by the CIE with a new coordinate L*. The resulting three-dimensional spaces were called: CIELUV, based on CIE UCS 1976 (L*u*v* represents three coordinates in the new diagram), and CIELAB, based on CIE 1931. Both CIELUV and CIELAB are therefore three-dimensional colour spaces, and they are today of large practical use in colorimetry.

6.2.1 Correlated Colour Temperature

The Correlated Colour Temperature (CCT) is a single and handy index to describe the colour of a white light source. It has been said that a black body assumes different colours at different temperatures, and these are described by the Planckian locus. Therefore, the colour of a black body could be described by one variable only - its temperature -, instead of two, e.g. $\{u,v\}$ in the CIE 1960 UCS. The CCT is the temperature in Kelvin (K) assumed by a black body having the same colour of the inspected light source. A traditional incandescent bulb is a good real-life approximation of a black body. When the bulb is dimmed down, the filament cools down and the light appears more yellowish (lower CCT).

For temperatures ranging from 2 700 K to about 17 000 K, the colour of the black body approaches white or bluish white. Since most of the commercial light sources for ordinary applications are titular white, their colour can be expressed through the CCT. Light sources of CCT around 2 700 K appear yellowish, and they are labelled warm. The above-mentioned incandescent bulb is an example of warm light source with 2 000–3 000 K. Above 4 000 K, the light appearance is blueish; these light sources are usually labelled cold white. For office applications, generally CCT 3 000 K to 4 000 K are preferred, and a clear blue sky has a CCT of about 10 000 K.

The CIE 1960 UCS is used in order to calculate the CCT of a light source (Figure 6.5). The word “correlated” indicates that light sources colour coordinates might be close to, but not exactly on the Planckian

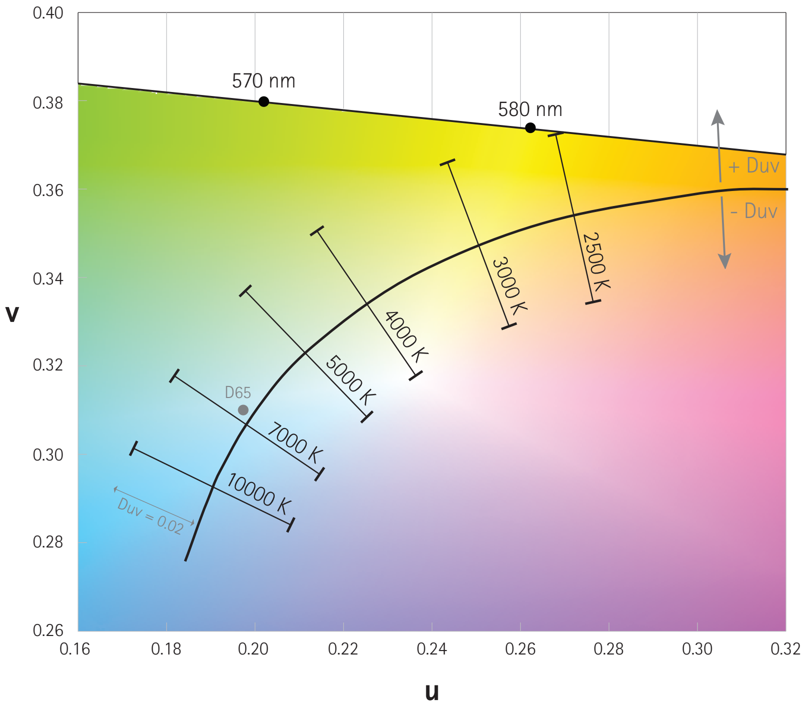

Figure 6.5
The Planckian locus on a detail of the CIE 1960 UCS, based on CIE 1960 data. The ISO-CCT in the figure extends to Duv ± 0.02. The point D65 represents the chromaticity coordinates for the standard illuminant D65, representing daylight with CCT = 6 504 K. Illustration: Niko Gentile, underlying data CIE.

locus, along any of the iso-CCTs which in the CIE 1960 UCS are perpendicular to the Planckian locus.

If the light source colour lies far away from the Planckian locus, the light cannot be considered nominally white, but coloured. In this case, the CCT does not apply. The distance from the Planckian locus for nominally white light source can be measured by means of the Duv, which stands for 'Delta u,v'. Positive Duv lies above the Planckian locus, while negative Duv lies below. Recommendations suggest using a limit of Duv ± 0.005.

CCT and Duv together define univocally the colour of a light source in the CIE 1960 UCS chromaticity diagram. While CCT is always mentioned in the lamp packaging, Duv is not usually reported in commercial titularly white light sources, since it is assumed that the colour point lies close enough to the Planckian locus.

It should be noted that the CCT works well if the light source has a continuous spectrum, similar to the black body; incandescent light sources fall into this category. Modern light sources, like fluorescent lamps or LED, may have very different spectral power distribution (SPD). Different SPDs may result in identical CCT, yet the actual colour of the light sources may be slightly different. Nevertheless, CCT is a consolidated standard on the market, and it is easy to understand for consumers, so it continues to be used for all types of titular white light sources.

In lighting design, it is a common belief that high illuminances link to higher preferred CCT[8], although this has been largely criticized[9]. Following research suggested that, rather than CCT, the SPD of the light source might better relate to preferred illuminance levels[10].

6.2.2 Colour Rendering Index (CRI Ra)

The Colour Rendering Index (CRI) provides a general advice on the colour rendering properties of a light source. A surface colour appears different if illuminated by different light sources. If the surface includes different colours, the colour rendering is generally better if the illuminating source comprises all wavelengths in the spectrum.

To define the CRI, the CIE proposed a palette consisting of 14 colours, ranging from pastel ones (1–8), to saturated colours (9–12), and earth tones (13–14)[11] (Figure 6.6). The palette is illuminated under incandescent light source for CCT < 5 000 K or under daylight for CCT > 5 000 K. Incandescent and daylight are chosen as reference light sources, as they have a continuous visible emission spectrum. It is arbitrary chosen that the reference light source renders 100% correctly the colours, that is CRI = 100.

The CRI of a light source can be calculated by comparing the colour generated for each one of the 14 colours in the palette against the respective colour generated by the reference source; in this case it is given for special or particular CRI for that specific colour.

The average of special CRIs for the first eight pastel colours in the palette (R1–R8) is called general CRI, often indicated with Ra. The general CRI or Ra is the one reported, for example, on lamp packaging. The supplemental six colours provide additional rendering information, but they are not included in the Ra. Incandescent and halogen lamps, as well as daylight, have CRI = 100 by definition. Other generic light sources for indoor applications, like fluorescent lights and LEDs, have

Figure 6.6
Colour palette for the CRI. Please note that the appearance of the colour on this book is purely indicative. Illustration: Niko Gentile.

CRI ≈ 70–95. Special LEDs may have CRI > 98. Outdoor lighting, such as the high-pressure sodium defining the yellowish appearance of cities at night, has CRI ≈ 20 since it renders fairly well only some yellow shades. High CRI is preferable when a wide range of colours must be enhanced, for example in clothing stores, where clothing colours change with seasons and trends. For office lighting, CRI > 80 is to be preferred. Indeed, light sources for indoor applications with CRI lower than 80 are generally not allowed in markets. For some special applications, say grocery stores, a lighting designer may prefer to focus on something else rather than CRI. For example, the designer may decide to use light with high red spectral components to enhance meat colour, or green to enhance vegetable colour.

The CRI is commonly used in lighting science. However, CRI has some limitations. For example, since there are two reference sources, the general CRI at low or high CCT is not really the same thing. The choice of reference may be problematic too. For example, at extreme CCTs, like 2000 K, the reference source makes colours appear reddish, yet it will be rated with CRI = 100. In addition, two light sources with the same general CRI may render colour differently, since it is an average over eight colours. The use of a limited colour palette itself is a constraint, since it should theoretically include all the possible colours. In particular, the eight pastel colours for Ra do not include any saturated colour. This may be particularly problematic with newer light sources like RGB LEDs, where the spectral distribution is characterized by peaks at specific wavelengths. In such case, the rendering of pastel colours may still be high, but that of the saturated ones may not be[12]. In addition, among other limitations[13], the CRI does not predict well how *natural* the colours appear[14].

6.3 Colour ordering systems

While the two-dimensional CIE colorimetric systems are very useful to measure colours of light sources, they cannot describe the colour of surfaces.

The first step to communicate colours is to organize them by qualities. This process generates a colour ordering systems. A number of colour ordering systems are nowadays used to define, for example, colour of materials and paints.

Attempts to organize colours date far back in time. Already around 330 BC, Aristotle proposed a one-dimensional colour ordering system based on their hues. He placed five chromatic colours on a line which spaced from white to black based on their darkness. On such chromatic line, the hue white was followed by the yellow, red, purple, green blue and, eventually, black.

However, it was soon clear that hue is not sufficient to describe a colour. As mentioned, colours rather requires three qualities (or dimensions) to be identified, these being:

- hue, that is what we commonly define "colour" (e.g. red, green, etc.),
- chroma or saturation, indicating the pureness of a colour, and
- value, which is related to the brightness of the colour and spans from black to white (Figure 6.7), or analogous qualities.

Munsell is one of the most widespread colour ordering systems. Colours in Munsell chart are defined for observers with normal vision, under daylight with grey or white background. The colour is communicated though an alphanumeric code that lists hue, value, and chroma. For example:

5YR 6/10

indicates a colour with equal mix (5, i.e. 50%) of hue yellow and red (YR), a value slightly towards the white (6), and the chroma is 10. The result is a light brown colour.

The Natural Colour System (NCS) is another well-known proprietary colour ordering system. The NCS was developed in Sweden[15] [16] [17], and it is the standard system in countries like Sweden and Norway. The NCS is based on the colour opponency theory[18] [19], which defines six psychological primary colours: white, black, red, yellow, green and blue. The choice of the six primary colours is based on how the brain processes the colour stimuli, therefore the name "natural". The colours in NCS are communicated in terms of darkness (or nuance, analogues to the value), saturation, and the percent mix of two psychological primaries. For example:

NCS 0510-G70Y

describes a light colour (5% darkness), little saturated (10% saturation), which is formed mixing 70% of yellow with 30% of green. The result is a very light cream colour.

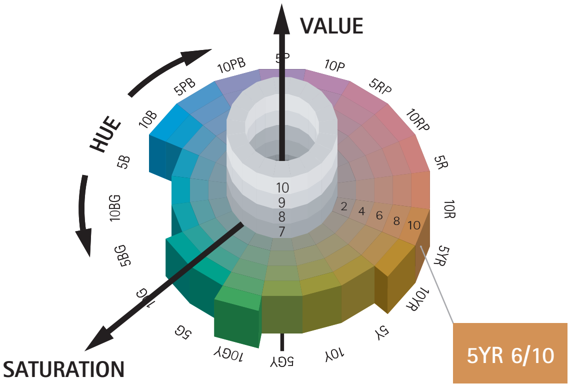

Figure 6.7
The Munsell three dimensional colour space. Illustration: Niko Gentile.

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CHAPTER 7

Fundamentals of daylighting

MARIE-CLAUDE DUBOIS

'We were born of light. The seasons are felt through light. We only know the world as it is evoked by light ... to me natural light is the only light, because it has mood – it provides a ground of common agreement for man – it puts us in touch with the eternal. Natural light is the only light that makes architecture architecture.'

LOUIS I. KAHN, ARCHITECT

'Daylight is a gift of nature. As civilised man learns to use artificial light sources which free him from total dependence on daylight, he also learns to appreciate the value of daylight and becomes aware of its special advantages'.

RALPH GALBRAITH HOPKINSON, 1966

'When the sun is covered by clouds, objects are less conspicuous, because there is little difference between the light and shade of the trees and the buildings being illuminated by the brightness of the atmosphere which surrounds the objects in such a way that the shadows are few, and these few fade away so that their outline is lost in haze'.

LEONARDO DA VINCI

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Sunlight, direct daylight, diffuse daylight, skylight, reflected light, circumsolar region, solar constant, zenith, turbidity, radiation, electromagnetic spectrum, ultraviolet radiation, visible radiation, near infrared radiation, far infrared radiation, declination, overcast sky, clear sky, intermediate sky, Ångström turbidity, Rayleigh scattering, standard sky models, CIE standard overcast sky, isotropic, CIE standard clear sky, uniform sky, circumsolar flare, CIE standard general sky, Perez all weather sky model, sky brightness, sky clearness, diffuse horizontal irradiance, direct normal irradiance, daylight metrics, static daylight metrics, dynamic daylight metrics, Climate-Based Daylight Modelling (CBDM), Daylight Glare Probability (DGP), Daylight Factor (DF), Average Daylight Factor (ADF), Median Daylight Factor (DF_{median}), Point Daylight Factor (DF_p), uniformity ratio (UR, Uo), Vertical Sky Component (VSC), Vertical Daylight Factor (VDF), Daylight Autonomy (DA), Continuous Daylight Autonomy (CDA), Maximum Daylight Autonomy (MDA), lighting dependency (LD), Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), annual sunlight exposure (ASE), annual daylight glare probability (DGPa).

This chapter starts by presenting and discussing the three main daylight sources: the sun, the sky, and the ground. Secondly, key concepts regarding how daylight sources are represented mathematically by standard sky models are discussed. Finally, this chapter introduces the concept of daylight performance metrics and discusses the most popular static and dynamic metrics used in practice.

7.1 Daylight sources

There are three essential components of daylight to consider when designing buildings, see Figure 7.1:

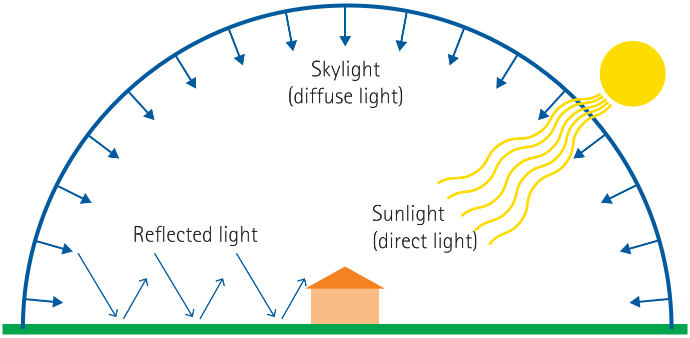

Figure 7.1
Direct, diffuse and ground reflected solar radiation.

7.1.1 Sunlight or direct light

The ultimate source of all daylight is the sun. It is by far the most important source of energy for all life forms on Earth. 'Almost all known physical and biological cycles in the Earth system are driven by solar radiation reaching the Earth'[1]. Solar radiation creates photosynthesis; it provides free daylight to humans and animals and keeps the Earth warm. Without solar radiation, the temperature on Earth would be below freezing. Solar radiation reaching a site without being scattered within the Earth's atmosphere is called *direct radiation* or simply *sunlight*.

The sun is located at approximately 150 million kilometers away from the Earth. It has a diameter of about 1.3 million kilometers[2]. The solar disk is only about 0.5 degrees in width as seen from the Earth, and can therefore be reasonably represented mathematically as an infinitely distant point source producing a beam of light with parallel rays. When viewed from the Earth, the solar disk is surrounded by a bright area due to scattering of light in the atmosphere called the *circumsolar region*.

The sun radiates an amount of power per unit area referred to as the *solar constant*, which is equal to approximately 1366 W/m^2 (with a measurement uncertainty of ±3 W/m^2) at a distance of one astronomical unit (AU)[*]. Sunlight is greatly reduced when passing through the atmosphere, so that the solar power arriving at the Earth's surface is close to 1 000 W/m^2 under clear sky conditions with the sun at the zenith (opposite of nadir). However, this value depends on atmospheric turbidity (cloudiness or haziness) and latitude. As the latitude increases, the sun's rays must travel larger distances through the Earth's atmosphere and a higher fraction of solar radiation is absorbed and/or scattered by atmospheric gases. The annual solar radiation in Lund, Sweden (lat. 57.7°N) is around 975 kWh/m^2 while it is around 775 kWh/m^2 in Kiruna (lat. 67.8°N) in the north of Sweden[3]. These values are low compared to annual solar radiation of the sunniest places on Earth. For example, in the South Sahara up to 2000 kWh/m^2 can be measured and, even in central Europe, values for annual solar radiation have been measured up to 1480 kWh/m^2 in Zermatt and 1109 kWh/m^2 in Lucerne, Switzerland[4]. Note that both latitude and cloudiness play a role in lowering the annual solar radiation available in the Nordic countries.

The overall solar radiation incident on the Earth's atmosphere adds up to about 1.5 x 10^{18} kWh/year. About 30% of this radiation is directly reflected back into space, 20% is absorbed by atmospheric gases and 4% is reflected by the Earth's surface. The remaining 46% are absorbed and converted into different forms of energy i.e., evaporation of water, wind and far infrared radiation. Only 0.1% of the absorbed radiation is converted into biomass and a fraction is stored as fossil fuels[2]. If humans managed to convert a fraction of a percent of the sun's energy into usable forms of energy i.e., heat or electricity, the energy needs of humans could be completely met by solar power alone.

The sun has a surface temperature of 5 500-5 800 K, which determines the spectral distribution of its radiation according to the Blackbody theory. In comparison, a blue sky and an incandescent light bulb have a surface temperature of 10 000 - 15 000 K and about 2 700 - 2 900 K respectively[2 5], see Table 7.1. A blackbody is an idealized physical object absorbing all incident radiation and emitting a temperature-dependent continuous electromagnetic spectrum[2]. Everyday objects are not blackbodies since they reflect some of the incident radiation, which makes them visible[2]. In general, a higher surface temperature or Kelvin value corresponds to bluer light whereas a lower surface temperature

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[*] One astronomical unit (AU) is the mean distance between the Sun and the Earth.

Table 7.1 Daylight characteristics. Adapted from Heschong & Mahone Group (2014)[5].

	Illumination (lux)	Brightness (cd/m^2)	Colour temp. (K)	Colour description
Sun at midday	86 000–108 000	1 600 000 000	5 500	Neutral white
Sun at horizon	32 000–86 000	6 000 000	2 000	Warm yellow-orange
Clear sky	10 800–21 600	8 000	10 000	Bluish
Cloudy sky	5 300–54 000	2 000	7 500	Cool white
Incandescent	Variable	Variable	2 700	Warm white
Fluorescent	Variable	Variable	3 000–5 000	Warm to neutral white

corresponds to yellower colour of light. Sunlight, which has a lower colour temperature than skylight, is thus yellower compared to skylight, which is more bluish[6]. In a snowy landscape, the snow directly lit by sunlight is yellowish while the shadows, which are lit by the sky, are blue (Figure 7.2). Similarly, rooms with a south orientation may be perceived as 'warm' and those with a north orientation as 'cool' (in the Northern

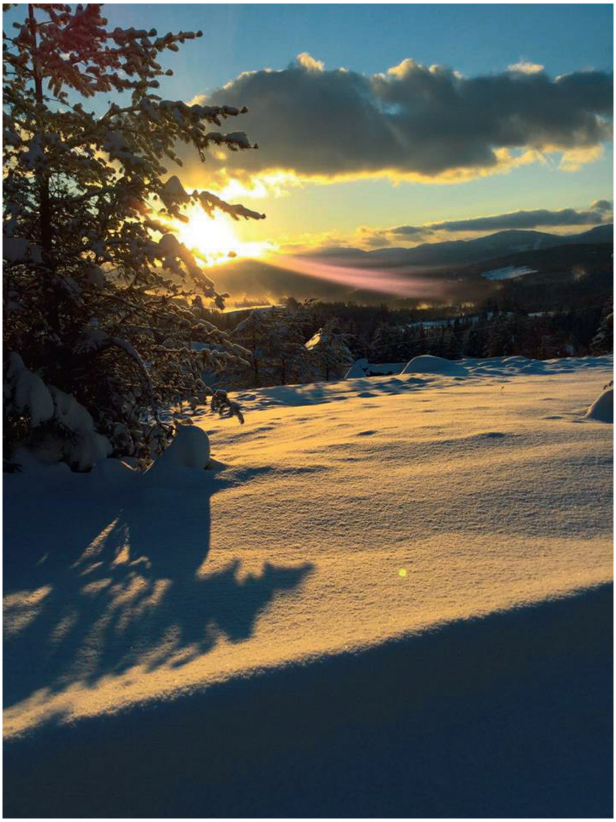

Figure 7.2
The ultimate source of daylight on Earth is the sun. Snow in sunlight is yellow while snow in shadow is blue. Photo: Martine Gagné, Quebec, Canada.

hemisphere)[7]. In the case of shadows on snow, this could be a combined effect of light source colour and visual perception, where colours in shadows are always perceived as complementary colours of the main illuminated objects[8].

The solar spectrum ranges from about 300 to 4 000 nm, and is characterized by distinct, non-overlapping radiation ranges (Figure 7.3):

- ultraviolet (UV) or short wavelength range, i.e. below 380 nm,
- visible range, i.e. 380–780 nm,
- near infrared range, i.e. above 780–2 800 nm.

Solar radiation in the visible range is called illumination or light.

Sunlight at the top of Earth's atmosphere is composed (by total energy) of about 50% infrared light, 40% visible light, and 10% ultraviolet light[1]. At sea level, the solar spectrum is reduced due to absorption by oxygen, carbon dioxide, helium and other gases. The resulting spectrum reaching the Earth thus has a slightly different distribution where 55% is in the visible range, 20% is in the UV/shortwave range and only 25% lies in the near infrared range between 790-2 800 nm [2].

Since the sun is so large and far from the Earth, illumination from

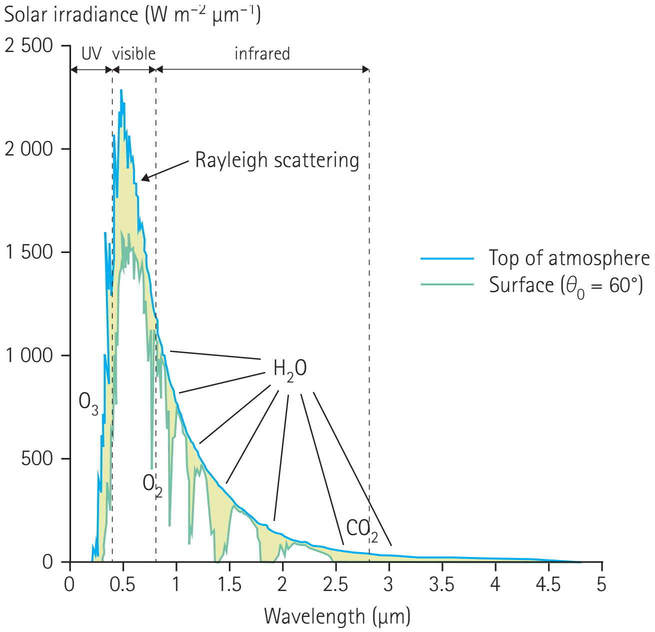

Figure 7.3
Solar spectrum at the top of the atmosphere and at the Earth's surface for a solar zenith angle of 60 degrees in a clear atmosphere. Adapted from Fu (2003).

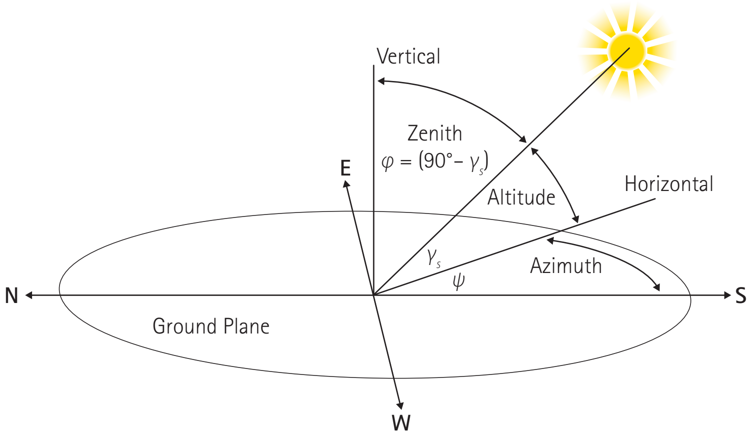

Figure 7.4
Solar altitude and azimuth.

direct solar rays can be considered parallel in practice. The direction of these vectors is described by the solar altitude and azimuth angles. The solar altitude is the angle between the sun and a horizontal plane, which varies between 0° during sunrise and sunset and around 58° on the summer solstice at noon in Southern Sweden. The solar azimuth is the angle between the sun's projection onto the horizon and south or north direction (depending on the convention used in each country), see Figure 7.4. The solar altitude (γ_s) at noon can easily be determined at the solstices and equinox using the following equation:

$$\gamma_s = 90° - \text{latitude} \pm \text{solar declination} \tag{7.1}$$

Example for Lund, Sweden (latitude 55.7°N):
Summer solstice: $\gamma_s = 90° - 55.7° + 23.45° = 57.7°$
Winter solstice: $\gamma_s = 90° - 55.7° - 23.45° = 10.8°$
Equinox: $\gamma_s = 90° - 55.7° - 0° = 34.3°$

Example for Kiruna, Sweden (latitude 67.8°N):
Summer solstice: $\gamma_s = 90° - 67.8° + 23.45° = 45.6°$
Winter solstice: $\gamma_s = 90° - 67.8° - 23.45° = -1.3°$ (the sun does not rise)
Equinox: $\gamma_s = 90° - 67.8° - 0° = 22.2°$

The Earth's rotation angle is tilted with respect to its elliptical path around the sun. The solar declination (d) is the angular distance of the sun north or south of the Earth's equator, Figure 7.5. The Earth's equator is tilted 23.45 degrees with respect to the plane of the Earth's orbit around the sun, so at various times during the year, as the Earth

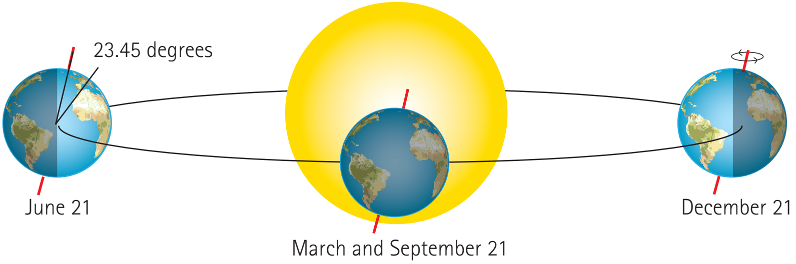

Figure 7.5
Solar declination.

orbits the sun, its declination varies from 23.45 degrees north to 23.45 degrees south. The solar declination (d) can be calculated with the following formula:

$$d = 23.45 \times \sin\,[360/365 \times (284 + N)] \qquad (7.2)$$

where:

d = solar declination (°)
N = day number, where for January 1, N = 1

Equation 7.1 shows that as the latitude increases, the solar altitude at noon time decreases at all times during the year, meaning that the sun is rather low above the horizon at high latitude, Figure 7.6. This means that in Nordic countries, the sun normally penetrates deep inside buildings and is thus more difficult to control, Figure 7.7. Note also that the sun

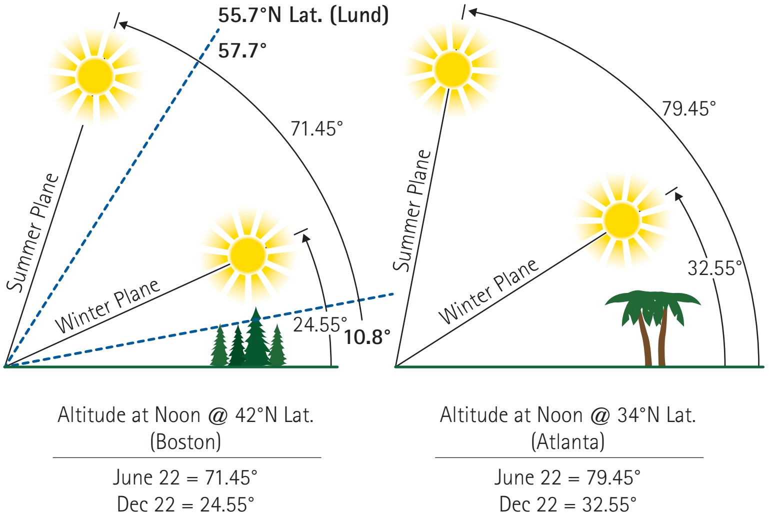

Figure 7.6
Solar altitudes are much lower for high latitude countries compared to lower latitudes. Adapted from Hastings & Crenshaw (1977)[86].

position can be calculated precisely at any time of the day and year using standard equations.

Sunlight is often measured or required in amount of hours per year or per day in building regulations. Qualitatively, sunlight is strong and directional and generally has a warm tone. Sunlight can be very pleasant in housing or social environments. However, sunlight can create sharp contrasts and glare that may make it difficult to carry out visual tasks indoors. Even in urban environments, the low sun angle creates sharp contrasts under clear sky conditions, where only part of street facades are sunlit, Figure 7.8. These sharp contrasts can give rise to problems with glare and even issues with visibility in traffic.

Figure 7.7
Deep sunlight penetration, Finnish interior. Photo: Malin Alenius.

Figure 7.8
Sunlight on building facades in Ålesund, Norway, at spring equinox. Photo: Marie-Claude Dubois.

Another aspect to consider when designing buildings at high latitudes is the fact that between the spring and autumn equinox, the sun rises and sets on the north side of buildings, Figure 7.9. Above the circumsolar polar circle, the sun never really sets and reaches the building from all directions during the summer solstice. The resulting light makes it possible to take a walk in a dense forest or swim in a lake in the middle of the night. The very low solar angle created by the combination of solar declination and high latitude generates long

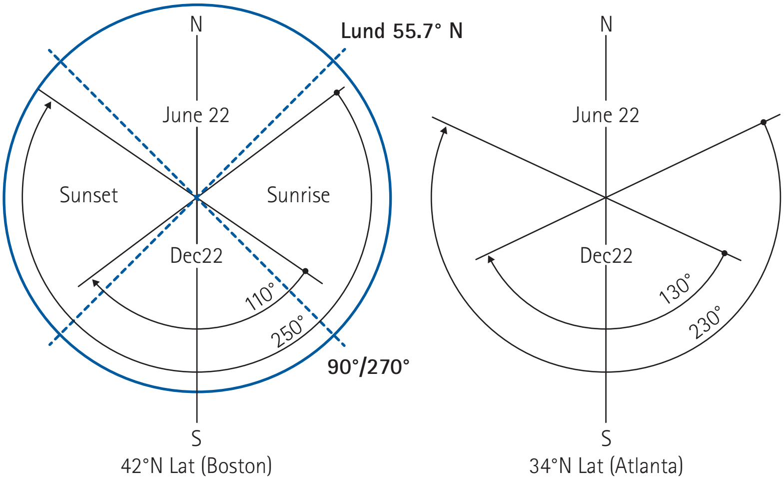

Figure 7.9
At high latitude, the sun rises and sets on the north side of buildings. Adapted from Hastings & Crenshaw (1977)[86].

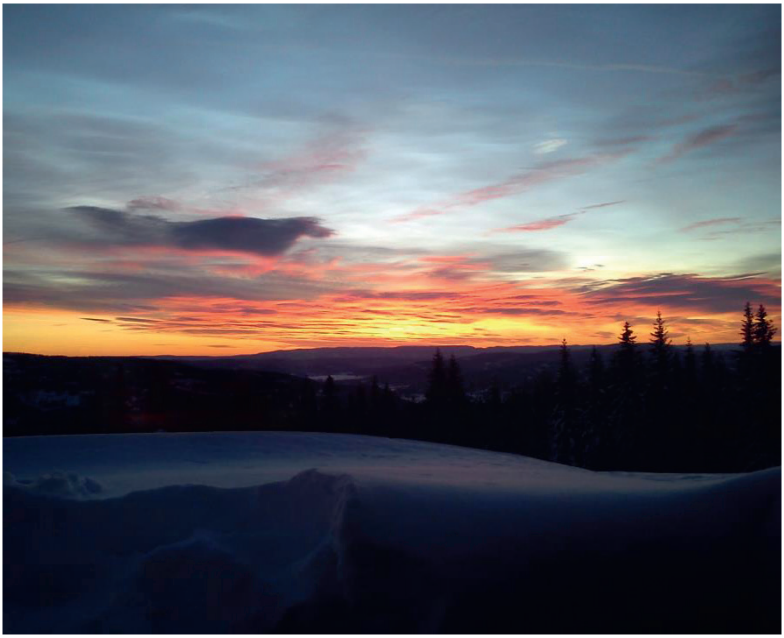

Figure 7.10
Sunset on Norefjell, Norway, winter solstice. Photo: Marie-Claude Dubois.

and spectacular sunrises and sunsets, producing extraordinary colour effects, see Figure 7.10.

On the other hand, around the winter solstice, the sun rises and sets much closer to the south direction, and barely rises above the horizon. The low solar altitude combined with predominantly cloudy sky conditions yields low exterior daylight levels during this time of the year.

7.1.2 Skylight or diffuse light

The second source of daylight on Earth is light coming from the sky, also called *skylight* or *diffuse light*. Diffuse light is sunlight scattered in the atmosphere before reaching the Earth or a building.

Skylight can consist of light coming from the blue sky or simply light scattered by clouds, through clouds or between clouds, see Figure 7.11. A sky which is totally covered with clouds is called overcast sky (Figure 7.12) whereas one which is totally devoid of clouds is called clear sky. A blue sky with clouds is called intermediate sky; see Figure 7.13. In Nordic countries, the overcast sky is clearly dominant, especially during the winter.

The sky luminance (sometimes called *brightness*) distribution varies spatially with geographic location, site altitude, time of day, time of year,

Figure 7.11
Skylight is light from the blue sky, reflected by clouds or passing through clouds, Norefjell, Norway. Photo: Marie-Claude Dubois.

Figure 7.12
A perfect overcast sky in Lund, Sweden. Photo: Marie-Claude Dubois.

Figure 7.13
Intermediate sky in Norway. Photo: Marie-Claude Dubois.

weather conditions (including clouds and aerosols such as smoke and airborne dust), and the dew point temperature[9].

The atmosphere is filled with oxygen, carbon dioxide and many other gases as well as water droplets. The thicker this layer of water droplets (described by the Ångström turbidity coefficient), the more light is dispersed in the atmosphere. Objects that are located further away generally look hazier, especially under very humid weather conditions because there is more water in the atmosphere, see Figure 7.14. This change in light dispersion provides additional information about distance, which is a useful environmental cue for the visual system when binocular vision cannot operate, Figure 7.15. In polluted areas, particles and gases may also cause daylight to be absorbed, which has an effect on the amount and quality of diffuse skylight[10]. This is rarely a problem in the Nordic countries however, where strict laws on environmental emissions have so far limited air pollution.

Figure 7.14
Water droplets in the atmosphere scatter light as above this Norwegian fjord, Lofthus, Norway. Photo: Marie-Claude Dubois.

Figure 7.15
Mountains which are further away look hazier and bluer, which provides a cue about distance, Lofthus, Norway. Photo: Marie-Claude Dubois.

Molecular scattering of light varies as a function of wavelength, where the blue end of the spectrum is affected more by light scattering than the yellow end[11], giving rise to blue sky. This phenomenon is called Rayleigh scattering after the British physicist Lord Rayleigh (1842-1919). The sun appears yellow since blue light has been scattered out of the beam[12]. The lower the angle of the sun, the greater the distance in the atmosphere through which sunlight travels. This is why deep blue skies are remarkable in the Nordic countries, where sunlight is scattered over thicker atmosphere and where atmospheric pollution is low, Figure 7.8 and 7.15. Note that blue sky and red sunset have, in fact, their origin in the same optical phenomenon (Raleigh scattering). As more of the blue (and green) wavelengths are scattered out of the beam, the sun appears progressively yellow, orange, and red as the sun sets[12].

Skylight should be a substantial source of natural illumination in buildings, especially in the Nordic countries, where the sky is commonly covered with clouds and where sunlight is scarce. Skylight is softer than sunlight and it is thus an interesting source of ambient illumination in buildings. Skylight, especially from blue skies, has a higher luminous efficacy than sunlight[13] [14] so it provides more luminous energy per unit of thermal energy than sunlight, Figure 1.2 and Table 7.2.

Daylighting design normally involves making good use of skylight and avoiding or reflecting direct light within the building envelope to prevent glare and overheating problems. Light reflected off the ground can also be a potential source of natural illumination.

Table 7.2 Luminous efficacy of various light sources. Adapted from: Mardaljevic, Heschong & Lee (2009)[14].

Source	Luminous efficacy (lm/W)
Sunlight	70–105
Clear blue skylight	130
Overcast skylight	110
Global daylight	105
Incandescent light bulb	15
Compact fluorescent	57–72
T5 linear fluorescent	70–100
LED	50–200 (theoretical limit ~270)

7.1.3 Reflected light

A portion of the total radiation is reflected by the ground and may significantly contribute to daylighting buildings. The amount of reflected light depends on the surface reflectance properties of the surroundings. The normal contribution of ground reflected light is 15% or more of the total amount of daylight on the facade of a building. However, in snowy locations predominant in Nordic countries, the ground reflectance can be very high (80% reflectance for new snow)

Figure 7.16 Ground reflected light can be important with snow covered ground, Lund, Sweden. Photo: Marie-Claude Dubois.

and thus strongly affects daylighting indoors, especially if the ground reflected light bounces off a white ceiling and reaches the back of the room, Figure 7.16.

Reflected light (especially sunlight) can provide a major contribution to daylighting when the building is located near water, whether the water plane is located further away as shown in Figure 7.17 or close by as in Figure 7.18. Note that sunlight reflected from a water surface can create severe glare problems, more critically if the sun reflection is located at some distance. This is an issue to consider in Nordic countries, since many cities are located along the coastlines and solar altitudes are low.

In dense urban areas, reflected light can even be the main supplier of daylight inside buildings[15]. Figure 7.19 shows some of the offices of the Caisse de Dépôt et Placements (CDP) in downtown Montreal, Canada. The reflectance of facing building facades strongly affects daylight quantity and quality in adjacent rooms. North-oriented rooms are particularly affected by reflected light as adjacent facades have southerly orientation and are generally more sunlit. Cantin & Dubois (2011)[16] showed that the directionality of daylight in a north facing room of the CDP was dominated by the reflected light from the facing building.

Issues related to reflected sunlight are arising more often as the use of glass facades or reflective material is on the rise and cities are densifying. Reflections from glass may also be an issue of consideration

Figure 7.17
Reflected light from water can be significant, Borstahusen, South Sweden. Photo: Marie-Claude Dubois.

Figure 7.18 Reflected light component on the peripheral ceiling from the surrounding water, Fukuoka, Japan. Photo: Marie-Claude Dubois.

Figure 7.19 Interior photo of the Caisse de Dépôts et Placements, Montréal, Canada. The main source of illumination comes from light reflected from the facing building in this dense urban environment. Photo: Arnaud Bontemps.

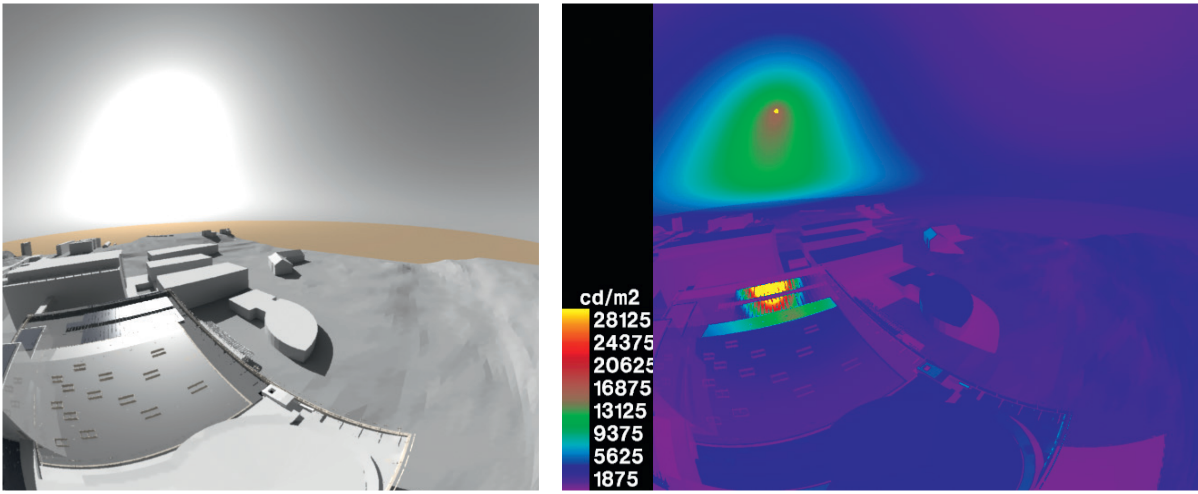

Figure 7.20 Example of glare study from sunlight reflected off photovoltaic panels on the roof of the NBS hospital, Gothenburg, Sweden. Simulations by Stephanie Jenny Angeraini, White Arkitekter.

for air traffic safety[17] [18]. As an example, Figure 7.20 shows a simulation study of reflections and glare from photovoltaic panels from the point of view of a pilot looking towards a helicopter landing platform on the roof of the NBS hospital building in Gothenburg, Sweden.

7.2 Standard sky models

Each minute of each day produces a unique sky, with a unique luminance distribution, which depends on the sun's altitude and azimuth, sky brightness, atmospheric turbidity, cloud cover, etc. It is practically impossible to replicate this constant variability of the sky's luminance distribution exactly moment to moment. This includes completely clear blue skies, intermediate skies with constantly moving clouds, overcast skies of variable brightness, etc. The miracle of daylight lies in this never-ending variation.

However, to be able to assess daylighting in buildings, it is necessary to make assessments under a known sky distribution to be able to 'compare apples with apples' since a room under overcast sky looks completely different from a room under sunlight or intermediate sky. Using reference skies allows comparison of different building designs with each other or assessing a particular building design according to accepted standards. For this reason, the Commission Internationale de l'Éclairage (CIE) has defined standard skies to use in daylight calculations, based on accepted sky models.

A sky model is a mathematical equation describing the variation in luminance across the hemispherical sky vault[12]. Several sky models are normally programmed in lighting simulation tools. Understanding the different standard sky models is important to be able to interpret simulation results correctly. The following sections briefly describe these standard sky models. The reader is referred to more elaborate publications on this complex subject, e.g. Beckers (2012)[19] and Enarun & Littlefair (1995)[20]. Note that sky models are typically described as colourless, although recent research shows progress towards a valid mathematical description of coloured skies[21]. This change is motivated by the need to predict the circadian potential or circadian efficiency of a space[22].

7.2.1 CIE Standard Overcast Sky (1955)

Generally, the overcast sky has a complete cloud cover (>95 %); the sun must be entirely obscured and there must be no hint of its position[20]. However, the sky cover should not be entirely due to obscuring phenomena near the surface, such as fog (see e.g. Figure 7.14).

The overcast sky is probably the most popular sky type since it is used in Daylight Factor calculations. It is the earliest sky model to be fully adopted internationally as the 'CIE standard overcast sky'(1955)[19 23] based on the work of Moon & Spencer (1942)[24].

Moon & Spencer (1942) used measured data to demonstrate the relationship between the luminance of a patch of an overcast sky and its zenith angle. This sky model describes a sky with an increasing luminance as the luminance meter moves towards the zenith. The Moon & Spencer sky has been standardized by the CIE in 1955, by this formula:

$$L_\gamma = L_z \left(\frac{1 + 2\sin\gamma}{3} \right) \tag{7.3}$$

where

L_γ is the luminance of the sky at the elevation γ.
L_z is the zenithal luminance.

This formula indicates that the luminance is the lowest at the horizon and it is then equal to one third of the zenithal luminance (i.e. when $\gamma = 0°$, $L_0 = (1/3)L_z$). The overcast sky thus typically has a luminance which

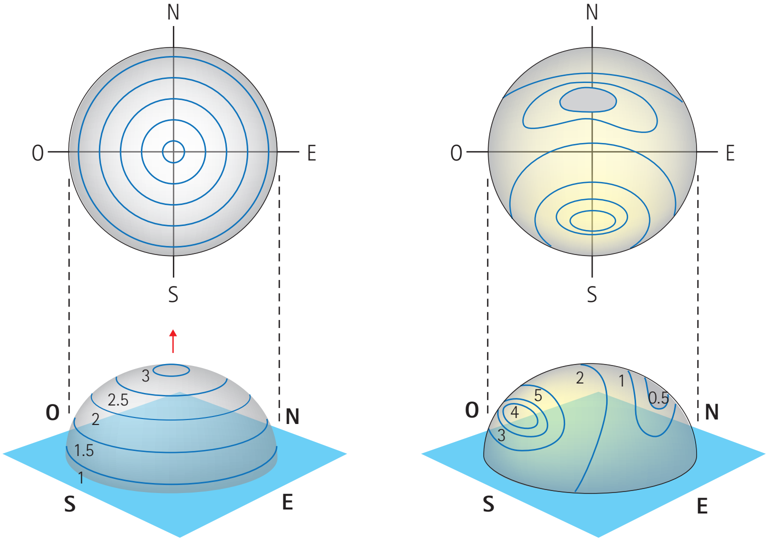

Figure 7.21
Overcast sky distribution (left) and clear sky (right).

is three times brighter at the zenith than at the horizon[25], Figure 7.12 and 7.21. The overcast sky is also isotropic, meaning that it has the same luminance regardless of the azimuth or cardinal orientation. This is also why Daylight Factor calculations under overcast skies return the same value regardless of room orientation.

Skies with the exact luminance distribution as described in equation 7.3 occur rarely even in predominantly cloudy climates[20]. Enarun & Littlefair (1995)[20] showed that the 'CIE standard overcast sky perhaps represents an extreme rather than the full range of cloudy skies encountered in practice'. Under a typical overcast sky, the ratio between the screened* vertical illuminance E_{vert} (on the unobstructed facade of a building) and the global illuminance (E_g) must ideally be 0.396, where ratios between 0.36 and 0.44 are considered acceptable[26]. Any other ratio means that the sky distribution is substantially different, and the Daylight Factor measurement will be substantially different. Note that the cloudy sky has also been modeled as a uniform sky in early daylight simulation programs such as Superlight and it is still possible to model this uniform sky in more advanced programs such as in the Radiance Lighting Simulation System. A uniform sky is one for which the luminance distribution is uniform over the whole sky hemisphere[27]. The recently proposed Aperture-Based Daylight Modeling (ABDM) approach by Mardaljevic & Roy (2017)[28] is based on the uniform sky.

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* The screened vertical sky illuminance is the vertical illuminance screened from ground reflection.

7.2.2 CIE Standard Clear Sky (1996)

The cloudless clear sky is typically blue because of light scattered out of the solar beam by molecules of atmospheric gases. Blue light is dispersed more than red light due to Rayleigh scattering[29]. When the sun is directly overhead, the solar disk is surrounded by a bright patch as most of the scattered light is diverted out of the beam by a few degrees creating a circumsolar flare. From the sun and its circumsolar flare, the sky brightness declines into deep blueness as the angle of vision from the sun increases, with the darkest patch of blue sky occurring at about 90° from the sun, Figure 7.21. However, the brightness of the clear sky increases again just above the horizon because there is a very long view through the atmosphere[29], Figure 7.22.

The luminance distribution of the clear sky was derived by Kittler (1967)[30] and adopted by the CIE in 1973 as the CIE Standard Clear Sky[31], which is a cloudless sky for which the relative luminance distribution is described in ISO Standard 15469. This model allows predicting the luminance of an arbitrary sky element from the zenith luminance, angular distance of the sky element from the sun, solar zenith angle, and altitude of the sky element. The equations describing the luminance patterns for clear and intermediate skies are more complex than that of the CIE Standard Overcast Sky previously discussed. The reader is thus referred to the original publications for further inquiry on this subject.

Figure 7.22
A perfectly clear sky showing that the horizon is brighter than the zenith. Photo: Marie-Claude Dubois.

7.2.3 CIE Standard General Sky (2003)

Following the establishment of the Standard Overcast (1955) and Standard Clear Sky (1996), the need arose to define other sky types since it was generally observed that these standard sky models are idealized models that do not occur often in reality[19 32]. In particular, it was necessary to be able to add a model of intermediate (partly cloudy) skies. The intermediate sky type is the most difficult one to describe in a model since its distribution changes according to atmospheric conditions, cloud and sun positions.

In 1998, Kittler et al[33] proposed an extended sky model using simultaneous sky measurements in different locations (Tokyo, Berkeley, Sydney). This extended sky model allowed for representation all sky types (clear, overcast, intermediate) based on different input parameters related to atmospheric conditions. This model was adopted as the Standard General Sky model by the CIE in 2003 and in the ISO 2004 Standard[34].

The resulting sky model is more advanced and complex, relying on inputs of the sun position and five input parameters a, b, c, d, e, which describe atmospheric conditions. Note that this standard is based on sky scans that produced 36 different skies, where rarely occurring skies were eliminated. This resulted in only 15 skies being represented in the model consisting of five overcast, five clear and five intermediate skies. In this sky model, the ratio of the luminance of an arbitrary sky element to the zenith luminance Lz is expressed in a functional formula following the previous CIE Clear Sky Standard.

Kittler and Darula (2022)[25] recently proposed an extension of this model allowing determination of the absolute sky luminance distribution as well as outdoor illuminance produced by sunlight and skylight dependent on extraterrestrial sunlight.

7.2.4 Perez All-Weather Sky Model (1993)

Perez, Seals & Michalsky (1993)[35] developed and evaluated a model for describing, from routine irradiance measurements, the mean instantaneous sky luminance angular distribution patterns for all sky conditions from overcast to clear, through partly cloudy skies. This model allows for the description of relative luminance distribution of the sky dome and has become an industry standard for daylighting calculations. This model, which is derived from a large pool of data (3 million data points) covering a wide range of insolation conditions, albeit at a unique site, is referred to as the Perez All-Weather Sky Model. It is a physically accurate sky model controlled by only two illuminance values. The two parameters that the Perez model uses are delta (representing sky brightness) and epsilon (representing sky clearness). The great advantage of this model is the fact that only two measured input parameters are needed i.e., the direct normal and diffuse horizontal irradiance. (The model also includes the dew point temperature as a measure of atmospheric moisture content, but this has only a minor effect on the predicted luminance distribution).[36]

Note that these parameters can be obtained from a standard weather database (EnergyPlus weather database for example). Diffuse Horizontal Irradiance is from the sky alone, measured horizontally. The units are watts per square meter. Direct normal irradiance is from the sun alone, measured by an irradiance meter aimed directly (perpendicularly) at the sun (also in watts per square meter). As previous models, the Perez all weather sky model is also described by the ratio between luminance of a sky element and zenith luminance.

In this model, five coefficients represent the distribution parameters describing the atmospheric conditions. These coefficients depend on sky clearness and sky brightness, which are calculated from horizontal diffuse irradiance and normal incident direct irradiance, see Perez et al (1993)[35] and Becker (2012)[19] for detailed information about this model.

Note that other all-weather sky models have been proposed, but various validation studies[37] have indicated that the Perez model is the most reliable. This model has thus been implemented in many daylight software and it has become the industry standard.

However, each sky model has its limitations. Beckers (2012)[19] mentioned that the Perez sky model cannot predict densely overcast sky reliably, a limitation which is important to consider in Nordic countries. Brembilla (2021)[38] expressed concern that a large number of inaccuracies in irradiance and illuminance time series start to emerge, and that the prediction of direct sunlight is even more prone to errors than diffuse skylight.

7.3 Daylight performance metrics

To evaluate the performance of buildings in use and predict their performance at the design stage, one should be able to identify what the appropriate measures of performance are, when and how these measures should be collected, and how the results should be interpreted to determine success or failure of the design[39]. A common methodology should in principle define what is to be measured as well as the manner and at which point(s) measurements are to be taken. Obviously, the most common way to measure illuminance and luminance is to use lux and luminance meters. However, this is hardly useful with daylighting since sky conditions vary from moment to moment. Nor can measurements with instruments be carried out when the building has not yet been erected. Calculating average values from an annual array of data is not useful either since the very high values from direct sunlight completely hide low illuminance values found on dark overcast days.

Over time, researchers have come up with other, indirect ways to measure the performance of daylighting design. This common methodology is partly explained through the concept of daylight metrics. A metric is 'some mathematical combination of (potentially disparate) measurements and/or dimensions and/or conditions represented on a continuous scale; it may not be directly measurable in the field'[14]. Daylight metrics allow for assessment of either the quantity or quality of available daylight and/or visual comfort inside buildings. Some metrics address both these aspects.

Daylight metrics can be simplified methods of static conditions such as the Daylight Factor or more advanced dynamic methods called dynamic daylight metrics (DDM). DDM require advanced computer simulations often referred to as Climate-Based Daylight Modelling (CBDM), which is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions derived from standard meteorological datasets[40].

Qualitative daylight metrics may also be used to predict the probability of glare or other relations such as illuminance uniformity or luminance ratios. One popular metric is the 'Daylight Glare Probability' (DGP), which is more complex compared to other commonly used quantifying metrics for glare[41].

7.3.1 Static daylight metrics

7.3.1.1 Daylight Factor

Devised in 1895 by Alexander Pelham Trotter (1857-1947) and introduced into British (BRE) publications in the 1940s and 1950s[42], the Daylight Factor is a measure of the illuminance within a room (usually on a horizontal plane), relative to the total amount of light available under an unobstructed hemisphere with an overcast sky[43]. The official CIE (2014)[27] definition is equivalent: 'the ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded'.

The DF is expressed as percentage and can be calculated using the following equation, see Figure 7.23.

$$DF = \frac{E_{indoor}}{E_{outdoor}} \cdot 100 \qquad (7.13)$$

The Daylight Factor remains the principal metric used in daylighting practice and guides, despite recent calls to replace it with other metrics[43]. For most building practitioners, the consideration of any quantitative measure of daylight begins and ends with Daylight Factor[44]. Over the past fifty years, this design practice has remained quite stable, and the DF is still used in many building regulations or environmental certification systems, despite its intrinsic limitations.

Some advantages of the Daylight Factor have been mentioned[45]:

- The DF allows expressing the efficiency of a room and its window(s) as a 'lighting system';
- The DF describes the relationship between interior and exterior spaces by indicating the contrast between the two environments (lower DF values correspond to higher contrasts between interior and exterior environments).

Reinhart, Mardaljevic & Rogers (2006)[46] also mentioned that the DF has the advantage that predictions are intuitive and easy to communicate within a design team. The DF is also useful as it provides information about 'a worst-case scenario', where exterior daylighting levels are low.

However, many researchers[44] [45] claimed that the DF is clearly insufficient alone to evaluate lighting quality in a space due to its intrinsic limitations:

- Light from the sun and non-overcast skies cannot be considered with the DF;
- The DF does not allow assessing the impact of building or room orientation since the overcast sky is isotropic (same in all directions)[47];
- A DF calculation returns the same value for the same building regardless of the location or latitude[47];

- DF values are very variable even under overcast sky conditions due to variable sky luminance distribution;
- The effect of mixed lighting (natural and electric) cannot be quantified with the DF;
- The non-horizontal light (from walls), which is critical for human perception, is not considered in the measurement of horizontal DF.

The DF only applies to a temperate or cold climate with many cloudy situations[48] (which is relevant for the Nordic countries). However, the real climate with a large share of intermediate skies may be quite different from the overcast sky paradigm. Mardaljevic (2006)[40] even claimed that the DF persists as the dominant evaluation metric because of its simplicity rather than its capacity to describe reality with any degree of precision. It is now known – to quote Mardaljevic (2021)[47] – that only a small portion of the occurring overcast skies approximate the CIE formulation (based on measurements by Moon & Spencer). Interestingly, it is important to emphasize that the DF was conceived as a means of rating daylighting performance independently of the occurring, instantaneous sky conditions[49]. The reason for using ratios rather than absolute values in daylight evaluations was to avoid the difficulty of having to handle 'frequent and often severe fluctuations in the intensity of daylight'[46].

The important point to remember when carrying out daylight evaluations is that the DF is both climate-, latitude-, and orientation-independent while daylighting is inherently climate- and orientation-dependent. Daylighting varies in time and space. Since the DF method cannot represent this complex reality, it is by essence incomplete and needs to be supplemented by other methods of evaluation.

Average Daylight Factor (ADF)

The Average Daylight Factor (ADF) is often used as a design criterion and an ADF value from 2% to 5% is recommended for offices[50]. If the ADF in a space is at least 5%, then electric lighting is not normally needed during daytime, provided the uniformity is satisfactory[51]. In this case, the DF is determined according to a grid of points in space and the arithmetic average is calculated over this array of numbers. Normally, a band of 0,5 m from the walls is excluded from the calculation area except when a task area is in or extends into this border area and typical values of grid spacing are prescribed; see e.g. European Standard

SS-EN-12464-1[52]. The ADF can be predicted with reasonable accuracy using a formula proposed by Lynes (1979)[53]:

$$ADF = \frac{A_{glazing} \cdot \tau_{vis} \cdot \theta}{A_{total} \cdot 2(1 - R_{mean})} \tag{7.14}$$

$A_{glazing}$ = Net glazing area (m^2)
τ_{vis} = Visual transmittance of glazing
θ = Sky exposure angle (°)
A_{total} = Total area of internal surfaces (m^2)
R_{mean} = Area weigthed reflectance of surfaces

where:

$$R_{mean} = \frac{A_{wall} \cdot R_{wall}}{A_{total}} + \frac{A_{ceiling} \cdot R_{ceiling}}{A_{total}} + \frac{A_{floor} \cdot R_{floor}}{A_{total}} + \frac{A_{glazing} \cdot R_{glazing}}{A_{total}} + \text{etc.} \tag{7.15}$$

This formula was later revised by Crisp & Littlefair (1984)[54]:

$$ADF = \frac{A_{glazing} \cdot \tau_{vis} \cdot \theta}{A_{total} \cdot (1 - R^2_{mean})} \tag{7.16}$$

However, Reinhart & LoVerso (2010)[55] recently showed that the Lynes formula resulted in more conservative and thus appropriate results at the early design phase since it includes a ‘safety margin’.

Median Daylight Factor (DF_{median})

The median DF requires the calculation of DF values according to a grid of points in a room, in the same way as the ADF. The difference is that

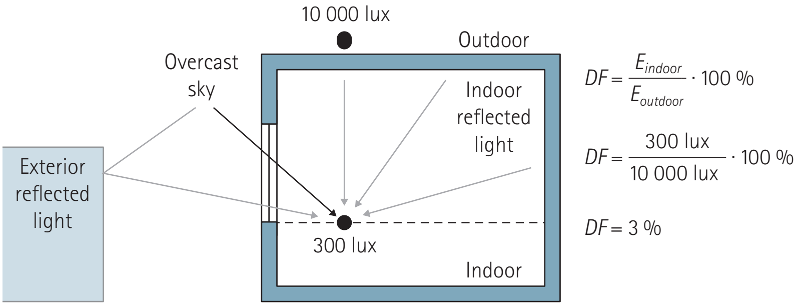

Figure 7.23
Daylight Factor.
Drawing: Stephanie Jenny Angeraini, White arkitekter.

the median[*] is determined instead of the average value. A recent study (2017)[56] demonstrated the superiority of the DF_{median} value compared to ADF to characterize daylight in a simple space. This study showed that the median is far more revealing about the luminous environment because it informs on the spatial distribution of the Daylight Factor: half the points are above the median and half are below. To this, we may add that the median DF allows for a more indicative result than a point DF when assessing asymmetrical rooms.

Point Daylight Factor (DF_p)

A point DF concept can commonly be found in many regulations and certification systems based on older measurement methods when computer simulation programs were not available. The DF_p value is a single measurement taken at 1 m from the darkest lateral wall, halfway along the room's depth, at 0.8 m from the floor, which is defined in the outdated standard SS 914201[57], Figure 7.24. The DF_p method has persisted in the Swedish building regulations BBR despite much criticism from the building industry, more due to historical reasons than relevance or logic[41]. It will soon no longer be an acceptable method to show compliance for building code applications and a phasing out of the current regulations is planned for January 1, 2025. Figure 7.25 shows an example of DF_p calculation compared to the DF_{median}, where the median value is clearly superior as it is more stable and representative of daylighting in the space compared to the DF_p value.

Recent research[58] showed that the DF_p definition is difficult to use in practice and prone to 'game playing' especially in rooms with windows on different facades or in irregularly shaped rooms. In addition, the same research showed that the DF_p correlates to a high level with the DF_{median} value (for most room types). A more recent study by Vogatzi (2018)[59] confirmed this finding. It is thus preferable to use DF_{median} instead of DF_p since it is more descriptive spatially and easier to use in complex geometries. Also, since most practitioners nowadays use computer simulations, the use of DF_{median} instead of DF_p value greatly simplifies the simulation process as one can simply pick a surface, assign a grid from this surface and calculate the median from this array of numbers.

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[*] The median is the value separating the higher half of a data sample, a population, or a probability distribution, from the lower half.

7.3.1.2 Uniformity ratio or illuminance uniformity (UR or Uo)

The uniformity ratio (UR or Uo) also called illuminance uniformity is defined by the CIE (2014) as the ratio of minimum to average illuminance on a surface:

$$\text{UR or Uo} = E_{min}/E_{average} \tag{7.17}$$

The uniformity ratio is more a qualitative than quantitative metric. This ratio can be used in addition to the DF to assess whether there are unevenly daylit areas across the studied space or not. High UR normally avoids large contrasts and glare, but complete uniformity should be avoided as it can create dull lighting conditions. The uniformity ratio is especially relevant in workspaces particularly where the task is related to foveal (detail) vision.

7.3.1.3 Daylight Glare Probability (DGP)

For situations with glare originating from daylight, particularly with side-lighting and computer work, the Daylight Glare Probability (DGP) developed by Wienold & Christoffersen (2006)[60] is a suitable index. The DGP expresses the degree of perceived glare for occupants performing a task (reading, working on task). No electric lighting was used in the development of this index. It is based on previous research[61] [62] which indicated that electric lighting had a negligible impact on glare level in a daylit space with lateral window since light from the window was clearly dominating the scene. With the DGP, the glare level is expressed as the probability that occupants will be disturbed by glare in a given situation (e.g. DGP = 80% means 80% probability of experiencing glare).

7.3.1.4 Vertical Sky Component (VSC)

The Vertical-Sky-Component (VSC) is a static daylight metric used in urban planning. It is an accepted method defined by Building Research Establishment (BRE) guidelines[63]. The Vertical Sky Component (VSC) is the ratio of direct illuminance on a vertical plane to illuminance on an unobstructed horizontal plane, from a CIE standard overcast sky[64]. The maximum value of VSC is 40%, which is a consequence of the overcast sky distribution[47]. The BRE guidelines state that 'if the Vertical Sky Component, with the new development in place is both less than 27% and less than 0.8 times its former value, then occupants of the existing building will notice the reduction in the amount of skylight.'[64] Figure 7.26 shows an example of a VSC evaluation for a building located in Ängelholm, Sweden.

7.3.1.5 Vertical Daylight Factor (VDF)

The Vertical Daylight Factor (VDF) is the ratio of the illuminance at a point on a vertical surface due to the light directly or indirectly received from the sky to the illuminance on a horizontal plane due to an unobstructed hemisphere of the same sky[65] [66] [67]:

$$VDF = \frac{E_s + E_{rb} + E_{rg}}{E_g} \tag{7.19}$$

where:

E_s is daylight coming directly from the sky
E_{rb} is daylight coming from the obstructing building(s)
E_{rg} is daylight reflected from the ground
E_g is the global illuminance received from an unobstructed sky.

In this definition, the contribution of direct sunlight to both illuminances is excluded. The VDF considers direct light coming from the sky and reflected light from surrounding buildings and the terrain both above and below the horizontal plane.

In dense urban environments, the outward view from a building facade may 'see' only a small portion of the sky and a larger area of obstructing surfaces. In this case, reflected light from facing facades, obstructions and the ground contribute to daylighting on vertical facades more than the direct sky angle described by the VSC. It should be noted however that reflected light is of a lesser magnitude than that which is received directly.

7.3.2 Dynamic Daylight Metrics

At present, building regulations and certification systems are going through a significant paradigm shift, where static daylight metrics are slowly abandoned and replaced by dynamic daylight metrics (DDM). The most common DDM used in practice are discussed below.

These new metrics are a result of the development of Climate-Based Daylight Modelling (CBDM), which allows for assessment of daylight in space considering a whole year of weather data instead of looking at

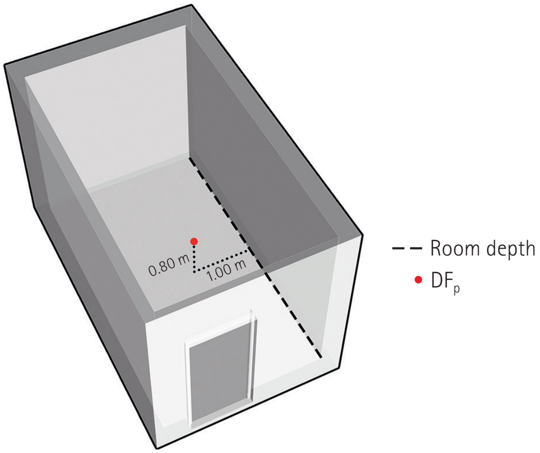

Figure 7.24
Position of the point of measurement for the DFp evaluation. Drawing: Paul Rogers, 2014.

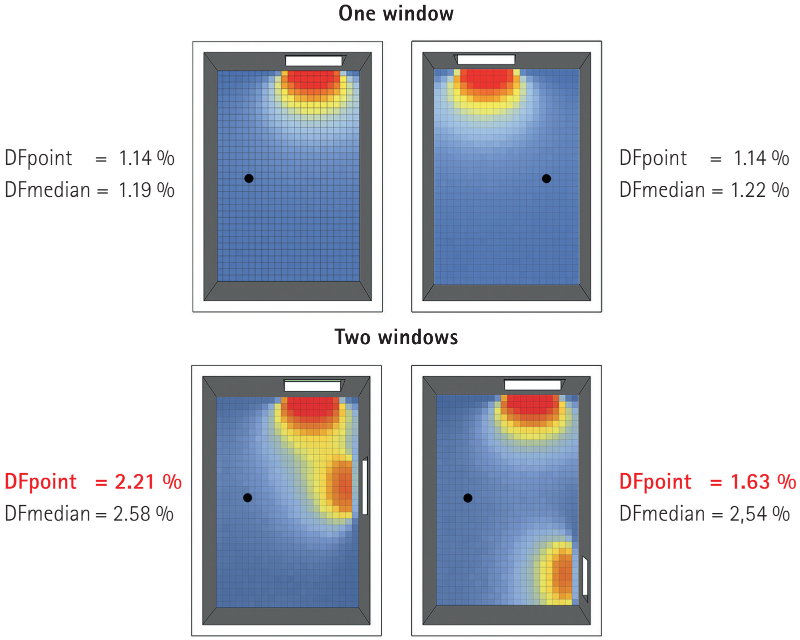

Figure 7.25
DFp compared to DFmedian values. Simulations: Iason Bournas.

single sky situations. As mentioned earlier, CBDM is the prediction of any luminous quantity (illuminance and/or luminance) using realistic sun and sky conditions derived from standardized climate data[68][69].

Recently, the author of CBDM extended his earlier work on CBDM and developed a new approach called Aperture-Based Daylight Modelling (ABDM), which seems promising. ABDM is rooted in the concept of 'view lumen', which is the illumination effect received at the building aperture from a visible external entity (i.e., ground, sky, obstructions)[70]. The view lumen is an extension of another recently introduced concept called 'sunlight beam index (SBI)'[71], which is an 'area measure of the 'connectedness' of a building aperture to all

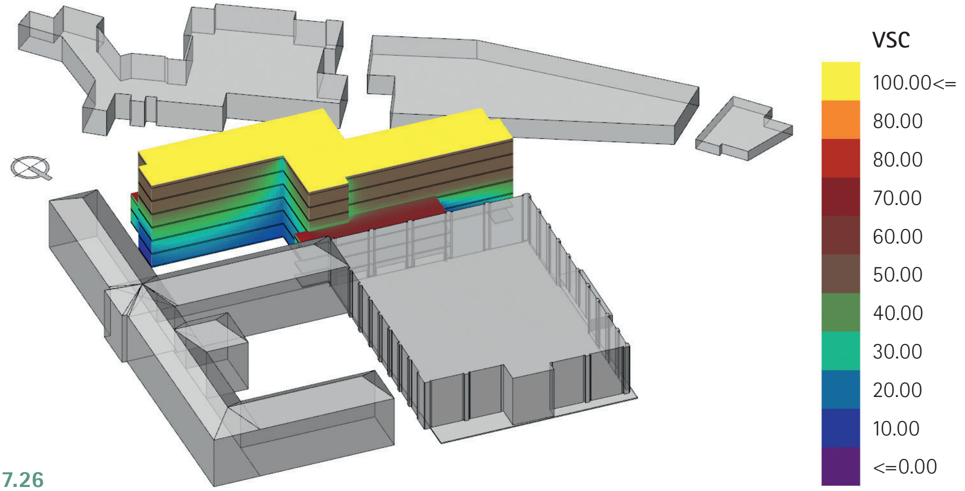

Figure 7.26 Example of a VSC evaluation, Hälsostaden in Ängelholm, Sweden. Simulations by Stephanie Jenny Angeraini, White arkitekter.

possible occurring sun positions for that locale and for that particular aspect of the aperture including all possible obstructing surfaces – averaged across the aperture'[71]. The SBI is measured in m^2 hrs. In the same way, the aperture skylight index (ASI) is an area measure of the 'connectedness' of an aperture to the sky vault in terms of the illumination received from a uniform luminance sky dome – averaged across the aperture[72]. Compared to sky view factors based on solid angle, the ASI is preferable because the illuminance received at the aperture relates more directly to the illumination potential of the aperture, since it includes the cosine weighting of the visible sky. Secondly, the aperture can be determined across the entire surface while the solid angle has to be made at a point in the middle of the aperture. Thirdly, the use of illuminance across the aperture allows for accurate evaluation of complex shading structures. In the ASI concept (which is measured in lumens), the CIE uniform sky (with a luminance of $2000/\pi$ cd m^2) is used instead of the CIE standard overcast sky since it has been shown that this latter is in fact occurring seldom in reality[20]. Also, the author notes that the ASI is a measure of connectedness between the aperture and the sky, which should be independent of specific sky luminance distribution.

It is not yet clear how these new concepts relate to the previously established CBDM, but ongoing work on this topic is expected to generate useful indicators that can be used at early design phase to predict the potential for sunlighting, skylighting, and view. This approach allows for an initial understanding of performance at the envelope level before spending large amounts of time to predict daylight metrics inside the spaces. One important aspect of this work is the fact that it is fundamentally geometric and therefore suited to be implemented as a Building Information Modeling (BIM) plugin.

7.3.2.1 Daylight Autonomy (DA)

Originally defined by Reinhart (2002)[73], Daylight Autonomy (DA) is the percentage of the occupied hours of the year when the minimum illuminance threshold at a point or a grid of points is met by daylight alone. The DA metric is used to indicate the percentage of occupied hours of the year when daylight is sufficient to eliminate the need for electric lighting[39]. The specific illuminance threshold to use in the calculations is chosen based on the visual tasks and the required amount of daylight needed to perform these tasks. These values are usually obtained from standards, building regulations or values to fulfill environmental certifications such as LEED or BREEAM. In offices, the commonly used threshold values for use in DA calculations are 300 lux or 500 lux, but it is important to note that the applicable threshold should vary depending on the task.

Daylight illumination levels are dynamic and time dependent; the influence of location and orientation also strongly affects the daylight availability in interior spaces. The Daylight Autonomy (DA) metric is advantageous compared to the DF metric because it provides location- and orientation-dependent results. In other words, the DA results will be different depending on orientation and location whereas the same value is obtained with a DF calculation, whether the room is oriented towards the north, south or west or whether it is located in Montreal, Stockholm, or Tokyo.

The calculation of DA necessarily involves using a climate file of a specific location to incorporate the global, diffuse and direct irradiance measurements. This climate data file generates the luminance sky distribution, and creates the global, diffuse and direct illuminance values as hourly data needed as input in the DA calculation.

7.3.2.2 Continuous Daylight Autonomy (CDA)

The Continuous Daylight Autonomy (CDA) metric is a modification of the initial Daylight Autonomy (DA). In the CDA concept, partial contribution from daylight to the room's illumination is computed even when the daylighting level is lower than the minimum required illuminance level[74]. For example, if the threshold is 500 lux, and 400 lux are provided by daylight alone, a 400/500 credit is attributed for this time step in the calculation.

Rogers (2006)[74] classified the CDA metric into different bins:

- 80–100% excellent,
- 60–80% good and,
- 40–60% adequate daylight design.

Even though this metric is not officially accepted in norms and standards, it has been used previously to study the effect of several design aspects such as orientation, window-to-wall ratio, and reflectance in a simulation study of an office room located in Sweden or Canada[75].

7.3.2.3 Lighting dependency (LD)

The lighting dependency (LD) metric was introduced by Danish researchers around 2013[76]. It is in reality more of an electric lighting metric since it defines the percentage of the occupation hours per year when electrical light has to be added to the lighting scene to maintain a minimum work plane illuminance threshold. In its nature, the LD is the reverse of the Daylight Autonomy (DA) or continuous Daylight Autonomy (CDA), mathematically calculated as:

$$LD = 100 - DA \tag{7.20}$$

The purpose of LD is to quantify the benefits of matching electrical dimming with daylight calculations. The LD metric represents the percentage of the occupied hours of the year when electrical light sources are required to maintain a minimum illuminance threshold when it cannot be met by daylight alone.

7.3.2.4 Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy (sDA) is defined as the percentage of an analysis area meeting a minimum horizontal daylight illuminance level (e.g. 300 lux) for a specified fraction (e.g. 50%) of the operating hours per year[77]. The sDA methodology has been approved by the Illuminating Engineering Society (IES) to define a standardized calculation and simulation-based modeling methodology to assess or predict daylight performance. The basis for the illuminance thresholds and performance criteria proposed by the sDA metric is derived from field research, where measured data and expert assessments were collected in 61 buildings[78]. The operating period used is from 8:00-18:00 every day, including weekends, leading to 3650 h per year, regardless of building type, space use, or project location (e.g. latitude). Note that the occupation time is highly problematic for Nordic countries, since the sun sets much earlier (i.e. before 16:00) in the winter and people normally leave work earlier than in North America where the metric was defined. Furthermore in the Nordic region during the winter months, the sun is below the horizon for a large portion of assessment period. Proposals have been made to have an occupation time adapted to the Nordic context. The LEED certification has an alternative compliance path for Nordic projects which allows for assessment during an alternative timespan.

The IES Lighting Measurements (LM) 83-12[79] has defined two performance criteria based on sDA outcomes, 'Preferred' and 'Nominally Accepted'. A $\text{sDA}_{300,50\%}$ value of 75% indicates a space in which daylighting is 'preferred' by occupants; that is, occupants would be able to work comfortably there without the use of any electric lights and find the daylight levels to be sufficient. On the other hand, an sDA value between 55% and 74% indicates a space in which daylighting is 'nominally accepted by occupants'. Although this can be challenging in the Nordic climate, designers should aim to achieve sDA values of 75% or higher in regularly occupied spaces, such as an open-plan office or classroom, and at least 55% in areas where some daylight is important[79].

7.3.2.5 Useful Daylight Illuminance (UDI)

The Useful Daylight Illuminance (UDI) metric originally involved calculating daylight illuminance at each point or grid of points in a room and then determining whether the illumination was insufficient (< 100 lux), useful (between 100-2000 lux) or in oversupply (> 2000 lux)[44]. The authors of this metric used these limits based on reports of occupant preferences and behaviour in daylit offices with user-operated shading devices. Occupation hours of the year where the horizontal illuminance values did not fall within these limits (100–2000 lux) were omitted from the annual summation of UDI.

First published in 2005, the UDI metric used 100 and 2 000 lux as the lower and upper limits for UDI useful or achieved. The upper bound (2000 lux) was revised upwards to 3000 lux a few years later when data from more recent studies became available[80] [81]. Also, a more recent paper[82] about this metric includes a fourth bin, where the different illuminance ranges read as follows:

< 100 lux	UDI fell-short (insufficient daylight)
100–300 lux	UDI supplementary (electric light should supplement daylight)
300–3 000 lux	UDI autonomous (total Daylight Autonomy; no need for electric lighting)
> 3 000 lux	UDI exceeded (daylighting in oversupply)

The 100-3000 lux UDI achieved or useful range is sometimes referred to as 'UDI combined'. Even though at least three numbers are needed to express this metric, the UDI provides an advantage over the DA since it also indicates the percentage of time of a year where over illumination occurs. Despite much criticism in the UK about the UDI metric[83], practical applications suggest that clients intuitively understand the UDI outputs and the metric is helpful in supporting constructive discussions about daylighting design[85].

In 2013, the UK Education Funding Agency (EFA) made Climate-Based Daylight Modelling (CBDM) a mandatory requirement for the evaluation of designs submitted for the Priority Schools Building Program (PSBP) in the UK[85].

7.3.2.6 Annual Sunlight Exposure (ASE)

The IES committee developed another metric to supplement the sDA called Annual Sunlight Exposure (ASE). The ASE is the number of hours per year at a given point where direct sunlight is incident on the surface. It thus describes the potential for visual discomfort in interior work environments[79]. The ASE is calculated using the same analysis points and analysis period as sDA and quantifies the percentage of analysis points that receive at least 1000 lux for at least 250 occupied hours per year, which is why it is expressed with the subscripts $\text{ASE}_{1000,\,250h}$. Three performance criteria for evaluating excessive sunlight penetration based on $\text{ASE}_{1000,\,250h}$ are proposed:

- Spaces with more than 10% $\text{ASE}_{1000,\,250h}$ are considered to have 'unsatisfactory visual comfort';
- Spaces with less than 7% $\text{ASE}_{1000,\,250h}$ are considered 'nominally acceptable';

- Spaces with less than 3% $ASE_{1000,\ 250h}$ are considered ‘clearly acceptable’.

The ASE methodology is also included in the LEED V4 and WELL Building Standard. One should be reminded here that ‘daylight metrics based only on direct sunlight are less robust and show higher sensitivity to simulation settings parameters’, as outlined by Brembilla (2021)[38]. The ASE is generally difficult to meet for the Nordic region because of low solar angles. Furthermore, the ASE is based on the assumption that direct sunlight is always a bad thing, which is not always the case in the Nordic region during the winter months.

7.3.2.7 Annual Daylight Glare Probability (DGP_{annual})

The DGP metric can also be determined using CBDM on an annual basis but some simplifications have to be made. Since all existing glare equations depend on source size, relative position, and luminance, predicting glare using daylighting software requires processing a pixel rendered image of a scene as perceived by a human visual field. When considering multiple positions, views, times of day and year, it is easy to imagine that an annual assessment of glare is very time consuming using traditional methods[84]. Figure 7.27 shows an example of results obtained with annual DGP calculation.

The recent European standard EN 17037:2018[85] defines an annual percentage of discomfort glare hours not to be exceeded (DGP, exceed), which should be lower than 5% for a shading device to protect against glare. The recommendation for glare protection depends on this threshold DGPt, with three levels i.e., minimum (DGPt = 0.45), medium (DGPt = 0.40), and high (DGPt = 0.35).

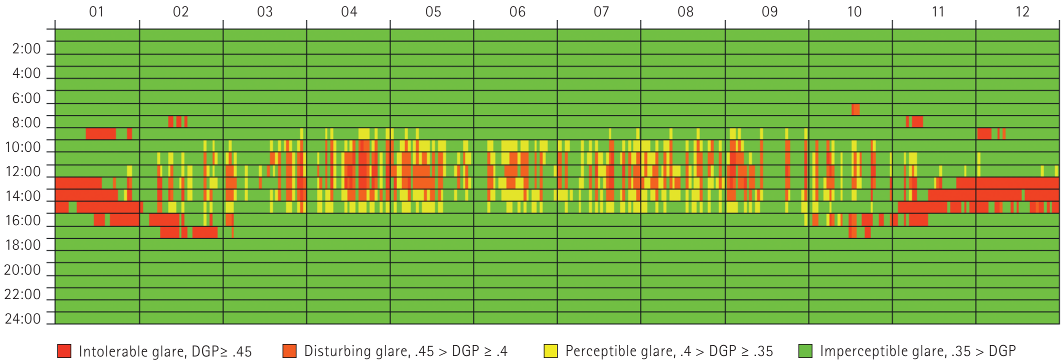

Figure 7.27
Annual DGP glare evaluation produced by Stephanie Jenny Angeraini, White Arkitekter.

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CHAPTER 8

Daylight quality

MARIE-CLAUDE DUBOIS
MALIN ALENIUS (SECTION 8.2)

‘Everything we see can be said to be a spatial context of contrasts.’

ANDERS LILJEFORS, 2000[1]

‘Quality is never an accident; it is always the result of high intention, sincere effort, intelligent direction and skillful execution; it represents the wise choice of many alternatives, the cumulative experience of many masters of craftsmanship. Quality also marks the search for an ideal after necessity has been satisfied and mere usefulness achieved.’

JOHN RUSKIN

‘Quality is generally transparent when present, but easily recognized in its absence.’

ALAN GILLIES, 2011[2]

‘Quality is hard to define, impossible to measure, easy to recognize.’

KITCHENHAM, 1989[3]

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Daylight quality, simplified daylight quality model, early design phase, absolute and relative illuminance, horizontal illuminance, light level, absolute and relative luminance, brightness, contrast, variability, luminance distribution, spatial distribution of light, illuminance uniformity, glare, glare index, discomfort glare, Daylight Glare Probability (DGP), annual Daylight Glare Probability (DGPs, eDGPs), adaptive Daylight Glare Probability ($DGP_{adaptive}$), vertical eye illuminance, colour, colour of light, colour rendering, spectral distribution, flicker, visual interest, directionality, modelling, cylindrical illuminance, cylindrical-to-horizontal illuminance, vector-to-scalar illuminance ratio, shadows, reflexes, mean room surface exitance (MRSE), perceived adequacy of illumination (PAI), luminance gradient, local contrast, visual perception, surround vision, detail vision.

This chapter starts by presenting some light and daylight quality models stemming from different knowledge traditions. The second part introduces a visual quality model for light in space developed and used in Sweden, and in the third part, a simplified model to assess daylight quality through photometric values in architectural spaces is proposed. This simplified model is limited and strictly aimed at assessments performed at the early design stage using computer simulations.

The previous chapters suggest that daylight is important for health and well-being, and generally preferred by building occupants. As a result, one aspect that has received considerable attention in the last decades is the necessary provision of minimum levels of illumination by daylight within built environments. This is reflected in building codes in several countries as well as in environmental certification systems.

Although regulations and certification credits are one step in the right direction to ensure minimum indoor environmental quality, they mainly address the aspect of daylight *quantity* and fail to provide useful information about daylight *quality*. Daylight quality is addressed to a very limited extent by the obligatory requirement on illuminance uniformity in some standards and certification systems. However, light quality depends on many other aspects and is not easy to define as a single concept. An assessment of light quality is nevertheless necessary since the quantity of illumination on the work plane cannot guarantee visual performance, comfort, or a visually interesting and stimulating environment.

Light quality has been addressed by different people associated with different fields of knowledge (illumination engineering, environmental psychology, lighting design, and architecture). Each field has its own methodology and terminology to describe and discuss light quality in space. Leonardo Da Vinci used words such as ‘penumbra’ and ‘shadow’ while some lighting engineers use terms such as ‘flow of light’ or ‘scalar-to-vectorial illuminance’ to discuss light modeling in space. Light quality is also multidimensional, meaning that several aspects of light must be considered in parallel to fully describe it. To make things even more complicated, some aspects of light can be measured with optical instruments (e.g. illuminance) while others can only be assessed through perception (spatiality, ambience, visual interest, pleasantness, etc.).

After presenting a few models of light quality in the engineering and lighting design fields, this chapter introduces a simplified daylight quality model based on photometric values, as a first step towards quality assessments. This model is aimed at the early design phase using computer simulations, where the analysis is based on photometric quantities. It is obviously much easier to evaluate light or daylight quality once the building is erected through observations or by using questionnaires to building occupants. This type of post-occupancy evaluation, which is elaborated in Chapter 14, may also be based on the examination of some of the variables considered in the present chapter.

As indicated by Ruskin's citation at the beginning of this chapter, 'quality marks the search for an ideal after necessity has been satisfied and mere usefulness achieved'. Seeking quality in indoor illumination thus represents an endeavor to move beyond the basic need of useful illumination towards an ideal of visual comfort and pleasantness, and perhaps even visual interest. However, as so rightly expressed by Gillies (2011)[2] 'quality is generally transparent when present, but easily recognized in its absence'. In other words, we normally know when poor quality is present in a room, but it is much harder to define the conditions for good lighting quality. A robust, generally applicable and widely accepted model of light quality has yet to be defined.

8.1 Daylight quality models

In the field of illumination engineering, lighting recommendations have historically emphasized visibility, with a primary focus on electric lighting throughout much of the last century. However, towards the end of the century, the concept of lighting quality—about which there is still no consensus—began to emerge in the scientific literature[4] [5]. Küller (2004)[6] noted a shift in focus from quantity to quality in recent discussions about lighting. Cuttle (2010)[7] claimed that the first stage of the lighting profession was the 'provision of uniform illumination over a horizontal plane,' while the second stage has focused on providing illuminance suited to human needs, based on visual performance.

As discussed earlier, the literature in the field of illumination engineering has traditionally focused on only one parameter to evaluate light conditions: the horizontal illuminance[8]. Measuring illuminance using a lux meter is both accurate and inexpensive, which partly explains why illuminance-based metrics have been widely used in the past decades[9]. However, illuminance levels are only one aspect of the lighting design problem: the qualitative aspect is an even more complex issue because it is affected by the combination of parameters namely, glare, contrasts within the space, colours, and the occupant's own visual and subjective perceptions of the environment[10]. Cai (2016)[9] added that when people see the world, their eyes perceive brightness not illuminance and thus, illuminance-based metrics cannot be used for interpreting the luminous environment of architectural space.

In brief, previous studies and practical experience show that it is not only the horizontal illuminance that is important; many other aspects of the lighting throughout the whole visual field (spectral distribution, luminance, temporal variation in illuminance, etc.) should also be considered[11]. Light quality is thus multidimensional, which is also in line with definitions of quality in other fields. In his book on software quality, Gillies (2011)[2] claimed that 'quality is multidimensional and has many contributing factors; some aspects of quality can be measured (e.g. maximum car speed, fuel economy) while others may not (e.g. car paint finish)'. In addition, Gillies (2011)[2] explains that the most easily measured criteria may not be the most important. Similarly, in the lighting field, the most easily measurable photometric value (horizontal illuminance) may not be the most important determinant of light quality in a room.

Literature in illumination engineering addressing the topic of lighting quality can be traced back to the 1990s and probably earlier. In 1994, the 'Quality of the Visual Environment Committee' of the IESNA[12] identified ten factors that contribute to lighting quality:

- brightness (comparative luminance) of room surfaces,
- task contrast,
- task illuminance,
- source luminance (glare),
- colour spectrum and colour rendering,
- daylight (view),
- spatial and visual clarity,
- visual interest,
- psychological orientation,
- occupant control and system flexibility.

While this model is quite comprehensive, it may be difficult to consider all these variables in practice at the early design phase in a large building. Furthermore, some variables such as visual interest, spatial and visual clarity are difficult to measure although recent developments in this direction are now emerging[13].

In line with the previous model, Veitch & Newsham (1995)[5] subsequently listed the following variables as the main ones to consider for the analysis of light quality:

- illuminance,
- luminance,
- distribution of luminance (contrast between surfaces),
- uniformity,
- glare control,
- flicker (fluorescent tubes),
- spectral power distribution.

This list of variables is approaching a more practical model of quality assessment at early design phases since most of these variables can be directly or indirectly obtained from simulations or measurements.

In 2000, a multi-author book[14] presented a simpler model of lighting quality evaluation including only four parameters namely, illuminance, distribution, glare, and directionality. Each variable was further developed as follows:

Illuminance	Generally a good visibility is defined by the presence of an adequate amount of light allowing the occupant to accomplish his tasks.
Distribution	A uniform distribution of illuminance and luminance is required.
Glare	The absence of glare is a necessity.
Directionality	A directionality of light allows distinguishing objects in space.

This model is much simpler than the previous ones and can be used rather easily in the current building practice for evaluations of light quality in workplaces. It was used as a basis for quality analysis in one research project[15] and is thus at the basis of the simplified model proposed in the third part of this chapter.

Similarly, the European Standard EN-12464 (2011)[16], which focuses on work environments, stated that the main parameters determining the luminous environment with respect to electric light and daylight are:

- luminance distribution,
- illuminance,
- directionality of light,
- variability of light (levels and colour of light),
- colour rendering and colour appearance of the light,
- glare,
- flicker.

This model is now appearing in various standards and monitoring protocols[17] [18] and seems more or less accepted as a comprehensive yet relatively simple way to assess light quality, especially in the context of work environments. It also contains most of the elements mentioned in several other publications. The advantage of relying on this standard is that it provides recommended values (in tables at the end of the standard) for illuminance and its uniformity, discomfort glare, and colour rendering index.

Recent research on the aesthetic judgments of space and daylighting, a subject that has received little scholarly attention so far, underscores that daylighting metrics are not the only factors to consider when evaluating daylight quality. This research found that both the daylighting system and sky type had significant effects on the evaluation of quality attributes (e.g., 'dull-exciting, simple-complex, chaotic-ordered')[19]. How this knowledge can be applied to building design or renovation is still unclear, but it points to a better understanding of the underlying mechanics of light quality and subjective assessments.

8.2 Visual model for light in space

A model based on visual perception to assess light quality in architectural spaces developed by Professor Anders Liljefors has for the last decades been important for lighting design, research and education in Sweden[20], which is why it is discussed in detail here. The model, originally developed for architectural students at the Royal Institute of Technology in Stockholm, is based on direct visual observations of light in space and is a more subtle model in terms of qualitative assessment than all the previous models proposed by engineers. Liljefors (2000)[1], proposed seven variables affecting the visual light experience in a room:

- level of light,
- spatial distribution of light,
- shadows,
- reflections,
- glare,
- colour of light,
- colours.

Liljefors' (2000)[1] model of light quality assessment established a clear distinction between two concepts from different epistemic traditions: light that is measured and light that is perceived. One is physical, pertaining to measurable visible radiation, and the other is visual, related to human perception. His model introduces lighting terminology based on the seven basic visual terms listed above and proposes a visual evaluation method for light in space, relying on these terms. The model was developed to educate Swedish architects and lighting designers, aiming to enhance their understanding of light and their ability to *see*. It generally helps students and practitioners become more aware of the visual environment, enabling them to discuss light with precise terminology.

8.2.1 Seven basic visual terms for defining light in space

A brief introduction to the seven terms for light developed by Liljefors is provided below. Each term is considered part of the overall visual experience of the space.

The seven visual terms are illustrated by images from the convent of La Tourette, Le Corbusier, 1960, Figures 8.1–8.5.

Figure 8.1 Photo: Malin Alenius.

Level of light
– how light or dark it is in a room

The term *level of light* refers to how light or dark a space is perceived. For example, the level of light in a work area may be regarded as high, while the overall space might be perceived as having a lower light level. A monotonous, even light distribution often causes the level of light to feel lower than if the same luminous flux was applied in a more varied way, where the presence of light becomes more noticeable. The level of light is closely linked to different moods. Moving from a bright room to a darker one provides a completely different experience than the reverse. Differences in light levels between adjacent rooms can be used architecturally to direct spatial sequences and create a light-level progression that allows the eyes to adapt.

Spatial distribution of light

– light and shadow as distributed and described by the space

The light distribution is influenced by the design and location of windows and electric lighting fixtures in relation to the room's surfaces and their ability to reflect, absorb and transmit the incoming light. The light distribution can vary from completely monotonous to dramatic and it is a fundamental tool in the design of a space. The daylight in a side-lit room is clearly directional, where the light decreases quickly away from the light source, whereas a room illuminated from above gives a more equally distributed illumination.

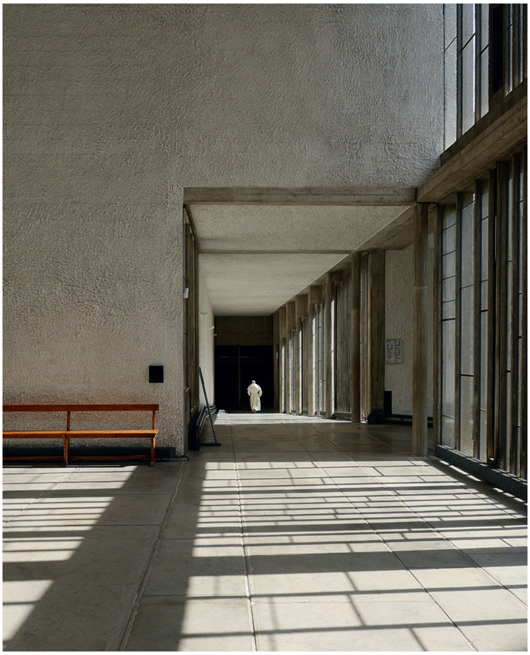

Figure 8.2 Photo: Malin Alenius.

Shadows

– where they fall and their character

Shadows are a highly descriptive component delineating form. They can both emphasize and deteriorate the perceived form of spaces and objects. Not the least, the shadow image is of great importance for how we perceive other people's faces and expressions. The overall shadow cast by the room itself down to the smallest detailed shadow provides information about shape, material, and light direction. Diffuse skylight and direct sunlight produce shadows that are very different. The shadow's character depends on the sharpness or diffusivity, its contour, and difference in brightness in comparison to the adjacent illuminated surface. The shadow image usually has a variation in brightness, where the darkest part is called centre shadow. A shadow is perceived to have colour if the shadow producing light source has a different spectral distribution than the shadow produced from another light source coming from a different angle.

Figure 8.3 Photo: Malin Alenius.

Figure 8.4 Photo: Malin Alenius.

Reflections
– where they occur and their character

Reflections refer to mirror effects on surfaces and may occur on all surfaces, which are not completely mat. Reflections enrich the visual experience by revealing shape, material, and the nature of the light source itself. Reflections are dependent on the direction of vision and as we move, reflections change, creating a sense of life within a space. The experience of reflections is influenced by the reflective properties of the room's surfaces and furnishings, as well as the position of windows and fixtures. Reflections can sometimes create glare and visual disturbance, a common problem in the work environment. Light must be directed correctly in relation to the visual task at hand.

Figure 8.5 Photo: Malin Alenius.

Glare
– where it occurs and how noticeable it is

Glare refers to situations where the brightness contrast in the visual field is too high for the eye to adapt. Glare is characterized as either discomfort or disability glare, as discussed in Chapter 3. The latter occurs when the eye is adapted to a higher brightness than the object of focus in question, such as a computer screen in front of a window. A sharp border between a glaring surface and its background increases the glaring effect.

Glare is mainly addressed in three ways:
- by screening off the glaring surface from the direction in which it is viewed,
- by reducing the contrasts by making the area around the glaring surface brighter,
- by a gradual transition between the bright glaring surface and the darker background.

Colour of light
– the colour experience of light

Colour of light refers to the colour tone perceived to be inherent in the space. The interpretation of the colour of light is the result of an interaction between the properties of the light source and the surfaces in the room. Daylight gives rise to a rich register of colour variations from the warm light at sunrise to the cold white light on a cloudy day. Room orientation also affects the colour of daylight[21]. The colour of light is most apparent when different colours of light are seen simultaneously in a space or when moving between rooms. Coated or tinted glass can significantly affect the perception of colour of light and the atmosphere in a room[22]. The more even the light distribution is in a space, the greater the risk that the colour of light is perceived as greyish. Note also that glare has a negative impact on the experience of light colour.

Figure 8.6 Photo: Malin Alenius.

Colours
– how they appear, as natural or distorted

This term refers to colours perceived directly on surfaces and objects. The experience of colour is influenced by the colour properties of the light source and how different colours in the room interact. Our natural point of reference for experiencing colour is that which we see in daylight, during all its different shifts. The level of light has a major impact on the colour experience. We are better at distinguishing different shades of colour if the light intensity increases; however, this does not mean that all colours are best perceived at a high illuminance level. Some blue colours are best perceived in relative darkness, while many yellow colours lose their luminosity in a dimly lit room.

Figure 8.7 Photo: Malin Alenius.

8.2.2 Visual appraisal – methods and tools used in the design process

Liljefors (2000)[1] expressed that there is no scientific instrument that works as well as our sense of vision. Physical instruments measure light waves of certain frequencies. Our vision, on the other hand, always perceives a spatial whole at the same time as it perceives all the parts that are in relation to each other. To learn more about the visual experience of light in space, we can therefore only truly consider our visual experience and that of others.

One way to map and understand the experience of light in space is through methodical visual evaluation. The qualitative method proposed by Liljefors is a good framework for visual evaluations after the building has been erected. It covers fundamental concepts that interact with each other in the spatial context. The lighting situation in the room is evaluated using the fundamental concepts, both in relation to the function of the room and its spatiality. Through methodical observation, a visual reference library of plausible light scenarios can be formed and then used as a tool in the design process.

The physical model is a reliable tool for investigating the interaction of light in space during the design process, provided that the model's material has valid reflective properties and is studied under correct lighting conditions, and a relatively large scale is used. Full-scale mock-ups placed under true light conditions are often necessary to evaluate colour and material choice in conjunction with light.

8.3 Simplified quantitative daylight quality model for early design phase

This section introduces a simplified quantitative model intended for early design phase evaluations performed by computer simulations, which has been tested in practice within an architectural firm. As opposed to Liljefors' model described in the previous section, the proposed simplified model is based on 'measurable' photometric quantities only. It does not involve direct visual observations although the designer is encouraged to supplement the quantitative evaluations by qualitative assessments of computer renderings or mock-ups, whenever possible. The model is valid only for workspaces such as offices, classrooms and the like. It focuses on identifying values outside known thresholds beyond which light quality is expected to be negatively affected, with a clear focus on task performance (and not overall spatial appraisal). In other words, unlike the recent advances proposed by Rockcastle et al. (2016)[23], this model is concerned with avoiding negative lighting quality rather than producing specific light quality outcome. The model is also mostly useful for spaces where daylight is dominant. We emphasize, again, that the quality of a light environment cannot be deduced solely from the quantity of light through metrics[19]. Thus, a visual assessment of the model (digital or physical) is judged essential before drawing any conclusion on light quality.

For simplicity and applicability at the early design phase of building projects, the focus of this model is on the four parameters:

1. Luminance (absolute and relative)
2. Illuminance (absolute and relative)
3. Glare
4. Directionality

The criteria and interpretation that can be used in the application of this model are summarized in Table 8.1. Each parameter is discussed in detail further down in this chapter. This model does not directly consider colour, flicker (TLM), shadows, and reflexes. Colour is normally not known at the early design phase and can easily be changed later in the design process by selecting appropriate wall or glazing colour. Flicker or TLM concerns the electric lighting system; the best way to avoid it is by selecting a non-flickering lighting system. Reflexes and shadows are difficult to assess because they are view dependent. While these variables should not be overlooked, they concern more detailed features of the architectural project that can usually be adjusted later in the design process, mostly through interior design.

This simplified model attempts to provide a way to verify minimum requirements of light quality in architectural spaces. However, an analysis based on renderings (before the building is built) and observations (after the building is built or with mock-ups) should supplement this quality assessment. In the simplified model, the proposed values (Table 8.1) should ideally be determined for as many points-in-time as possible, ideally using dynamic daylight metrics (DDM) such as sDA and UDI. In a Hong Kong study, the $\text{sDA}_{300\ 50\%}$ has been found to highly correlate with the residents' satisfaction with daylighting in their apartments[24]. However, when annual evaluations cannot be performed due to time constraints, it is possible to analyze daylight conditions at the times listed in Table 8.2 under sunny skies in addition to studying the overcast sky. Note that, at high latitudes,

Table 8.1 Photometric values for work spaces, benchmarks and interpretation in the simplified daylight quality assessment method.

Parameter	Metric	Criteria	Interpretation
Luminance (vertical)	Absolute luminance L_abs	30 cd/m^2	Minimum luminance of surfaces
		100 cd/m^2	Preferred luminance of vertical surfaces behind the VDU
		500 cd/m^2	Maximum average luminance of vertical surfaces and walls Maximum (point) luminance of vertical surfaces for spaces with VDU
		1 000 cd/m^2	Maximum (point) luminance of surfaces and walls (electric lighting only)
		2 000 cd/m^2	Maximum (point) luminance of surfaces and walls (daylighting only)
	Relative luminance L_ratio	< 1:3:10 (or 10:3:1)	Preferable (main task: immediate surroundings: remote surroundings)
		< 1:6:20 (or 20:6:1)	Tolerated (main task: immediate surroundings: remote surroundings)
		> 1:40	Unacceptable (between any surface in field of view)
Illuminance (horizontal)	Absolute illuminance (E_abs, whole space)	20 lux	Lowest threshold for ordinary perception
		100 lux	Threshold for switch-on probability of electric lighting (lower bound of UDI_{reach})
		200 lux	Lower acceptable threshold for continuously occupied spaces
		300 lux	Preferred daylight illuminance in continuously occupied spaces (threshold for sDA)
		500 lux	Upper acceptable threshold for spaces with VDU
		3 000 lux	Upper acceptable threshold (upper bound for UDI_{reach})
	Relative illuminance (ADF)	≤ 1%	Gloomy appearance. Electric lighting on
		2%	Areas distant from window look underlit Electric lighting needed in supplement of daylighting
		2–5%	Preferable range for offices
		5%	Brightly daylit appearance Daylight autonomy Upper threshold for work spaces
		10%	Character of a semi-outdoor space High risk for glare
	Rel. illumin. (Uo)	> 0.4	Informal areas (eating, circulation)
		> 0.6	Task concentration areas (reading, writing)
Glare	Daylight Glare Probability (DGP)	< 0.35	Imperceptible glare
		0.35-0.40	Perceptible glare
		0.40-0.45	Disturbing glare
		> 0.45	Intolerable glare
Directionality	Cylindrical-to-horizontal illuminance (Ez/Eh), room centre or task specific areas	< 0.3	Lighting is too diffuse
		> 0.6	Lighting is too directional

more points-in-time need be studied in the summer as the day is much longer compared to winter. The following sections present a detailed discussion about each variable presented in Table 8.1.

Table 8.2 Suggested days and hours that should be studied for point-in-time studies with sunny sky conditions.

Minimum dates to study under sunny conditions	Times (solar time)
Spring or autumn equinox (20 March or 22–23 September)	9, 12, 15
Summer solstice (21 June)	6, 9, 12, 15, 18
Winter solstice (21 December)	9, 12, 15

8.3.1 Luminance

Several studies have demonstrated the importance of the distribution of luminance within a space, and particularly those of vertical surfaces, where the walls are especially important. Even the ceiling may need to be included depending on the size and height of the room and how much of the ceiling is seen[25].

In the 1980s, a team of researchers surveyed photometric conditions and occupants' assessment of the lighting conditions in 912 workstations in 13 buildings across the United States[26]. They found that the pattern of luminance resulted in low ratings of the lighting system, which called attention to luminance distribution as a key determinant of good lighting design. A few years later, in a study involving 180 subjects, another study[27] showed that wall luminance contributed significantly to the way a room is experienced. With increasing wall luminance, the room was experienced as more stimulating, and it was easier to concentrate on a task. Subsequently, in a study about electrically lit spaces, Carter et al. (1994)[28] demonstrated the importance of luminance of vertical surfaces. They found significant differences between ratings of adequacy and comfort of the lighting of an area with different lighting installations affecting the luminance of walls (under constant horizontal illuminance). The same year, the NIST[29] conducted post-occupancy evaluations (POEs) in more than 20 buildings and found that subjective brightness was clearly an important contributor to perceived lighting quality. The relationship between subjective brightness and average room luminance was stronger than that between brightness and task illuminance. A pilot study[30] indicated that whatever the task, wall luminance had a significant impact on users' satisfaction and appeared to deserve more attention.

Cuttle (2010)[7] introduced a new metric called 'mean room surface exitance (MRSE)' defined as the average value of flux density reflected from all surrounding surfaces in a room excluding direct light from either luminaires or windows. Duff, Kelly & Cuttle (2017)[31] tested this new metric and found a clear relationship between MRSE and both perceived adequacy of illumination (PAI[*]) and spatial brightness, but not between horizontal illuminance and either items.

Two factors accepted as influencing view-dependent visual perception are: average luminance and luminance variation (sometimes called 'luminance distribution')[10 32]. The former has been linked with perceived brightness and the latter with visual interest[33]. Some studies have shown that both mean luminance and luminance distribution within an office environment contribute to occupant preference[34 35 36], whereas others have found that the distribution of luminance values across an occupant's visual field[37 38] and the strength of variation are factors affecting preference[39 40]. Conventional luminance-based metrics include target luminance, background luminance, surrounding luminance, luminance contrast, task-to-background luminance ratios, and luminance uniformity, etc[9]. The European Standard SSI-12464 (2011)[16] states that the luminance distribution in the visual field controls the adaptation level of the eyes, which affects task visibility. This standard expresses that the following should be avoided:

- 'too high luminances which can give rise to glare;
- too high luminance contrasts which will cause fatigue because of constant re-adaptation of the eyes;
- too low luminances and too low luminance contrasts which result in a dull and non-stimulating working environment'.

To translate this long list into simpler words and simplify the assessment task, our model proposes to assess luminance according to two main categories: absolute and relative luminance. The thresholds for each of these two categories are discussed below.

8.3.1.1 Absolute luminance

Even though luminance perception is relative and strongly dependent on the adaptation state of the viewer, there appears to be absolute

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[*] The level of illumination likely judged just sufficient to make a space acceptably bright.

lower and upper thresholds beyond which light quality appears to be negatively affected, which is discussed below.

Minimum luminance

An experiment by Carter et al. (1994)[28] indicated that lighting installations where the wall was darkest were considered both less adequate and less comfortable. In a pilot study with electric lighting, Miller (1994)[12] reported that 60% of the 74 subjects preferred a scene where there was approximately equal lighting energy on the walls and horizontal work plane. Most people preferred the middle-to-high range of wall luminance (58-157 cd/m^2). Another study[27 41] obtained a marked relationship between the preferred work plane luminance and the wall luminance, where the preferred wall luminance was dependent upon the task performed. Reading, writing and interviewing a person indicated preferences in the range 30-60 cd/m^2, while work on a computer screen called for lower luminance, i.e. 20--45 cd/m^2.

One study[33], where a commercial office type interior was investigated, indicated that for the room to be assessed as 'bright', the average luminance within a horizontal band of 40° centered about the eye needed to be at least 30 cd/m^2. In a review of research, Rothwell & Campbell (1987)[42] observed that subjects reported that the light was getting 'dim' when the luminance on a simple visual acuity task ranged from 28 to 110 cd/m^2, while values between 3.6 and 28 cd/m^2 were judged as 'gloomy'. Shepherd, Julian & Purcell (1989)[43] studied subjective assessments of three ambient lighting levels in a complex realistic visual field. They found that ambient lighting was described as 'gloomy' only when the adaptation luminance in the field of view ranged from 5 to 9 cd/m^2. The two other adaptation luminance conditions used in the experiment (6-11, and 38-60 cd/m^2) were not judged gloomy.

In summary, while there is plenty of evidence suggesting that low wall luminance is generally disliked in work environments, a generally accepted minimum luminance value has yet to be defined. However, a value of around 30 cd/m^2 is mentioned several times in the literature[33 41 44 45]. This corresponds to the luminance of a white diffusing surface which receives 100 lux of illuminance. Since many lighting standards recommend 100 lux as the minimum illuminance value, it seems reasonable to consider 30 cd/m^2 as the lower bound for luminance of vertical surfaces in workspaces.

Preferred luminance

A Swedish experiment[46] involving 36 subjects (18-67 years) carried out in two identical office rooms where the ambient electric lighting in the visual field was adjusted to different levels (20, 100 and 350 cd/m²) and colour temperatures (CCT 3 000K and 4 000K), showed that background luminance had an influence on visual, emotional and biological aspects. Alertness was increased when ambient illumination was increased. An increase in ambient light influenced the stress hormone cortisol. Regarding emotional aspects, there was a negative response at the highest ambient luminance, i.e. 350 cd/m², and the subjects perceived the environment in the room as brightest with 100 cd/m². In this experiment, the most positive reactions were found with 100 cd/m² looking at visual and emotional aspects. They thus recommended a preferred luminance of 100 cd/m² for future lighting applications (office context with 500 lux on task). Note that a previous Swedish study[47] on preferred luminance distribution indicated slightly lower preferred luminance of around 80 cd/m² with a horizontal illuminance of 500 lux within the task area.

In line with the Swedish results, a French study[30] indicated preferred average wall luminance of around 120 cd/m² (60 cd/m² at eye level) for reading-writing tasks, and 130 cd/m² (65 cd/m² at eye level) for receiving a visitor in the office room. They also found that for work on VDT screens, a wall luminance inferior or at most equal to the VDT luminance was preferred and that a balanced (i.e. symmetrical) luminance was preferred for the walls surrounding the subjects on each side.

In summary, a preferred luminance value of around 100 cd/m² is mentioned several times in the scientific literature and is thus regarded as the preferred luminance value for walls surrounding the computer screen (considering a horizontal task illuminance of 500 lux).

Maximum luminance

Collins (1994)[29] reported that scenes perceived as bright tend to have high surface luminance (above 100 cd/m²) in the central field of view, but that there is a point beyond which brightness becomes excessive. He stated that luminance values above 800 cd/m² are considered glaring rather than bright. This recommendation is in line with that of the CIE (1983)[48], which indicated that any highlight spots in the room brighter than a threshold of 500-700 cd/m² may cause discomfort glare. In America, the ANSI/IESNA RP-1 VDT Lighting Standard[49] [50] recommended that all room surfaces within the peripheral view, including the window, should not exceed 850 cd/m² given an average VDT screen luminance of 85 cd/m².

For electric lighting, an older Swedish guideline for offices[51] stated that the maximum allowed luminance should be 1000 cd/m² within the visual field and 2 000 cd/m² outside the visual field. Van den Wymelenberg et al. (2010)[52] identified luminance threshold of 2 000 cd/m² for glare sources in a daylit office environment, or seven times the mean luminance of the task position. A recent study[53] about glare concluded that for predominantly saturation (disability) glare scenes, it would be beneficial to use an absolute threshold of 2 000 cd/m². On the other hand, Sutter et al. (2006)[54] found that mean window luminance values should not exceed 3 200 cd/m².

In a more recent Swedish book[20], recommendations for the luminance of the ceiling are also provided: not higher than 1 500 cd/m² at any point and 500 cd/m² for the average luminance of the ceiling. It also recommends that the maximum luminance of walls should not be higher than 1000 cd/m² at any point and the average wall luminance should not be higher than 500 cd/m². In the UK, CIBSE (1994)[55] and Perry (1993)[56] recommended that surface luminances should not exceed 1 500 cd/m² where work on computer is performed and that the luminance of the surfaces and objects behind the screen be kept low, preferably below 500 cd/m².

In summary, although the recommended values for maximum acceptable luminance vary according to research and lighting standard, at least three sources recommend avoiding luminance values above 1 000 cd/m² at any point, and 500 cd/m² appears preferable, especially for surfaces surrounding the VDU and when the surface is in the central visual field. However, these recommendations are mostly valid for electrically lit spaces. For situations with daylighting, it is possible that higher values are tolerated. Vandeplanque (1993)[57] claimed that threshold values used for electric lighting can easily be doubled with daylighting. This may explain why the value of 2 000 cd/m² is found for studies with daylighting.

Thus, considering previous research applied to work environments with daylighting, the analysis framework used to interpret absolute luminance values in the visual field has been simplified to the following benchmarks: 500, 1 000 and 2 000 cd/m² as expressed in Table 8.1.

8.3.1.2 Relative luminance

The importance of considering luminance ratios in the visual environment comes from the fact that the human eye, despite its capacity to sustain great variations in luminance, cannot adapt to large luminance variations at once[58]. Extreme contrasts between two adjacent surfaces can create visual fatigue. It is the average luminance of different surfaces which determines the adaptation of the eye. The speed at which the eye adapts to different luminance ratios depends on the difference between the light and dark patterns[44 59]. For this reason, most lighting guidelines and standards contain recommendations about luminance ratios[16 55 60].

Early research emphasized the need to consider ratios of illuminance or luminance. For example, a Dutch study[61] conducted in four north-facing offices which involved 170 subjects participating in full-day sessions of normal work, concluded that vertical planes and illuminance ratios were important to create the optimum luminous environment and that keeping a constant working plane illuminance would not meet the occupants' needs and preferences. A Finish study[62] reached a similar conclusion after observing how 20 subjects working in an east-facing office adjusted their dimmable lighting system. They observed that some subjects increased the level of electric lighting with increased daylight levels, a behavior which was attributed to the high ratio between the vertical illuminance available at the back of the room and the vertical illuminance near the windows and a high vertical-to-horizontal illuminance ratio.

In general, research about recommended luminance ratios focused on work environments with screen; acceptable luminance ratios in other types of environments have not been studied thoroughly. Cuttle (2013)[77] proposed an approximate guide to perceived difference of illumination brightness related to target-to-ambient illumination ratio based on work by Lynes & Bedöcs (1998)[63], expressed in Table 8.3. According to Madsen & Osterhaus (2008)[64] and Osterhaus (2009)[59], typical recommendations assume a 1:3 ratio between the visual task and its immediate surroundings, a 1:10 ratio between the visual task and other nearer surfaces in the visual field. Meyer, Francioli & Kerhoven (1996)[65] claimed that the maximum luminance ratios of 1:3 in the ergorama (central field of view) and 1:10 in the panorama (peripheral field of view) should be respected[*]. Researchers have also found that for VDU work, screen-to-background luminance in the range of 3:1 to 1:1 are preferred,

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[*] The ergorama is a cone of 60°, centered about the main line of sight while the panorama is a cone of 120-140° centered about the line of sight.

with complaints being more likely when screen-to-surround luminance exceeds levels of 5:1[30 66 67].

Recommendations from the IESNA (2011)[60] are in line with all previous reported research:

1:3	between task and adjacent light-coloured surroundings,
3:1	between task and adjacent dark-coloured surroundings,
1:10	between task and distant light-coloured surfaces,
10:1	between task and distant dark-coloured surfaces,
20:1	between daylight admitting surfaces and adjacent surfaces.

A Swedish publication[44] recommends the following luminance ratios for workspaces:

- the ratio between the task area and the directly surrounding area should not exceed 3:1,
- the ratio between the task area and the 'exterior' surrounding area should not exceed 5:1,
- the ratio between the task area and the peripheral surrounding area should not exceed 10:1.

Table 8.3 Approximate guide to perceived difference of illumination brightness related to target-to-ambient illumination ratio (TAIR), from Cuttle (2013)[77].

Perceived difference	Illuminance ratio
Noticeable	1.5:1
Distinct	3:1
Strong	10:1
Emphatic	40:1

The recommended luminance ratios are challenged by the fact that most people tolerate luminance ratios that clearly exceed the recommended ratios if they are provided with conditions that present 'daylight with a view' [68]. Sutter, Dumortier & Fontoynont (2006)[54] carried out an experiment to validate the 1:3:10 luminance ratios. During a period of four days, they measured the luminance in the visual field of eight employees who spent about 70% of their time working on a task. The measurements were carried out when the occupants expressed that they were satisfied with the light conditions. Data analysis revealed that the satisfying situations corresponded to conditions where the 1:3:10 luminance ratios were respected. However, when a window was present in the visual field, ratios of 1:6:20 were judged acceptable.

A tolerance for a ratio of 1:50 was even observed when the luminance from the window occupied a small portion of the visual field (about 5%). Note that a ratio of 1:20 for the more distant surfaces in the visual field and 1:40 ratio between the task and any surface in the field of view is generally seen as the maximum permissible. A Canadian study[69] in a windowless laboratory experiment involving 47 participants and six workstations in open-plan office showed that the preferred maximum-to-minimum luminance ratio in the visual field was around 20:1 and that luminance ratios experienced during the day had an effect on end-of-day luminance ratio choice.

More recently, van Den Wymelenberg & Inanici (2014)[70] made an analysis of luminance ratios and concluded that current ratios are not able to predict subjective discomfort. Jakubiek (2014)[71] also commented that these recommendations are not based on any human subject studies. He also mentioned that there is a general attitude within the design community that they are too stringent for daylit spaces and only concern electrically lit spaces.

Considering previous research applied to work environments with daylighting, the analysis framework used to interpret luminance ratios has been simplified to values found in Table 8.1. The goal of the luminance ratio analysis is to outline extreme contrasts. Note that the ratios are normalized in Table 8.1, where 1 represents the task, but people normally prefer higher illumination on the task than the surroundings. Therefore, the ratios are also expressed the other way around (10:3:1 instead of 1:3:10). However, in daylit spaces, it is rarely the case that the task receives more illumination than the surroundings as illumination is normally the highest around the window, see Figure 8.8.

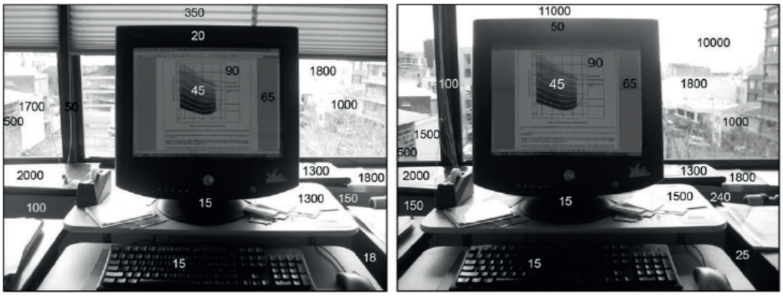

Figure 8.8 Example of photographs of a task with superposed luminance spot measurements, by Madsen & Osterhaus (2014).

8.3.2 Illuminance

According to the standard SSI-12464 (2011)[16], ‘the illuminance and its distribution on the task area and on the surrounding area have a great impact on how quickly, safely and comfortably a person perceives and carries out the visual task’. In addition to illuminance sufficiency for visual tasks, other concerns for sufficient circadian stimulus levels, or excessive daylight levels leading to glare conditions or overheating, can also be deduced through analysis of horizontal illuminance[72].

Generally, a positive association has been found between illuminance levels and task performance[73]. Boyce (1973)[74] reported that as light levels increased, both satisfaction and performance increased. However, these earlier studies examined light levels at low illuminance ranges only. Other studies have shown that satisfaction and performance increased with the increase of illuminance up to a certain point, but as illuminance reached very high levels, satisfaction no longer increased but rather diminished while performance remained unchanged[10]. As expressed by Goodman (2009)[11], ‘simply increasing recommended lighting levels is not the answer: quite apart from the increased energy consumption that would result, more light may lead to increased glare and hence a reduction of visual performance’.

8.3.2.1 Absolute illuminance

Mardaljevic & Christoffersen (2017)[75] pointed out that recent studies have shown either a preference for absolute rather than relative illuminance values, or a better correlation between user assessments of daylight adequacy and the simulated occurrence of absolute values rather than the relative illuminance (as expressed by the daylight factor). The following sections discuss the different benchmarks for absolute horizontal illuminance found in the literature. These values should be analysed for a few typical hours and days (solstices and equinox). However, a more thorough analysis using annual metrics (UDI, sDA) is suggested whenever possible.

Grid size

Illuminance and daylight factor should be analysed for the entire space based on a grid of points. The appropriate size of the grid can be determined based on SS-EN-12464-1 (2011)[16]. According to this standard, grid systems shall be created to indicate the points at which the illuminance values are calculated and verified for the task area(s), immediate surrounding area(s) and background area(s). Grid cells approximating to a square are preferred, and the ratio of length-to-width of a grid cell shall be kept between 0.5 and 2. The maximum grid size can be calculated using the following formula:

$$p = 0.2 \cdot 5^{\log_{10}(d)} \tag{8.1}$$

where

p ≤ 10 m
d Longer dimension of the calculation area (m), however if the ratio of the longer to the shorter side is 2 or more then d becomes the shorter dimension of the area,
p Maximum grid cell size (m).

The number of points in the relevant dimension is given by the nearest whole number of d/p. The resulting spacing between the grid points is used to calculate the nearest whole number of grid points in the other dimension. This will give a ratio of length-to-width of a grid cell close to 1. A band of 0.5 m from the walls is excluded from the calculation area except when a task area is in or extends into this border area. Typical values of grid spacing are also given in the standard[16].

The height for illuminance should be according to the standard work plane height of each specific country. If no standard exists, the measuring height can be 0.85 m as stated in the recent European Standard 'Daylight in buildings'[76].

Minimum horizontal illuminance

Under normal lighting conditions, approximately 20 lux is required to discern features of the human face and is the lowest value taken for the scale of illuminances[16]. Cuttle (2013)[77] noted that for a normal sighted 25-year-old subject, the typical reading task of black 12-point type on white paper requires just 20 lux to provide for the relative visual performance criterion of RVP = 0.98. It is also interesting to note that for vertical surfaces and the ceiling, standard SSI-12464 (2011)[16] recommends that in all enclosed places, maintained illuminances on the major surfaces shall have the following values:

$\bar{E}m > 50$ lux with $Uo \geq 0.10$ on the walls and
$\bar{E}m > 30$ lux with $Uo \geq 0.10$ on the ceiling.

The same standard[16] also requires a minimum cylindrical illuminance (E_z) of at least 50 lux with a uniformity (Uo) of at least 0.10. Cylindrical illuminance is the illuminance on an imaginary cylinder at a relevant height (1.2 m for sitting and 1.6 m for standing positions). These different numbers are an indication that values in the range 20-50 lux should be considered as absolute minimum illuminance values.

Studies have also indicated that the switch-on probably for electric lighting is high for illuminances less than 100 lux and very low for illuminances of 300 lux or greater[78]. Nabil and Mardaljevic (2006)[79] have also considered the range of useful illuminances to be between 100–2 000 lux for workspaces when developing the concept of UDI but this range was later revised to 100–3 000 lux. The recent European Standard 'Daylight in Buildings' [76] also uses values of 100 lux and 300 lux as key benchmarks for the minimum and target daylight illuminance respectively. These different values provide some indication that a lower bound for illuminance should be around 100 lux in workspaces.

Preferred horizontal illuminance

In an American report about daylight metrics[80], the 300-lux illuminance represented the best correlation to occupant preference for daylight sufficiency, based on 61 spaces in California, Washington and New York, comprising 484 occupant questionnaire responses and 324 expert questionnaire responses.

A French study (1997)[30] indicated an average preferred horizontal illuminance of around 325 lux for work on computer, while 425-500 lux was preferred for other tasks (reading/writing, receiving visitors). Mardaljevic & Christoffersen (2017)[75] recently argued that several studies have demonstrated that 300 lux of natural illumination is considered adequate by the majority of building users and also correlates with the notion of a well daylit space[81 82]. A 2003 review of daylighting in schools[83] emphasized that 300 lux of daylight is recommended in several guidelines. Additionally, design levels for electric lighting are increasingly being set at or close to 300 lux[75]. Note also that the 300-lux value is used in the spatial daylight autonomy ($sDA_{300\,lux\ 50\%}$) requirement in the last version of LEED.

Working on computers normally requires illuminance levels which are generally lower compared to reading and writing tasks, while the illuminance level should be adapted to the surrounding luminance. For example, the working plane illuminances recommended for offices in the UK are in the range 300-500 lux, the lower limit being recommended for mainly computer-based work and the upper limit for mainly paper-based work[84].

In Sweden, the average illuminance for each task shall not fall below the value prescribed in SSI-12464 (2011)[16], regardless of age and conditions of installation. In continuously occupied areas, the maintained illuminance shall not be less than 200 lux[44]. The target daylight illuminance stated in the recent European Standard 'Daylight in Buildings' [76] is also 300 lux. For windows, this standard recommends that a minimum illuminance level of 300 lux should be exceeded for over 50% of the space for more than half of the daylight hours in the year. For roof windows, the same standard demands 100% of the relevant area to exceed 300 lux for more than half of the daylight hours in the year.

Maximum horizontal illuminance

While low illuminances may create a gloomy atmosphere, very high illuminances are known to be strongly associated with occupant discomfort[79]. A field study, where workers were allowed to create their own lighting environment by controlling Venetian blinds and varying the intensity of electric lighting, indicated acceptable illuminances in the range 840-2 146 lux in the morning and 782-1 278 lux in the afternoon. In another study in office rooms where the workstation was perpendicular to the window, Roche et al. (2000)[85] found that the visual environment was judged comfortable when the work plane illuminance was below 1 800 lux.

Based on a comprehensive review of data from field studies of occupant behavior under daylit conditions, Nabil & Mardaljevic (2006)[79] suggested that illuminances within the range 100-2 000 lux should be considered as useful while they would be in the category 'exceed' when above 2 000 lux. First published in 2005, the UDI scheme had 100 and 2 000 lux as the lower and upper bounds for acceptable illuminances. A few years later, the 2 000 lux value was revised upwards to 3 000 lux when more data[86] [87] was made available.

8.3.2.2 Relative illuminance

Two aspects of relative illuminance have been traditionally addressed in the literature: the daylight factor (DF), which describes the simultaneous relation between indoor and outdoor illuminance and the illuminance uniformity ratio (Uo), which describes the relation between minimum and average illuminance on the work plane or throughout the space.

Daylight Factor

At present, building regulations and certification systems are moving away from the DF paradigm due to its intrinsic limitations. The DF metric is slowly being replaced with dynamic daylight metrics (DDM) such as the spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI). It is always preferable to perform such climate-based (DDM) calculations when possible. However, at early design phase, it is not always possible to perform DDM calculations due to time and budget constraints and thus, the DF analysis is still worth considering. This metric is also still in use in building regulations and certification systems. Some key benchmarks to interpret DF results are provided below.

Roche et al. (2000)[85] reported on the findings of a survey conducted in the UK in 16 daylit buildings with the participation of 270 office workers. The surveys included questionnaires administered to the facility managers and about 20 occupants in each building in the winter and summer. For each building, they calculated the design average daylight factor (ADF). The results showed that the ADF was a useful predictor of the general daylight level in a space, as well as of the general level of combined daylight and electric lighting. Interestingly, they observed that people were more likely to be dissatisfied with daylight when the ADF was higher than 5%. In line with recommendations of the British Standards Institution[88], they found that ADFs between 2 and 5% resulted in the highest levels of satisfaction. They also observed that satisfaction varied among offices with the same ADF, indicating that other design factors such as orientation and the effectiveness of blinds are also important. Interestingly, high levels of daylighting were generally viewed as more unpleasant than lower levels, which suggested a strong link to glare and overheating[89].

The USGBC (2001, 2003)[90] [91] states that values between 2 and 6% are a design goal while values greater than 6% normally correspond to glaring situations. Tregenza & Wilson (2011)[92] proposed the criteria in Table 8.1 for assessing light quality using DF values, which are in line with previous research discussed in the last sections. The experience of the authors of this book is also that this table of interpretation is quite reliable in practice. Assuming an overcast sky of 10 000 lux, which is standard in Northern Europe, a DF of 1% = 100 lux; DF of 2% = 200 lux; DF of 5% = 500 lux. These values correspond to the absolute illuminance thresholds discussed in the previous section. This framework is thus consistent.

Illuminance uniformity

Illuminance uniformity is normally important in the task area. It is normally measured or calculated on the horizontal work plane as the minimum-to-average illuminance. Illuminance uniformity has been said to be highly desirable, both across the working surface and across rooms[93]. The perception of uniformity has been pointed out as an important factor for assessing daylighting quality among researchers in a questionnaire survey[94]. Another study recently carried out in Hong Kong[95] investigated the effect of daylighting and human behavior on luminous comfort in residential buildings. A total of 340 questionnaires were collected and statistically analyzed. They found that six factors influenced the occupants' satisfaction with daylighting: perception of uniformity, thermal discomfort, external obstruction, solar access hours in summer, expected sunlight hours in winter, and orientation. However, it is important to understand that most of uniformity requirements are valid for workspaces and strive to avoid too low uniformity close to the task. The preferred uniformity ratio may be different in other applications.

The question of what metric to use for energy efficiency and luminous comfort was further investigated for typical Hong Kong residences[96]. This study showed that a static metric uniformity is a key factor of luminous comfort: low uniformity indicated lower luminous comfort. The dynamic metric average daylight autonomy 300 lux (DA_{300}) also showed a high impact on the luminous comfort, with the conclusion that these two metrics could be a useful combination in daylighting design.

The standard SSI-12464 (2011)[16] also states that large spatial variations in illuminances around the task area can lead to visual stress and discomfort. Precise illuminance uniformity recommendations can be found in this standard for specific room functions. Many other lighting standards require a uniformity ratio of 0.8 (minimum/average) or 0.7 (minimum/maximum), but some research indicates that a ratio of 0.5 (minimum/maximum) may even be acceptable, see Dubois (2001)[97]. Researchers[98 99] have argued that these criteria may not be appropriate for interiors lit by side windows, where the tolerance for illuminance non-uniformity may be greater than in the case of electric lighting.

The certification systems BREEAM and LEED also include uniformity criteria. In BREEAM, one compliance path requires a uniformity ratio of at least 0.4 (spaces with glazed roofs, such as atria, must achieve a uniformity ratio of at least 0.7) or alternatively, a minimum point daylight factor in accordance with values provided in a table.

On the other hand, the overall larger scale luminous environment should not be too uniform. Although uniformity is desirable on and around the task area, complete uniformity at larger scale should not be a goal of lighting installations[6 100]. Bean & Bell (1992)[101] found that illuminance uniformity was far less important than illuminance level when they tried to correlate judgements of lighting quality by office workers and lighting performance index.

In summary, the values recommended vary according to room functions but in general, they are within the range 0.4–0.8 for minimum-to-average illuminance in workspaces. In our simplified model, we refer to the standard SSI-12464 (2011)[16], which generally recommends values in Table 8.1. However, it is important to understand that most uniformity requirements are valid only for workspaces (offices, classrooms) and strive to avoid too low uniformity, especially around the task area. The preferred uniformity ratio may be different in other types of applications.

8.3.3 Glare

Glare occurs when excessive brightness in the visual field is present (saturation or disability glare) or when contrasts are too high (discomfort or contrast glare). The avoidance of glare is a necessity for light quality to exist in a room. Glare can be an important issue for users of daylit spaces, particularly glare associated with a direct view of the sky or clouds through windows. Glare levels in buildings can be determined using glare indices, either through direct measurements or computer simulations. A glare index is simply an empirical formula connecting measurable photometric quantities with the glare experienced by research subjects at the moment when these quantities are measured. Many glare indices have been devised over time with various degrees of reliability and it is impossible to review all of them here. The reader is referred to previous publications on this subject[71 87 97].

According to Pierson et al. (2018)[53], the five most commonly used daylight discomfort glare indices are: the Daylight Glare Probability (DGP), the Discomfort Glare Index (DGI), the CIE Glare Index (CGI), the modified Discomfort Glare Index (DGI_{mod}), and the Unified Glare Probability (UGP). The most common glare indices are the ones implemented in the program Evalglare, which is a Radiance-based tool[102]. Apart from the DGP, all glare indices have been derived from research with electric lighting. Therefore, for situations with glare from daylight origin, the Daylight Glare Probability (DGP) elaborated by Wienold & Christoffersen (2006)[102] is the most reliable index currently available, especially for situations involving typical office work with daylighting. The DGP is also the glare index recommended in the recent

European Standard 'Daylight in buildings' [76]. In a recent PhD thesis[71], the DGP was found to be the most robust glare metric, it responds to most simulated daylit scenes including those with many or large solid angle direct or specular luminance sources; it is the least prone to produce misleading or inaccurate glare prediction under a wide variety of daylight conditions.

In a study comparing a side-lit office and an open office, Jakubiek (2014)[71] compared the output of five glare indices (DGP, DGI, UGR, VCP, CGI) and showed that DGI, UGR and CGI correlate strongly, differing often only in their relative intensities. He also showed that the DGP was not very sensitive to contrast but was reliable for identifying situations with excessive luminance. In many simulation studies, the authors of this chapter have also found that the DGP generally returns low values even when luminance ratios are not within the acceptable ranges. Figure 8.9 shows an example of this phenomenon from a student study. The luminance ratio limits should therefore be considered as generally more restrictive than the DGP when studying visual comfort.

However, even the DGP should be used with care as there is to this day, too little research about the validity of this metric in full-scale environments. Van den Wymelenberg & Inanici (2014)[70] found that neither the DGI nor the DGP were capable of accurately predicting subjective occupant responses to glare. Jakubiek (2014)[71], citing the work of Painter et al. (2009)[103], Hirning et al. (2013)[104] and van Den Wymelenberg & Inanici (2014)[70] expressed that detailed surveys and measurements studies of discomfort glare metrics have not shown a strong correlation between perceived and predicted visual comfort. The post-occupancy field study in open-plan green buildings of Hirning et al. (2013)[104] found no correlation between assessments of glare and glare metrics, including the DGP. Another study[103] also indicated that in dim situations, neither DGP nor DGI can predict visual discomfort reliably. However, the DGP has been found to perform consistently better than the DGI for glare predictions[103 105], but it seems to respond poorly to contrast-based discomfort glare (as discussed above). However, it correlates most reliably to subjective ratings[71].

8.3.3.1 Daylight Glare Probability (DGP)

As discussed previously, the Daylight Glare Probability (DGP) is the most reliable glare index to predict glare from daylight origin. It expresses the degree of perceived glare for occupants performing a task (reading, working on task) in a room where the window is covered with a Venetian blind and a foil system or a shading fabric system[106]. This index was developed with no electric lighting based on previous research[107] [108] indicating that electric lighting has a negligible impact on glare level in a daylit space since light from the window is dominant in such situation. The glare level is expressed as the probability that occupants would be disturbed by glare in a given situation (e.g. DGP = 80% means 80% probability of experiencing glare). For clarity, the DGP formula is reproduced below:

$$\mathrm{DGP} = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log\left[1 + \sum_i \left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right)\right] + 0.16 \qquad (8.2)$$

where:

E_v is the vertical illuminance at the eye (lux);
L_s is the luminance of the glare source (cd/m^2);
ω_s is the angular size of the source (perceived at the eye position, -);
P is Guth's position index (-);
s refers to the glare source;
i is the number of glare sources.

The validity of the DGP equation originally lay in the range of DGP values between 0.2 and 0.8 and a minimum vertical eye illuminance of 380 lux[87]. However, the limitation regarding low light condition has since been removed[109]. The constant of 0.16 on the right side of the equation implies that there is a minimum DGP value of 0.16, meaning low glare probability where only 16% of people are likely to experience glare. Note that the left side of the equation represents the illuminance at the eye of the occupant, which has been shown to be an important predictor of glare in previous studies[108]. Jakubiek (2014)[71] observed that the DGP returns values between 0.16-1 (16-100% probability), but that its real range is narrower: values less than 0.35 are typically imperceptible while values greater than 0.45 are typically intolerable[87]. Table 8.4 provides the interpretation for DGP values, as found in Jakubiec & Reinhart (2010)[110] and SS-EN 17037[76]. For annual evaluations, SS-EN 17037[76] provides guidance regarding the maximum allowable time when each glare category can be exceeded (5% for DGP 0.45, 0.40, and 0.35 corresponding to minimum, medium, and high glare protection respectively). The exceedance time is calculated as the percentage of time of space usage time.

Finally, we should mention that no glare index has been developed under the conditions of open-plan office environments or with clerestory or roof windows. It has also been found that interesting views increase the tolerance for glare[111] and this is not yet accounted for in any glare index.

The program Evalglare, which incorporates the DGP and other glare calculations, allows using three different methods for glare source detection: 1) the factor method, 2) the threshold method, and 3) the task area method. The factor method detects pixels with a value higher than the mean luminance of the 180° map of pixels multiplied by a given factor. In the threshold method, all pixels of the 180° luminance map that have a luminance above a certain value, for example 1 000, 2 000, 4 000 cd/m² are identified as glare source, while the task area method detects all pixels with a luminance value higher than the mean luminance of a defined task area in the 180° luminance map multiplied by a given factor. The task method thus requires definition of a task area. The task area method has been shown to provide the most reliable glare prediction method[53 87]. However, one should know that the factor method is more widely used in practice because it is the default method when performing point-in-time glare analysis in the daylight simulation software DIVA-for-Rhino and there is currently no easy way to change this parameter in the standard interface[53]. The user should be aware of this limitation.

For climate-based (annual) simulations, Wienold (2009)[87] also introduced two additional simulation methods: the simplified (DGPs) and the enhanced simplified method (eDGPs). The simplified DGPs method relies on vertical eye illuminance and neglects the influence of peak glare sources. It is thus only valid if the facade neither transmits a direct component nor a peak reflection or scattering in the user's main gaze direction. The enhanced simplified method (eDGPs) uses illuminance values from a DAYSIM simulation for the vertical eye illuminance combined with DGP values obtained from simplified luminance images. This latter method was validated against two hour-

Table 8.4 Interpretation of DGP values.

Degree of glare perceived	Glare value range
Imperceptible glare (mostly not perceived)	$DGP \leq 0.35$
Perceptible glare (perceived but mostly not disturbing)	$0.35 < DGP < 0.40$
Disturbing glare (perceived and often disturbing)	$0.40 < DGP < 0.45$
Intolerable glare (perceived and mostly intolerable)	≥ 0.45

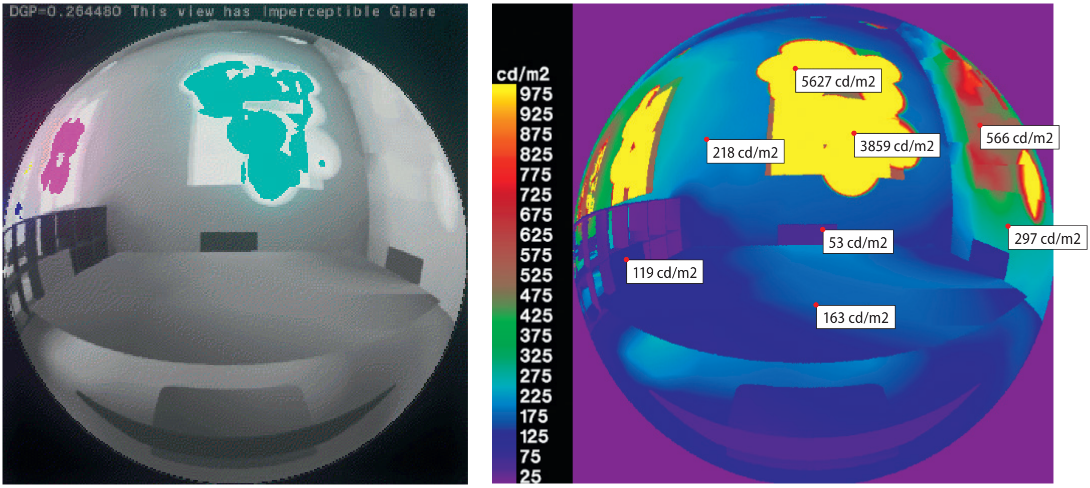

Figure 8.9
DGP calculation (left) compared to luminance ratio analysis (right) by students Rafael Campama, Kinga Erika Fodor, Saima Iqbal.

by-hour full year datasets where a fabric and a Venetian blind shading systems were assumed.

Finally, note that the current DGP index is calculated from a fixed view position and that in reality people normally avoid glare by selecting a body or gaze position away from large glare sources. Based on this simple observation, Jakubiek (2014)[71] introduced a more refined version of the annual glare prediction called adaptive DGP ($\text{DGP}_{\text{adaptive}}$), where the user is allowed to move ±45° from an initial position. He showed that allowing this simple adjustment of gaze angle would significantly reduce glare predictions in many cases.

8.3.4 Directionality

The directionality of light also needs to be checked since a poor light directionality may create poor visual communication and difficulty in recognizing objects and human faces. Interior lighting should not be too directional as this will produce harsh shadows nor should it be too diffuse, which will create a loss of modelling effect.

Adequate light directionality normally creates adequate modelling of light on objects and human faces and makes it easy to recognize them. Modelling describes the balance between diffuse and direct light. According to standard 12464 (2011)[16], the ratio of cylindrical-to-horizontal illuminance (Ez/Eh) at a point is an indicator of modelling. For uniform arrangement of luminaires or roof lights, a value between 0.30-0.60 is an indicator of good modelling according to the same standard. This simple ratio is relatively easy to obtain at the early design phase when running computer simulations. Directionality can be checked either at a single point (e.g. the room center) or at key positions in the room.

When more time and budget are available for light simulations, directionality can be further analyzed by measuring (or simulating) luminance on a perfectly diffusing white sphere located at the center of the room or at any other point of interest. For example, in a classroom, the position of the teacher's head may be of importance for light directionality in space. Note that directionality is easier to evaluate under overcast than clear sky conditions, especially when direct sunlight meets the sphere directly. The directionality can be determined by calculating the vector-to-scalar illuminance ratio[112] as proposed by Cuttle (1971)[113] through the concept of 'flow of light', see Dubois & Gentile (2015)[114] for further details.

8.4 Future of light quality assessment

8.4.1 Mean room surface exitance

It is impossible to conclude this chapter without discussing a recent promising development of a new metric, which paves the way for a more accurate assessment of how appropriately bright a room may appear. This concept introduced by Cuttle (2010)[7] is called 'mean room surface exitance' (MRSE). MRSE is the average value of flux density measured in lux (lm/m²) reflected from all surrounding surfaces in a room excluding direct light from either luminaires or windows. Cuttle presented a simplified equation for calculating the MRSE:

$$\mathrm{MRSE} = \frac{\mathrm{FRF}}{A\alpha} \tag{8.3}$$

Where

FRF is the sum of the direct flux reflected from each surface s after the first reflection only, calculated as:

$$\mathrm{FRF} = \Sigma\, E_{s(d)} \cdot A_s \cdot \rho_s \tag{8.4}$$

$A\alpha$ is the sum of surface areas (A_s) times their absorptance (α) values calculated as:

$$A\alpha = \Sigma\, A_s(1 - \rho_s) \tag{8.5}$$

Where

$E_{s(d)}$ = direct illuminance on surface s (lux)

ρ_s = reflectance of surface s (–)
A_s = surface area of surface s (m^2)
α = absorptance (–)

Dai et al. (2018)[115] recently tested the accuracy of this equation and demonstrated that it was sufficiently accurate when comparing its predictions with the results based on numerical simulations of a wide range of surface reflectance combinations. However, they also showed that the measurement method proposed by Cuttle (2010)[7] may not provide accurate results and suggested that more work is needed regarding measurement of the MRSE.

The MRSE allows assessing average room brightness where there is no specific viewpoint. Thus, it is a promising method useful in architectural practice where hundreds of rooms must be evaluated at once since only one number is needed for each room. According to Cuttle (2010)[7], the MRSE offers the 'prospect of a simple measure that may relate to how adequately illuminated a space will appear to be'. It expresses the average value of indirect illuminance falling on any surface, which may include the cornea of an observer's eye and thus it is believed to correlate more closely to how adequately bright a space appears. Clearly, this new concept represents a radical shift in thinking from assessing light incident on work planes to light arriving at the eye.

A recent study[116] carried out in a small office room with electric lighting demonstrated that the MRSE was found to be a better predictor of perceived adequacy of illumination (PAI) and spatial brightness than horizontal illuminance. While this study confirms that the MRSE is a promising concept for future lighting evaluations, it is limited by the fact that there was no daylight present in the space, non-uniform light distribution was not investigated, the number of participants was limited to 26, and spectral power distribution was not varied, etc.

Raynam (2016)[117] recently tested the hypothesis of 100 lux of MRSE as the lowest level for acceptable bright appearance and found that this level of MRSE would entail that significant extra luminous flux would be required to meet this target and that light distribution with a significant upward component would also be needed. There is thus doubt at the moment whether the 100-lux minimum threshold is acceptable as this would lead to more energy use for lighting.

In summary, although the MRSE is a promising metric to assess perceived adequacy of light in the future, a few aspects of this method need to be solved before it can be used in practice. Moreover, a simulation script or methodology sufficiently robust and simple to be accepted by practitioners needs to be developed.

8.4.2 Local contrast and luminance gradient

Many promising recent developments regarding the assessment of luminance in computer images are worth mentioning as a conclusion to this chapter.

Moving on from earlier work on light quality, a team at EPFL[23] recently worked on light quality models aiming to establish a link between quantitative measures and human perception of daylight composition in digital renderings and their varied effect over time. The originality of this work is that it is moving beyond the identification of negative quality attributes towards positive perceptual performance indicators that can be semantically described as 'contrast, uniformity, variation, direction, complexity, excitement, and stimulation'. This work showed that local neighborhood contrast measures (RAMMG and modified spatial contrast RAMM5) were good predictors of contrast-based visual effects, especially ratings of diffuse–direct, calming–exciting and subdued–stimulating environments. While their research opens possibilities for future evaluations of complex light scenes, the proposed model has so far been essentially based on online surveys only. More work, including a broader range of full-scale architectural spaces and immersive view conditions, is needed before this model can be generalized and implemented in a computer simulation program.

Motivated by a similar endeavor, Cai (2016)[9], introduced the concept of luminance gradient as a metric to assess common non-uniform luminous environments. Luminance gradient is defined as the largest change rate and the polarity of spatial luminance variation on a large surface or across the entire visual field. His luminance gradient was programmed into a MatLab code openly available. While extremely promising, this work is relatively new, and its results have not been validated with assessments from human subjects.

8.5 Conclusion

In conclusion, assessing light or daylight quality is a complex, multi-dimensional task. This chapter presented some of the quality models discussed in the literature within the field of illumination engineering and lighting design. Key variables and benchmarks found in the literature and lighting standards were also discussed, with a focus on identifying ranges beyond which light quality is likely to be negatively affected. However, much more research is needed before these various variables and benchmarks cease to be the subject of lively debates, within and between academic and professional fields. Recent advances in computer imaging and processing certainly pave the way for a smarter future, where the identification of more precise quality aspects seem at least plausible given the powerful imaging and measuring technology available today. More research linking the distribution of photometric quantities in space to the experience of research subjects could establish the bases for a new light quality model (and practice), where detailed quality assessments would be possible at the early design phase, with different benchmarks and outcomes depending on room function, materiality, and context.

It is important to remember that although light can be measured with relative exactitude using instruments and tools like advanced light simulations, direct experience of the space (or a large-scale mock-up) should remain an important part in any assessment, as emphasized by Liljefors. It is the hope of the authors that professionals, academics and researchers gather, discuss and agree on a common light terminology, considering the difference between what we can measure and what we can perceive. Such common terminology would bring clarity to the discussion on light quality with a possibility for advancements and even consensus.

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CHAPTER 9

Design strategies for side lighting

MARIE-CLAUDE DUBOIS

'Architecture is the masterly, correct and magnificent play of masses brought together in light.'

LE CORBUSIER[1]

'A room is not a room without natural light. Natural light gives the time of day and the mood of the seasons to enter.'

LOUIS I.KAHN[2]

'There is a crack in everything. That's how the light gets in.'

LEONARD COHEN[3]

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Functional daylighting, emotional daylighting, side lighting, top-lighting, sky exposure angle, obstruction angle, effective aperture, adjusted effective aperture (AEA), daylight feasibility factor (DFF), daylight feasibility test, no sky line (NSL), daylight zone depth, floor-to-window-head-height rule, window lining, window-head-height, window-to-wall ratio (WWR), spectrally selective glass, glazing visual transmittance, light-to-solar gain (LSG) ratio, Sumpner's law.

The last chapters covered information on the reasons for using daylight, the fundamentals of photometry and colour, the human eye and brain, and the non-visual effects of light. The goal of these chapters was to provide foundational knowledge and concepts to enable the creation of architectural spaces based on daylighting principles, which is the focus of this chapter.

Architecture books are often filled with beautiful images of dramatic daylighting or lighting effects, as seen in Figures 9.1 and 9.2. These images typically depict scenes where direct sunlight enters through small apertures in a much darker room, creating striking contrasts and well-defined light patterns. Such effects are captivating and tend to draw the attention of both architects and the general public.

In the following sections, we will refer to this type of effect as 'emotional daylighting.' Emotional daylighting aims to create striking visual effects that evoke a strong emotional response in the observer. It is a suitable design approach in spaces where a low level of visual performance is required, allowing the gaze to move freely with a distant focal point. This type of daylighting design is often used in churches, crematoria, or other environments intended to foster a contemplative atmosphere.

The daylighting design strategies discussed in the following sections differ substantially from an emotional daylighting approach, as they focus on spaces where:

- visual performance is essential (one must see clearly and distinguish colours and details in both near and far fields of view;
- screens (computers, phones, mobile devices) are used.

This type of environment requires an approach we refer to as 'functional daylighting'.

Functional daylighting aims to provide optimal conditions for visual performance. In functional daylighting design, daylight is used as the primary ambient light source, though it often needs to be supplemented by electric lighting to achieve the necessary visual performance. Figure 9.3 shows an excellent example of functional daylighting at the Malmö City Library, designed by architect Henning Larsen. In this daylight atrium, it is possible to read a book placed on a table on the ground floor, even on a dark, overcast day, without the need for electric lighting.

Both emotional and functional daylighting should be considered in every project, whether it is a functional, circulation, or contemplative space. The circulation area at Kastrup Airport (Figure 9.2) achieves

Figure 9.1
Altar of the MIT Chapel, Boston, Eero Saarinen architect. Photo: Jouri Kanters.

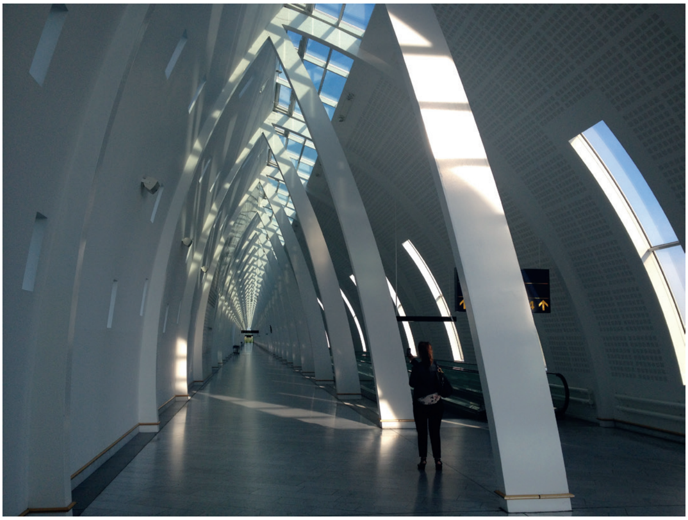


Figure 9.2
Circulation space at the Kastrup airport, Copenhagen. Photo: Marie-Claude Dubois.

Figure 9.3
Functional daylighting at Malmö City Library, Henning Larsen architect. Photo: Marie-Claude Dubois.

sufficient daylight for spatial orientation while also creating dramatic lighting effects. In workspaces, classrooms, healthcare environments, and similar settings, the functional daylighting approach generally prevails, while in social, contemplative, or circulation spaces, the emotional daylighting approach may be more significant. Good daylighting design incorporates both approaches, often within the same building and sometimes even within the same space.

This chapter addresses functional daylighting design through windows, more commonly referred to as side lighting. The next chapter will cover top-lighting strategies, which are useful in deep buildings or spaces where facade access is limited. While side lighting is typically used in offices, classrooms, patient rooms, and similar spaces, top-lighting can be applied in circulation areas (atria, halls), large warehouses, sports halls, and other expansive spaces.

9.1 Side lighting

Side lighting is the most common method of providing daylight in a building. A successful side lighting design requires consideration of at least ten aspects (in this order):

1. Climate and site
2. Orientation
3. Room depth
4. Window size, shape and position
5. Window niche and frame
6. Window glazing properties
7. Visual protection devices
8. Indoor and outdoor reflectances
9. Light distribution within the space
10. Glass in intermediate partitions

These aspects, which can form a basic design framework for side lighting, are discussed in detail in the following sections.

9.1.1 Climate and site

9.1.1.1 Climate

Considering the specific climate of the building's location should be the starting point for any architectural project. The goal is to maximize the benefits of local climatic characteristics and context while minimizing any negative aspects.

The climate of the Nordic countries is unique. Despite some regional variation, it is generally characterized by a high frequency of overcast skies, especially in winter, with sunny conditions occurring relatively rarely. In particularly gloomy years, sunny days may be almost non-existent from early November to mid-February. Matusiak (2017)[4] brilliantly summarized the typical characteristics of natural light in the Nordic countries:

- Low solar altitudes throughout the year.
- Extended periods of twilight with very low solar altitudes.

- White nights around the summer solstice, with occurrences of midnight sun in locations north of the Arctic Circle.
- Low frequency of sunny skies year-round, especially during winter (see Figure 9.4).

We may also add that high latitude results in extreme differences in day length between summer and winter. The short daylight hours in winter

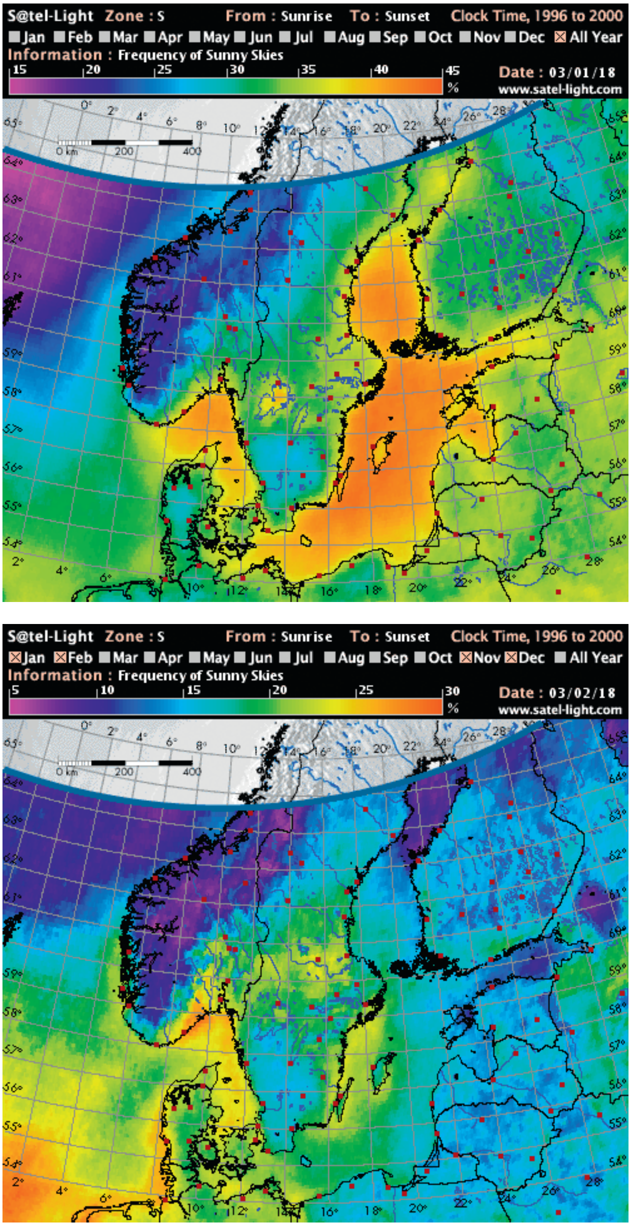


Figure 9.4
Maps of Nordic countries showing the frequency of sunny skies annually (top) and from beginning of November to end of February (bottom), data retrieved from www.satel-light.com.

pose a psychological challenge for people in the Nordic countries, as they leave for work or school in darkness and return home in darkness. The only opportunity to experience daylight during the day is through windows and skylights, unless one takes a regular walk outside at lunchtime. However, even if a midday walk is possible, the typically dark, overcast winter sky provides weak illumination, sometimes less than 2 000 lux of global illuminance in November and December. On the other hand, in northern areas, snow cover can reflect a significant amount of skylight, which helps mitigate winter gloom to some extent.

During the relatively rare occurrence of clear skies, the solar altitude in high-latitude locations is low compared to most inhabited places on Earth. This has implications for facade design, as sunlight penetrates deeply into rooms. Matusiak (2017)[4] showed that in Trondheim (latitude 63°26' N), the sun is between 0° and 10° in altitude 35% of the time over the course of a year. This means that for more than a third of the annual daytime hours, one can expect nearly horizontal sun beams.

Under predominantly overcast conditions, the sky exhibits a brightness pattern typically three times more intense at the zenith than at the horizon. Working with daylighting in such conditions involves utilizing zenithal illumination, especially when incorporating roof lighting. An overcast sky functions as a large, bright diffuse light source. According to a Canadian daylighting guide (2002)[5], 'diffuse light is ideal for daylighting designs, as it is less intense than direct sunlight and therefore easier to control.' Consequently, although the Nordic climate has limited sunlight for much of the year, it is rich in diffuse daylight,

Figure 9.5
Perfectly overcast sky is very common in Scandinavia, Visby, Gotland. Photo: Marie-Claude Dubois.

with zenithal daylight serving as the primary light source. In dense urban streets, an overcast sky is advantageous because it provides a strong vertical skylight component on the street surfaces, which can be diffusely reflected onto adjacent building facades (see Figure 9.5). This effect can be enhanced by using bright, reflective colours for pavements and building facades.

9.1.1.2 Site

Daylighting a building in an open landscape is quite different from daylighting one located in a dense urban setting. Dense urban areas are more challenging due to shading from neighbouring buildings, which primarily affects the lower floors and presents a significant daylighting challenge.

A Master's thesis[6] investigated daylight conditions in a cellular office room located in Lund, Sweden. A total of 11 124 cases were studied using the Rhino-Grasshopper-Honeybee suite. The results showed that an obstruction angle of 60° made it impossible for any design to achieve an average daylight factor (ADF) of 2.1% (BREEAM requirement) or a spatial daylight autonomy (sDA) of 55% (LEED requirement) (see Figure 9.6). This thesis demonstrated that increasing window size cannot compensate for daylight loss in a dense urban context.

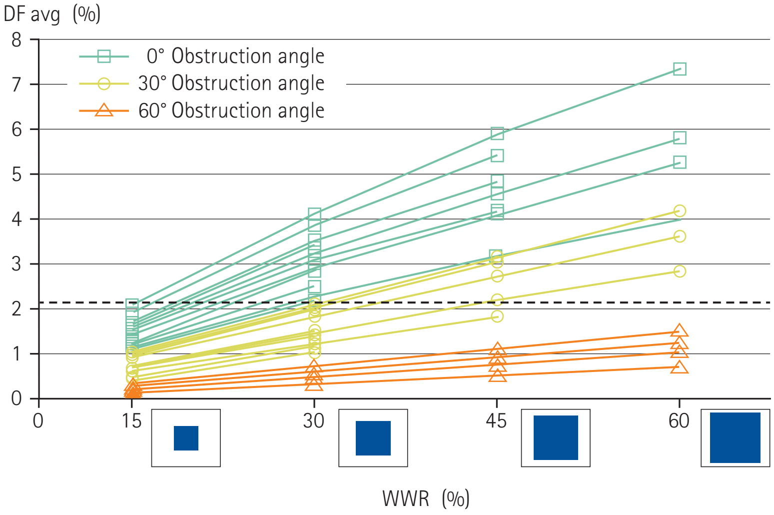


Figure 9.6
Effect of obstruction angle on average DF, according to varying WWR, adapted from Vogiatzi (2018)[6].

Although dense urban environments pose greater challenges for daylighting, they can offer advantages for solar control. For example, in an open landscape, the lower floors of east- and west-facing facades are dramatically exposed to low-angle sunlight, while in a dense urban context, adjacent buildings provide protection (see Figure 7.8). Additionally, in dense urban environments, the reflected light from neighbouring facades significantly contributes to indoor illumination levels.

The issue of urban densification has received increased attention from urban planners in recent decades, as discussed in detail by Rogers et al. (2015)[7]. Rapid urban densification is leading to reduced daylight access in city centers, particularly for the lower floors near ground level.

In some countries, local urban zoning regulations have sought to limit building heights and spacing to control the impact of new buildings on their surroundings. The origin of such restrictions was often related to fire protection. According to Ruck et al. (2000)[8], these regulations evolved into legislation aimed at protecting the right to daylight. This legislation was initially drafted as early as 1792, when electric light sources were scarce, and access to daylight was essential for basic illumination needs.

For example, in England and Wales, the right to light is established under the Prescription Act of 1832. This right is acquired when light has been continuously enjoyed through specific openings in a building for an uninterrupted period of 20 years. Additionally, rights to light can be obtained through three other methods outlined in the legislation. Currently, there is no equivalent legislation to protect daylight access in existing buildings in the Nordic region, but with ongoing densification, it is anticipated that such legislation may be developed in the future.

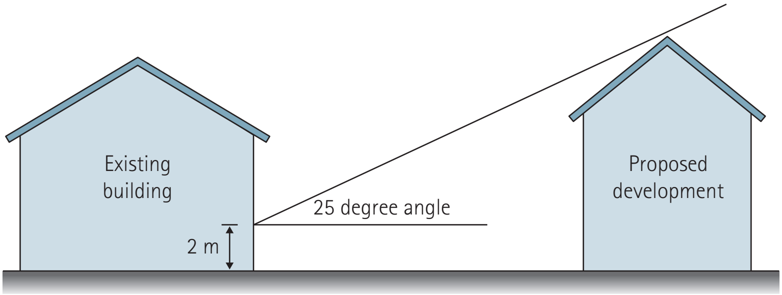


Figure 9.7
The 25 degree angle, according to a British design guideline. Adapted from Littlefair (2011).[36]

When selecting daylighting strategies, designers should consider the extent to which a new building may obstruct daylight access for existing buildings or reflect sunlight that could create glare or increase thermal loads in neighbouring buildings. Separate from the ‘right to light,' which is a civil matter, the UK has also developed guidelines for planning applications. These guidelines include two rules of thumb for use by local authorities.

The first guideline is called the '25-degree test'. This test involves drawing a line from a point 2 meters above ground level on the existing building (assumed to be the height of the window head) toward the top of the proposed building, as shown in Figure 9.7. If the entirety of the proposed development falls below the 25-degree line, it is unlikely to have a detrimental effect on the daylight in the existing property. However, if any part of the proposed building extends above the 25-degree line, further tests are required to assess its impact on daylighting in the existing property.

Other guidelines instead use the sky exposure angle to determine daylighting potential. The sky exposure angle is the angle of visible sky between a line starting 2 meters above ground level indoors and the highest point of the facing building, as shown in Figure 9.8. It is the complementary angle to the 25-degree rule discussed above in the British guidelines. The Canadian guidelines[5] recommend the following limits:

Latitude 50–54°N	Minimum sky exposure angle 64°
Latitude > 54°N	Minimum sky exposure angle 66°

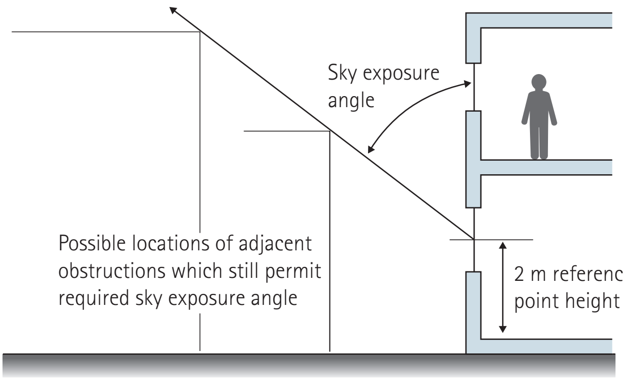


Figure 9.8
Sky exposure angle according to a Canadian daylight design guideline[5].

This recommendation is nearly equivalent to the British recommendation, as 90° - 64° = 26°. Current urban planning schemes in Sweden often involve sky exposure angles that are significantly smaller, typically less than 30° (resulting in an obstruction angle of 60°)[7].

When advanced simulations are not possible, Reinhart & LoVerso (2010)[9] proposed a daylight feasibility test to identify which zones within a building have daylighting potential. The test indicates that if a zone's Adjusted Effective Aperture (AEA) is larger than a specified threshold, known as the Daylight Feasibility Factor (DFF), the zone has potential for daylighting. The original guidelines (PWGSC[10] and LBNL[11]) recommended DFF thresholds of 0.22 and 0.25, respectively. The DFF test was originally defined as follows:

$$\mathrm{AEA} > \mathrm{DFF} \tag{9.1}$$

where

$$\mathrm{AEA} = \mathrm{EA} \cdot \mathrm{OF} = \mathrm{GWR} \cdot \tau_{vis} \cdot \mathrm{OF} \tag{9.2}$$

Where

AEA = Adjusted effective aperture (-)
EA = Effective aperture (-)
τ_{vis} = Glazing visual transmittance (-)
OF = Obstruction factor (-)
GWR = Glazing-to-Wall Ratio (%)

The GWR (Glazing-to-Wall Ratio) is defined as the total area of all transparent or translucent facade openings, excluding mullions and frames, divided by the zone's exterior wall area (A_{wall}). Here, A_{wall} represents the area of the window wall bordering the space, calculated as the product of the space width and the floor-to-ceiling height. The OF (Obstruction Factor) approximates the effect of external obstructions and is determined based on the percentage of the view obstructed from a typical task location.

Based on advanced daylighting simulations with Radiance, Reinhart & LoVerso (2010)[9] recently proposed a revised version of the DFF test:

$$\mathrm{GWR} > \frac{0.088 \cdot \mathrm{ADF}}{\tau_{vis}} \cdot \frac{90°}{\theta} \tag{9.3}$$

where

GWR = Glazing-to-Wall Ratio (%), same as in equation 9.2.
ADF = Target average daylight factor for the space measured at work plane height (%)

θ = Sky exposure angle, i.e. vertical angle of sky calculated from the centre of the glazing (°)

τ_{vis} = Assumed glazing visual transmittance (-)

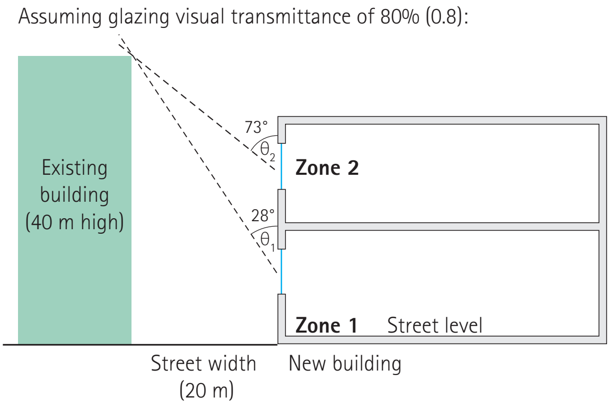
Reinhart & LoVerso (2010)[9] asserted that if Equation 9.3 yields a GWR greater than 80%, the room would require a GWR above 80% to have daylighting potential—a value that is unachievable since frames and mullions typically occupy at least 20% of the external wall. In such cases, the conclusion is that the room has no daylighting potential. Figure 9.9 provides an example of Equation 9.3, reproduced here for clarity.

In complex urban contexts, it is preferable to perform either a VSC (Vertical Sky Component) or VDF (Vertical Daylight Factor) analysis, as recommended in the British guidelines discussed above. The use of VSC analysis has become increasingly common in the Nordic region in recent years. An example is the healthcare project NSM in Malmö, Sweden (Figure 9.10). In this figure, each blue-coloured area on the facade indicates a potential difficulty in meeting indoor daylight criteria.

9.1.2 Orientation

Vitruvius emphasized the importance of carefully considering window orientation in the climate of Rome:

> 'The baths and winter dining rooms should look towards the winter setting sun, because there is a need for the evening light. Besides, when the setting sun faces us with its splendour, it reflects the heat and renders this aspect warmer in the evening. Private rooms and libraries should look to the east, for their purpose demands of morning light...Not less the picture galleries, the weaving rooms of the embroiderers, the studios



Zone 2 Daylight potential

$$GWR > \frac{0.088 \cdot 2\%}{0.8} \cdot \frac{90°}{73°} = \mathbf{27\%}$$

Zone 1 Smaller daylight potential

$$GWR > \frac{0.088 \cdot 2\%}{0.8} \cdot \frac{90°}{28°} = \mathbf{71\%}$$

Figure 9.9
Typical section of a building showing the daylight potential for two specific zones.

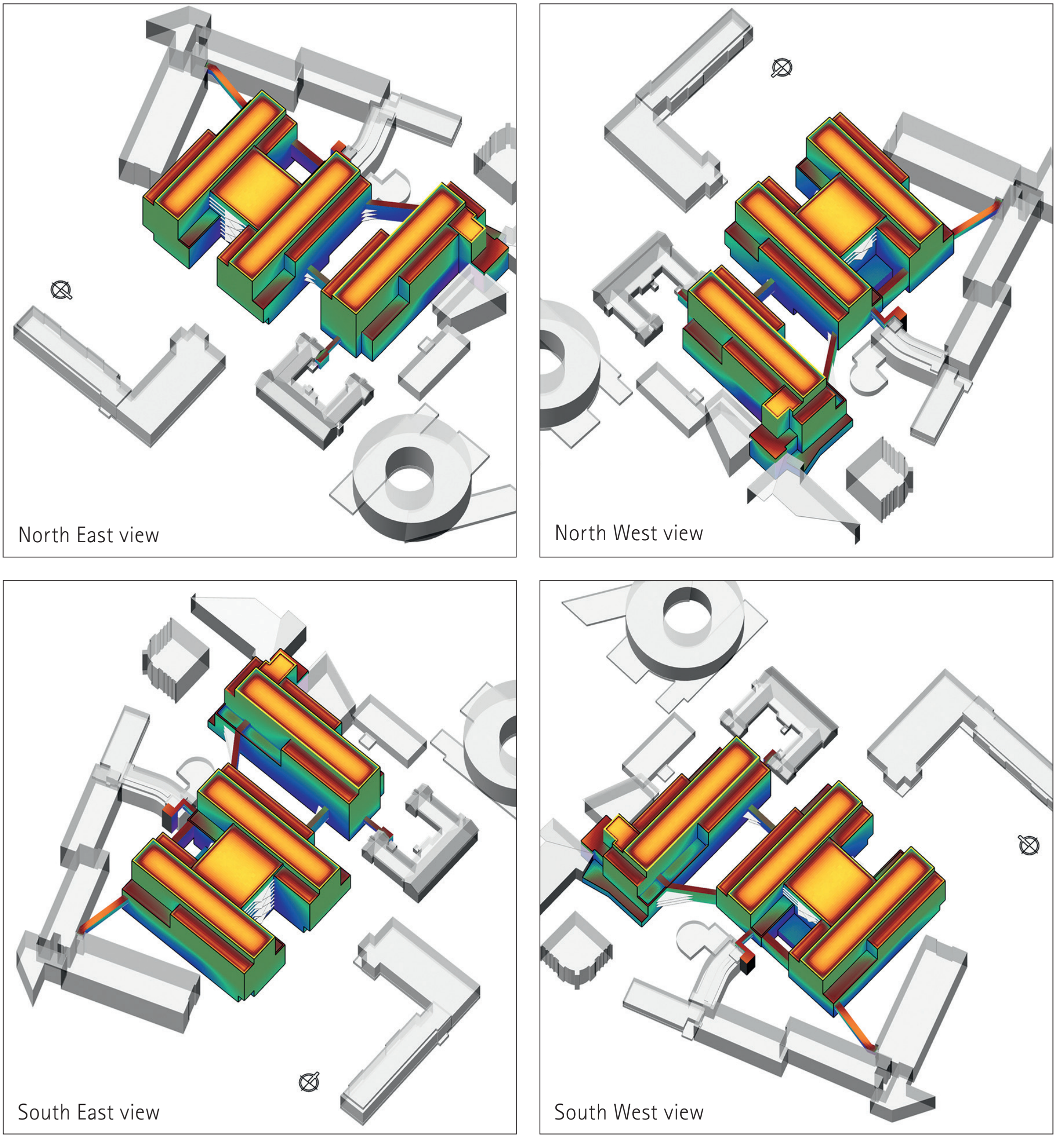


Figure 9.10
VSC analysis of the NSM project, Malmö, Sweden. Simulations: Stephanie Jenny Angeraini, White arkitekter.

> of the painters, have a north aspect, so that, in the steady light, the colours in their work may remain of unimpaired quality.'[12]

This text suggests that orientation affects not only daylighting quality in building interiors but is also critically related to thermal aspects. The issue of orientation cannot be considered separately from glare, thermal comfort, and energy use. Orientation is also closely linked to the dominant colour temperature of light in a space[13], as well as to shading or visual protection strategies, which are discussed later in this chapter.

Orientation is especially important to consider in low-density environments, where buildings are not shaded by adjacent structures, vegetation, or landscape. In dense urban settings, it may not always be possible to determine the orientation of a room or building, as the site is typically constrained by neighbouring buildings. However, when a building is situated in an open landscape, the following guidelines are suggested for buildings with high internal heat gains (such as offices and commercial spaces) located in the Northern Hemisphere:

- Optimize south orientation for daylighting (using adequate solar shading).
- Exploit north orientation for spaces requiring visual performance.
- Avoid east and west orientations.

These recommendations are not directly transferable to residential premises, where sunlight from a west-setting sun may be desirable in a living room, while morning sun from the east may be beneficial in a kitchen or bedroom. A recent simulation study[14] of a residential living room in Malmö, Sweden, occupied between 18:00 and 22:00, indicated that a west orientation achieved higher daylight autonomy than other orientations, as the occupancy schedule aligned with sunlight availability.

South orientation

In the Northern Hemisphere, south orientation provides the highest solar heat gains, and these gains are generally easier to control since the sun is higher in the sky when facing this direction. South orientation also offers the highest daylight autonomy[6] and is best suited for rooms that require abundant daylight during the day, provided that an efficient and correctly sized shading device is installed to prevent glare and overheating. A properly shaded south facade also offers symmetrical sunlight conditions with respect to noon, meaning that abundant daylight is available throughout the workday. Note that only marginal reductions in daylighting performance will occur for windows facing 30° east or west of true south[5].

A successful shading solution for south facades includes a horizontal overhang above the window, horizontal slats, or a movable awning. However, in the Nordic climate, a horizontal overhang may not always

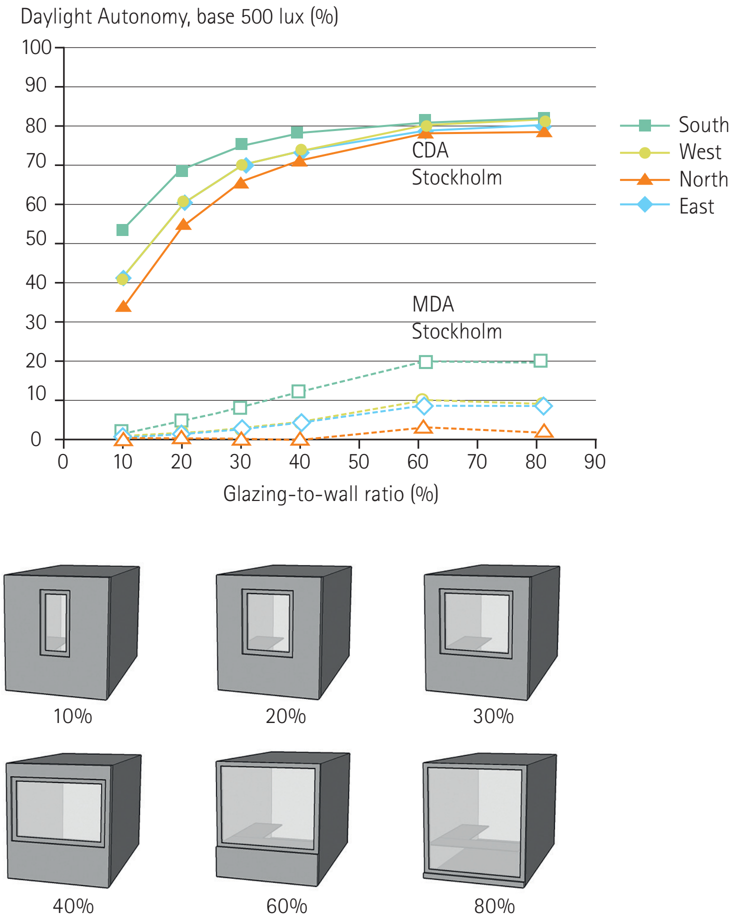


Figure 9.11
Continuous daylight autonomy for an office room of varying glazing-to-wall ratio in Stockholm (glass LT was 72%).

be effective. Because the sun's path is so low on the horizon, the overhang can allow solar rays to reach a significant portion of the glass area at angles close to normal, which can lead to glare and overheating. Additionally, a horizontal overhang may unnecessarily limit daylight access on overcast days. Therefore, movable or dynamic shading devices are often a more suitable solar shading solution in the Nordic context.

North orientation

Although daylight exposure is less abundant on the north facade, the near-constant availability of diffuse skylight makes this orientation desirable for functions with high internal heat loads (such as offices and commercial spaces). In larger buildings, where light uniformity and quality are important, moderate to large north-facing glazing areas can minimize reliance on electric lighting. Consequently, north-facing rooms can be ideal for ambient daylighting in landscape offices, artists' studios, or any other function requiring good visual performance without the nuisance of direct sunlight. Additionally, north windows offer the lowest probability of glare in offices[6].

A study[15] on continuous daylight autonomy (CDA) for single office rooms located in the building periphery indicated that CDA was as high as 70% for a non-obstructed, north-oriented office with a 40% GWR (LT = 72%) in Stockholm (Figure 9.11). In comparison, the CDA value for the same office oriented towards the south without a shading device was 77%. A south-facing window would require shading, and the CDA of the south-oriented room would likely be at the same level or even lower than that of the north facade. Reinhart (2002)[16] studied the influence of various design variables on daylight availability and electric lighting requirements in 1 000 open-plan office settings relevant to 186 North American metropolitan areas. The simulation results revealed that daylight availability in perimeter offices was highly dependent on the underlying blind control strategy. If the blinds were permanently retracted, the northern facade exhibited the lowest energy savings; however, when an automated shading system was employed to exclude direct sunlight, the resulting energy savings were similar for all facade orientations.

These studies generally suggest that daylight potential is not insignificant for north-oriented rooms, even in the Nordic context. In landscape offices, the north orientation works particularly well, as the absence of external solar shading devices ensures that all office workers—even those sitting close to the core—can maintain a view through the windows. This solution was successfully implemented in the GSK building in Quebec City, Canada (Figure 9.12), where visual comfort was investigated by Cantin (2011)[17] using Evalglare (Radiance) and Lightsolve. This study showed that there was no glare probability during working hours for the north-facing landscape office. Additionally, a post-occupancy evaluation of the building confirmed a high level of satisfaction among office workers regarding indoor climate and visual comfort.

When landscape offices face any direction other than north, there is a high risk that shading devices will be deployed by the workers sitting next to the window and remain down for the entire day (see Figure 9.13).

East–west orientations

Daylight on east and west orientations is difficult to control under sunny conditions, as the sun is generally much lower when shining on east or

Figure 9.12 North facing landscape office of the biotechnology company in Quebec City by Coarchitecture. Photo: Stéphane Groleau, plan drawings (below) by Coarchitecture, Quebec.

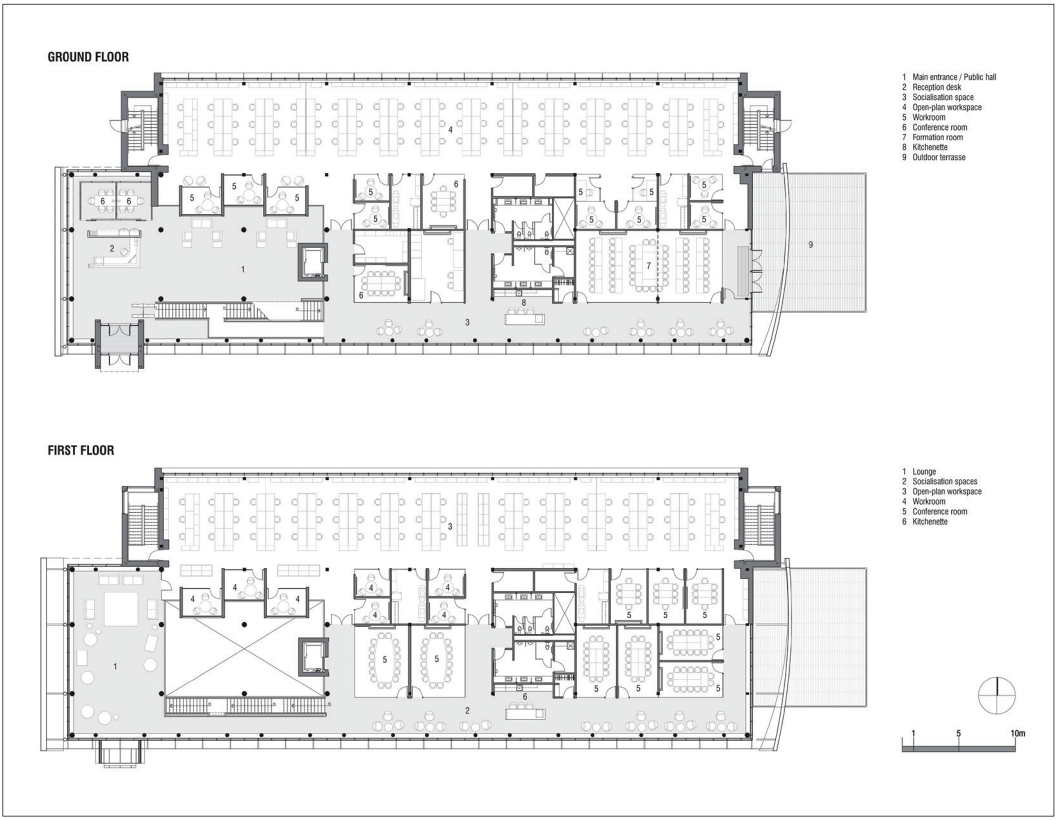


Figure 9.13 Landscape office in Stockholm showing blinds left down even after occupation. Photo: Marie-Claude Dubois.

west facades. This is especially critical in Nordic countries, where the sun can be incident on these facades for extended periods.

Bülow-Hübe (2007)[18] analyzed the impact of Venetian blinds on the indoor climate and energy use of an office room through computer simulations and measurements conducted in a laboratory in Lund, Sweden. She demonstrated that during all studied periods for the east-facing office, the effective solar altitude reached 90°, indicating that fully closed slats were necessary to prevent sunlight from entering the room. This shading solution, however, blocked both diffuse daylight and view.

In terms of thermal aspects, east and west orientations differ significantly. In buildings with high internal heat gains, the west orientation is the most problematic due to the building's thermal inertia and accumulated heat at the end of the day, leading to overheating or increased cooling demand. In contrast, the east orientation is more acceptable and can even be preferred in buildings where morning sunlight is desirable, such as residential kitchens, bedrooms, daycare rooms, or classrooms equipped with movable shading devices.

When the design goal is to maintain views and diffuse daylight, dynamic vertical screens or a sawtooth facade profile can be utilized with glass oriented toward the northeast or northwest, as demonstrated in a student project (Figure 9.14). Angling the glass away from direct sunlight is one way to reduce intense sunlight beams and the need for shading. However, a sawtooth arrangement of the facade or roof generally results in higher thermal losses, as both the envelope surface area and thermal bridging are increased.

Additionally, east and west orientations create an asymmetrical sunlighting situation with respect to the normal work schedule. One alternative solution for east and west-oriented facades is to design a shallow building plan, where rooms on the east side are shaded in the morning and illuminated by diffuse sky light from the west side, and vice versa in the afternoon (Figure 9.15). However, this solution necessitates the use of either an open-plan layout or glazed partitions between individual rooms and the corridor.

Figure 9.14 Sawtooth profile of the West façade (left side on the picture). On the south side (right), the glass is oriented towards the street. Student project, Laval University. Photo: Marie-Claude Dubois.

9.1.3 Room depth

Once the site, building shape, and orientation are determined, the next aspect to consider in the design process is the depth of the daylight zone. In the case of an ordinary rectilinear room illuminated by windows, it is important to note that daylight diminishes rapidly from the facade (Figure 9.16). This rapid decline in daylight is often viewed as a major drawback of sidelit spaces, particularly in deep rooms.

A well-known and validated rule of thumb for determining the daylight zone in a sidelit room is the floor-to-window-head-height rule. Some researchers have referred to this as the 'ubiquitous rule-of-thumb (URT)' for window sizing. This rule of thumb is found in various design guidelines (see Reinhart, 2005)[37]. The URT relates the depth of daylight penetration, or daylight zone, to the window head height (H) from the

Figure 9.15 Rotating vertical slats for the east-west façade of the GSW building in Berlin. Photo: Michael von Aichberger/Shutterstock.

floor, with the depth of the 'effective daylight zone' ranging from 1.5H to 2.5H (Figure 9.16).

According to a validation study[19], the exact relationship of the URT (1.5 or 2.5H) is largely influenced by glazing type and target illuminance. When a room does not require shading devices, the ratio can increase to 2.5H. What Reinhart (2005)[37] referred to as the daylight zone corresponds to the area in which target illuminances are routinely met through daylighting during occupancy hours, indicating a daylight autonomy (DA) of 50%. The URT helps determine where to place spatial programs that require daylight within the building envelope. Circulation areas, storage, or service functions can then be positioned in areas outside the daylight zone, closer to the building core.

Boubekri (2014)[19] argued that the URT is vague; the conditions under which it applies, and the window size are not specified. He tested the URT through simulations and showed that the window-head-height is not the only parameter affecting the daylight zone depth. The window width also has a significant effect, leading to the following statements:

- The URT may have some validity only when the window width is nearly equal to the room width.
- Both window height and width are equally important in allowing daylight into a room.

To summarize, while the URT is not precise, it is sufficiently precise for the early design phases when daylight zoning needs to be established

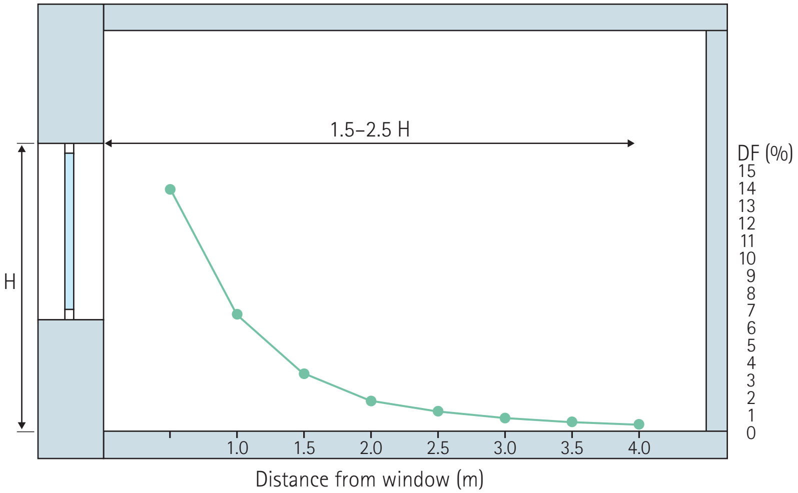


Figure 9.16
Daylight diminishes rapidly from the window. Depth of the daylit zone where daylight autonomy is at least 50% is approximately twice the window-head-height.

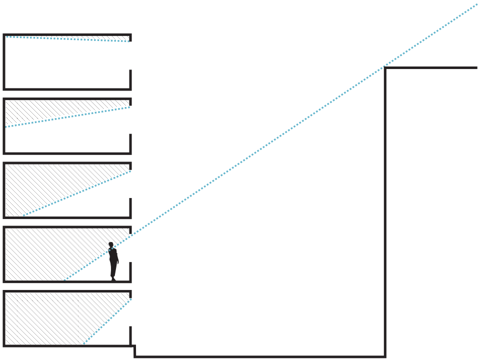


Figure 9.17
The no sky line changes in relation to level. Drawing by Malin Alenius.

in the building plan, especially if the window can be assumed to cover most of the room's width.

In addition, this rule of thumb is only valid for buildings with a low level of obstructions (obstruction angle < 30°). In dense urban areas, the daylight zone is instead determined by the no-sky line (NSL), which is a line between the top of the window and the top of the facing building. This line essentially determines the boundary between direct and indirect daylight inside the room. It is important to note that the area behind the NSL only receives indirect daylight. A simple sectional drawing of such a situation shows that as building height increases, the obstruction angle also increases, and the daylight zone is shallower on the lower floors compared to the upper floors (see Figure 9.17). In some cases, additional glass may be needed on the lower floors to compensate for reduced daylight access.

When the urban context is very complex, it is preferable to determine the interior daylight zone during the early design phase using computer simulations. This type of analysis was conducted for the NSM project in Malmö. In this case, an advanced Grasshopper script using Radiance was programmed to determine the daylight zone depth on each floor, assuming a continuous window strip along the external wall (see Figure 9.18). This information was useful in placing the spatial program inside the building, with peripheral areas designated for patient rooms or spaces for continuous work (offices or the like).

9.1.4 Window size, shape and position

9.1.4.1 Window size

Since even high-performance glazing provides inferior thermal resistance compared to insulated wall constructions, window areas need to be carefully sized to achieve the right balance between daylight, heat loss, and solar gain. Optimal window sizes depend on whether the building's energy balance is dominated by envelope losses (referred to as 'envelope-dominated buildings') or by internal heat loads (referred to as 'internal-load dominated buildings').

Envelope-dominated buildings

In the Nordic climate, envelope-dominated buildings, such as residential premises, benefit from passive solar heat gains during daytime. However, passive solar gains can only compensate for nighttime heat losses on south-facing orientations, provided the building envelope is very well insulated (U-value 0.1 W/m^2K) and equipped with high-performance windows (U < 1.0 W/m^2K). A recent study[14] for a multi-family residential tower located in Malmö, Sweden, showed that it is preferable to have slightly larger window sizes on the south (60% window-to-wall ratio, or WWR), intermediate window sizes (40% WWR) on the east and west, and small WWR (30%) on the north side (see Figure 9.19). On the south facade, the objectives of daylighting and low heating loads are not in conflict due to beneficial passive solar heat gains, which reduce heating demand. Therefore, larger south-facing windows are advantageous for both good daylighting and low heating demand. However, the study also indicated that large windows could

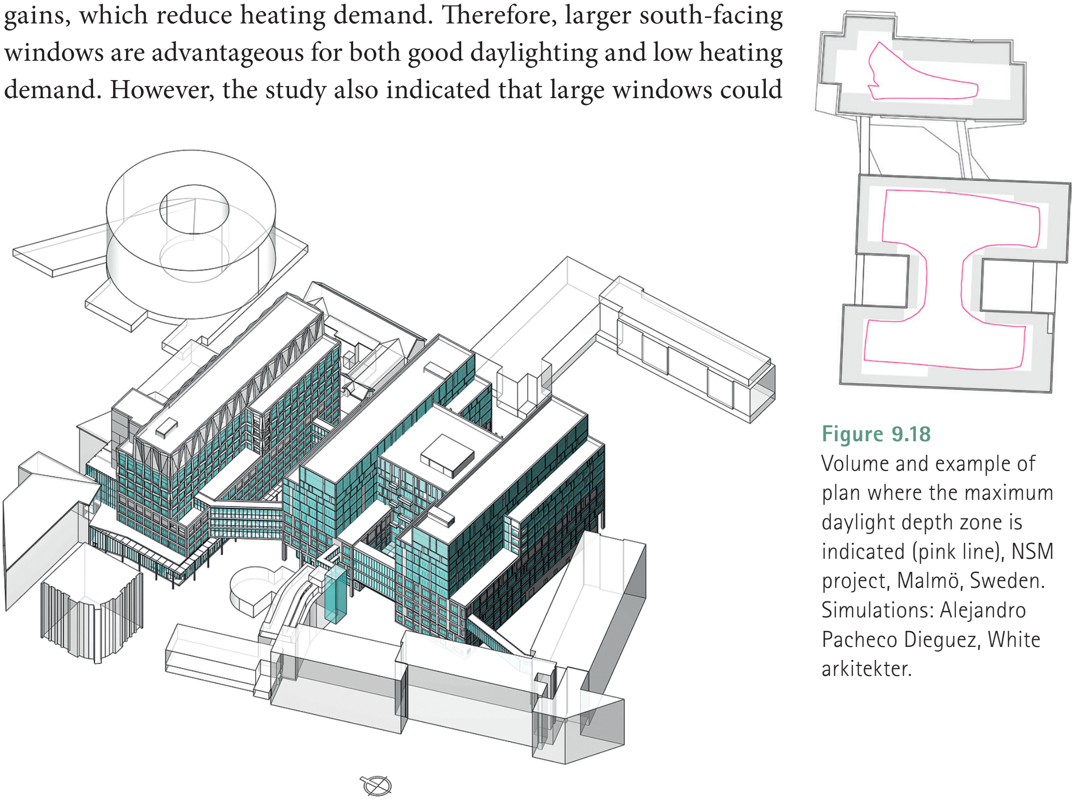


Figure 9.18
Volume and example of plan where the maximum daylight depth zone is indicated (pink line), NSM project, Malmö, Sweden. Simulations: Alejandro Pacheco Dieguez, White arkitekter.

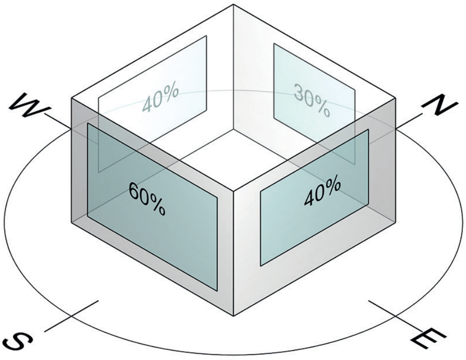


Figure 9.19
Optimal WWR (with respect to interior wall) for envelope-dominated buildings (houses), Sweden. Drawing: Stephanie J Angeraini, White arkitekter.

lead to problems with overheating, necessitating efficient exterior dynamic solar shading devices on the south side of the building.

On all other orientations, passive solar heat gains are not sufficiently large to compensate for the additional heat losses associated with large windows. Therefore, one should be cautious when selecting large windows for east, west, and north orientations. Fortunately, previous research and past experiences indicate that a window-to-wall ratio (WWR) of around 30% is sufficient for properly daylighting a room.

Internal loads-dominated buildings

In buildings where the energy balance is dominated by internal heat loads from people, equipment, and lighting—such as in office buildings—large windows often lead to overheating and glare problems. Most research in cold climates at high latitudes suggests that a relatively moderate window-to-wall ratio (WWR) of 30-40% is optimal in such buildings. For example, a post-occupancy evaluation[20] of 20 Danish office buildings with perimeter offices and workstations positioned up to 7 meters from windows indicated that, regardless of orientation, the

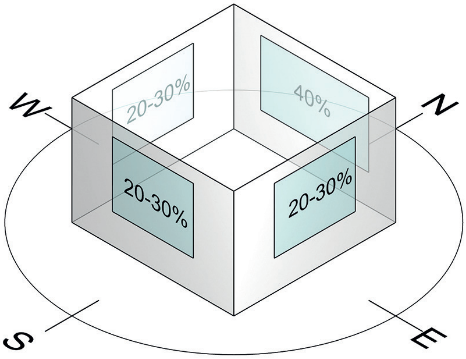


Figure 9.20
Optimal WWR (with respect to interior wall) for internal-load dominated buildings (offices). Illustration: Stephanie J Angeraini.

number of office workers judging the windows to be either too small or too large increased when glazing areas were smaller than 20–25% or larger than 30–35% of the building facade.

A study[21] conducted in Montreal, Canada, for a perimeter office indicated that, with a 30% window-to-wall ratio (WWR) and a south orientation, daylight provided the space with 500 lux on the work plane for 76% of the annual working hours. Increasing the WWR above 30% did not yield a significant increase in useful daylight (only 9% more for 80% WWR). Thus, the 30% WWR was identified as the daylighting saturation region for south-facing facades in Montreal. These results align with findings from other studies[22 23].

In Sweden, Bülow-Hübe (2008)[18] investigated light distribution, daylight factors, daylight availability, and lighting electricity use in individual and open-plan offices using computer simulations for Gothenburg with a south orientation. The effects of several facade solutions were compared, with window-to-wall ratios (WWR) of 30%, 60%, and 100%. The results indicated that, for the case with 100% WWR and louvres, daylight autonomy was 50%, while it decreased to 45% for the case with 60% WWR and louvres. She concluded that an office glazed to 100% does not provide significantly more daylight at the office desk than a 60% glazed office, both with and without a shading system. The results also showed that the daylight factor does not increase in direct proportion to the glazed area. She concluded that very large windows do not automatically ensure better or more abundant daylight.

The same conclusion was reached in a study[15] of daylighting in single office rooms located on the perimeter of buildings in the climates of Sweden and Canada. This study showed that the optimal glazing-to-wall ratio (GWR) for an office in Stockholm, Malmö, Gothenburg, or Östersund was between 20% and 40%, considering only daylighting aspects, with a glazing light transmittance (LT) of 72%. Continuous

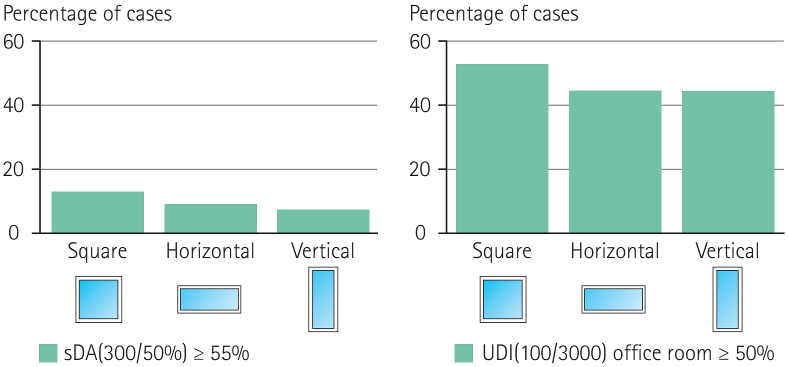


Figure 9.21
Effect of window shape on daylighting according to sDA and UDI, from Vogiatzi (2018).[44]

daylight autonomy sharply increased as GWR increased from 0% to 30% but stabilized afterward, typically following a 'diminishing returns' benefit curve, as demonstrated in numerous previous studies. The study showed that the benefits of increasing the GWR from 40% to 60% are marginal and negligible for an increase in GWR from 60% to 80%. For the south orientation, a 20% GWR provided good daylight design without major direct sunlight risk. The authors concluded that there were significant benefits to increasing the GWR from 10% to 20%, but the benefits of increasing the GWR from 20% to 40% must be weighed against the additional costs of cooling and heating. However, for the north orientation, the 40% GWR provided significantly higher continuous daylight autonomy (CDA) compared to the 30% GWR, without any additional direct sunlight risk (see Figure 9.11). It is important to note that these results are valid only for a building without obstructions and with a high LT.

In internal load-dominated buildings, the optimum window-to-wall ratio (WWR) is between 20% and 30% for the south, east, and west facades, while it can be slightly larger (40%) for the north facade, which is devoid of direct solar heat gains during the workday (see Figure 9.20). The west facade is especially at risk of overheating since the

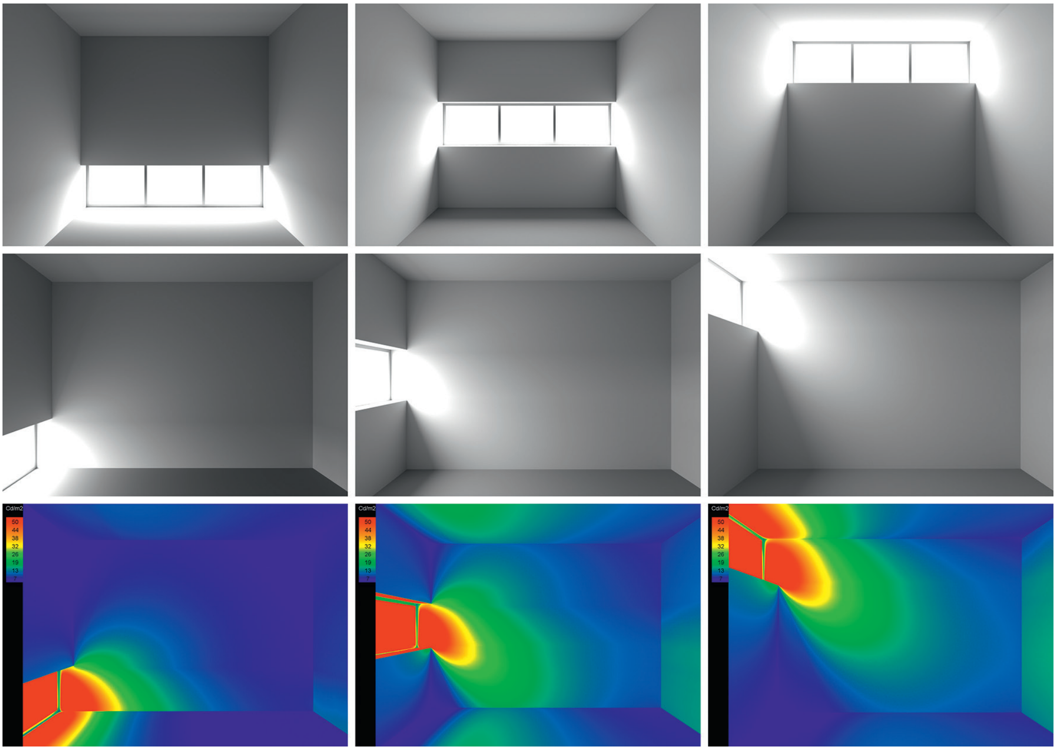


Figure 9.22
The same window shape and size yield the same heat losses and gains but very different daylight distribution in the room. Simulations by Stephanie J Angeraini.

Figure 9.23
Example of windows placed high up: Mariavalls kloster, Tomelilla, Sweden (photo: Jouri Kanters; top) and at the Medborgarhuset in Eslöv, Sweden (photo: Nicholas Wakeham; bottom).

building tends to be warmer toward the end of the day. Large WWRs usually mean that the shading devices will be pulled down more often, drastically blocking views and daylight.

9.1.4.2 Window shape

The window shape also affects daylight levels and distribution within a room. A recent master's thesis[6], which simulated 11 124 cases for a cellular office in Lund, showed that square windows more frequently complied with $sDA_{300\text{-}50\%}$ and $UDI_{100\text{-}3000}$ metrics. Vertical window shapes demonstrated the lowest performance in terms of $sDA_{300\text{-}50\%}$,

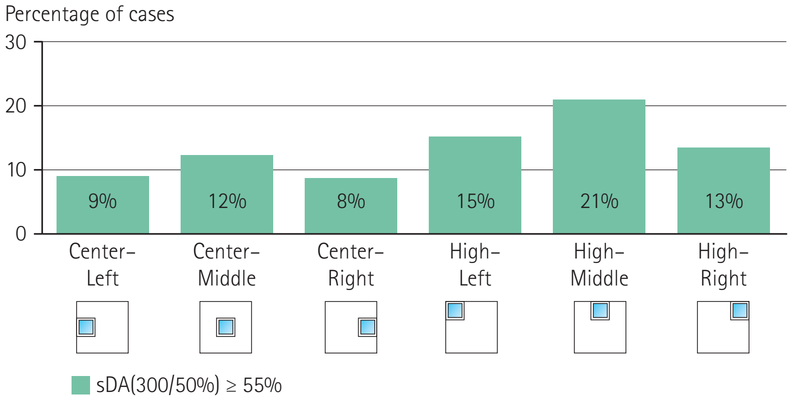


Figure 9.24
Effect of window position on sDA, according to Vogiatzi (2018)[6].

while for the $UDI_{100\text{-}3000}$ metric, both vertical and horizontal window shapes showed approximately the same performance (see Figure 9.21).

It is noteworthy that vertical windows have been used across cultures and eras because this shape allows for deep daylight penetration (through the upper window glass), natural ventilation (via the upper glass), and an unobstructed view (through the lower glass), while also minimizing structural stress in load-bearing structures. On the other hand, a horizontal window may be more satisfying for viewing purposes, as the visual field is wider than it is high. A horizontal window shape may also be more suited to framing the horizon, which is

Figure 9.25
Example of high window position for good ambient daylighting, Alvar Aalto studio, Helsinki, Finland.
Photo: Malin Alenius.

Figure 9.26
Low placed window, School, Switzerland. Photo: Marie-Claude Dubois.

an essential aspect of a quality view[24]. In large spaces, such as open-plan offices, horizontal window bands are preferable to avoid the contrasting effects created by a series of punched windows[5].

9.1.4.3 Window position

Windows of identical size, g-value, and U-value yield the same heat gains and losses in a room. However, the position of the window on the wall has a dramatic effect on daylight distribution and quality (see Figure 9.22). A window placed higher on the wall floods the room with daylight, provides good daylight uniformity, and emphasizes the room's height, though it typically only offers a view of the sky (see Figure 9.23). Tall windows allow much deeper daylight penetration, which can

Figure 9.27
Swimming hall Vilunda in Upplands Väsby, White arkitekter. Photo: Thomas Zaar.

Figure 9.28
Example of a vision and daylight window (upper part) and its consequences on the façade expression of the façade. Trondheim, Norway. Photo: Marie-Claude Dubois.

accommodate deeper floor plates—an alternate way to interpret the URT discussed earlier. A window at eye level offers an outward view but results in shallow daylighting and high contrasts in lighting levels. A window close to the floor emphasizes the ground view and creates darker areas at the back of the room, resulting in high contrasts.

As a rule, the higher the window head height, the deeper the daylight can penetrate into the space. Vogiatzi (2018)[6] found that windows positioned higher on a wall performed considerably better than those in other positions. Windows placed toward the center of a façade also

Figure 9.29
Kathleen Grimm School, USA. Photo: James Ewing/OTTO.

performed better than those in lateral positions, whether the windows were high or centered on the vertical axis (see Figure 9.24). Her study further showed that windows positioned higher on a wall increased daylight uniformity within the room.

Alvar Aalto's studio in Helsinki (see Figure 9.25) is an excellent example of high window placement. In this case, the room has windows on both sides, providing a high degree of daylight uniformity. Visual conditions in this space are excellent, even with the electric lighting turned off.

Window glass positioned below desk height (in an office or classroom) does not provide daylighting on the desk, instead illuminating only the floor's periphery. Since floors are generally darker than other surfaces, they do not typically reflect enough light to impact daylighting throughout the room. Therefore, additional glass below desk height does not significantly contribute to daylighting and primarily adds to cooling and heating loads[18].

Figure 9.30
Example of windows in a load bearing construction, Cathedral of Lund, Sweden. Wall cavity around the window is splayed, which provides subdued contrast and better daylight penetration. Photo: Marie-Claude Dubois.

However, it is important to consider that low-level glazing enhances the perception of light, space, and view, particularly when an interesting view is situated lower down. Additionally, a low-placed window can be suitable in contemplative spaces, where the darker areas may help emphasize interiority. Sometimes, a low window position is preferred simply for its pleasing view of the ground. In such cases, the architect must determine whether the benefits of the low glazing outweigh its disadvantages. Figure 9.26 shows an example of low glazing at the Bois-Genoud School in Lausanne, Switzerland, where the design emphasized a ground-level view to foster children's connection with the surrounding nature.

When window size is restricted by energy considerations and the floor-to-ceiling height is large, good daylighting design practices suggest that the window should ideally consist of two components: a daylight window and a view window (see Figure 9.27). This approach has become common in recent years as energy codes limit glazing sizes,

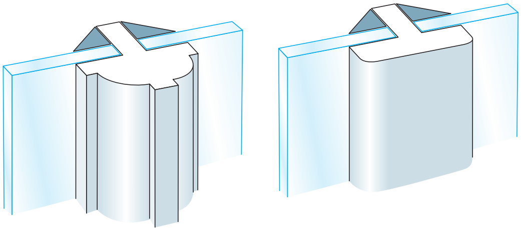


Figure 9.31
Older wood frames allowed for light gradations, which allowed better light transitions compared to modern frame (right side).

Figure 9.32
Windows with splayed openings to allow for better daylight distribution and better light transitions. Villa Åkarp, Sweden. Photo: Marie-Claude Dubois.

while both views and deep daylight penetration are still desired (see Figure 9.28). This type of design may also include an upper window with special glass, such as translucent glass, to spread more daylight toward the ceiling (see Figure 9.29). In the Kathleen Grimm School in New York, the ceiling is also sloped to capture and reflect daylight from the upper translucent glass.

Along with window shape, the window position should be determined based on the view out, which is a crucial aspect of window selection and design. This topic is discussed in detail by Matusiak & Klöckner (2015)[25], among others.

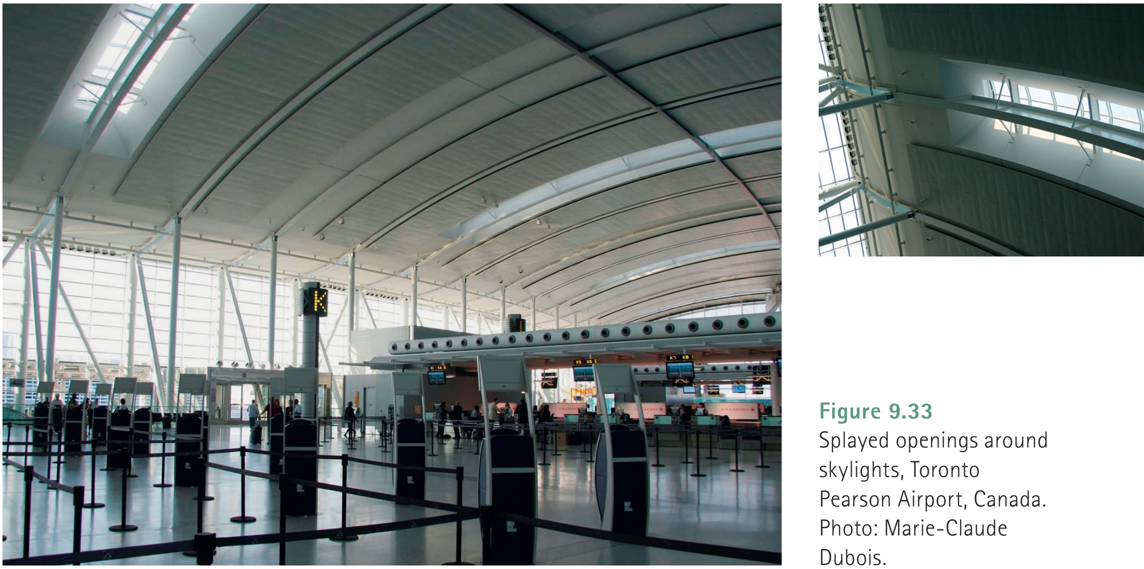


Figure 9.33
Splayed openings around skylights, Toronto Pearson Airport, Canada. Photo: Marie-Claude Dubois.

9.1.5 Window niche and frame

It is generally acknowledged that the details surrounding window frames and linings influence the daylight illumination of a room. Before the invention of lightweight frame constructions, load-bearing structures required thick walls, typically made of stone or brick. Since electric lighting was unavailable before the modern era, one feature of load-bearing construction was the use of splayed openings, which helped spread daylight toward the lateral walls and floor (see Figure 9.30).

Vogiatzi (2018)[6] tested several splay angles around the window.

Figure 9.34
Splayed opening around the skylight of the Bois-Genoud school in Lausanne, Switzerland, by Localarchitecture. Photo: Marie-Claude Dubois.

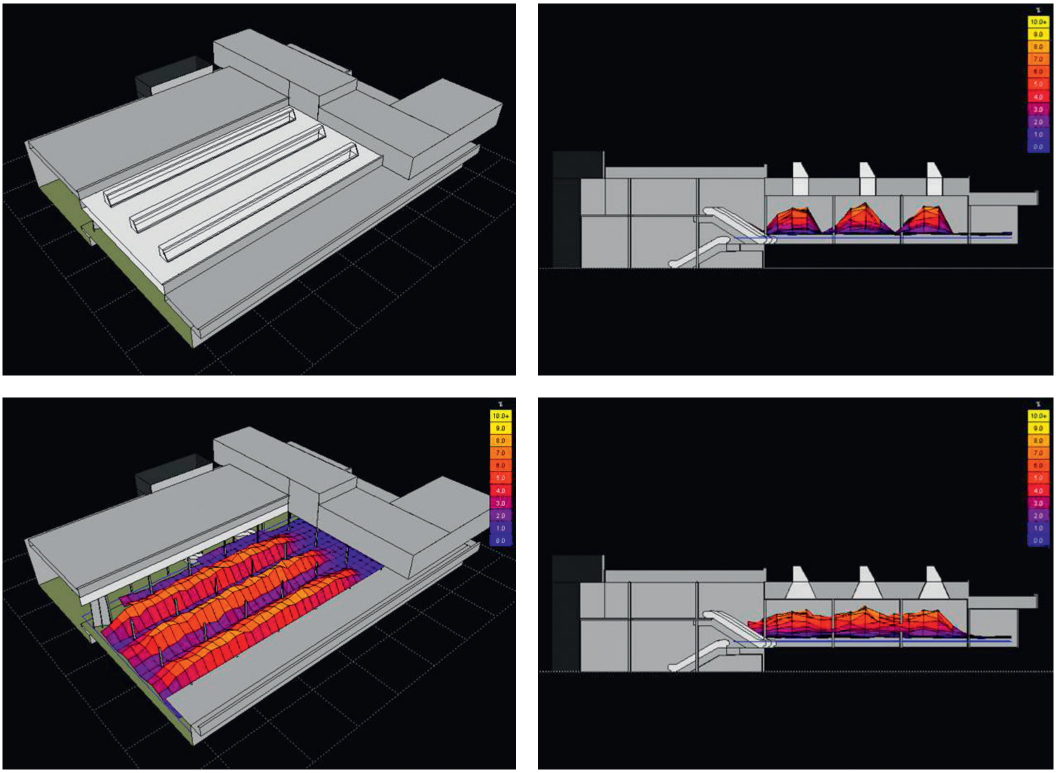


Figure 9.35 Shopping mall of La Maison Simons, Sainte-Foy, Quebec, Canada, showing the effects of splayed openings at the ceiling level. Simulations by François Cantin.

Contrary to the initial hypothesis, the results indicated that splaying the window had a negligible effect on illumination levels in the room. The splay angles only influenced daylight distribution immediately adjacent to the window area but had little impact on overall daylighting levels in the entire room.

However, windows with splayed openings produce less glare; thus, splaying or rounding the edges creates a light transition that is more visually comfortable. With the invention of lightweight frame structures, external walls became thinner, leading to a decline in the common use of splayed window linings. Window frames were also simplified into straight lines, often in dark colours, which do not provide the same quality of light and shade gradations as older windows (see Figure 9.31).

The passive house and net-zero construction standards, which feature super-insulated thick walls, have renewed the need to design window linings that promote good daylight distribution within a room. Figure 9.32 shows photographs of Villa Åkarp in Southern Sweden, a plus-energy house, where the windows are designed with splayed openings to enhance visual comfort.

Even in roof construction details, splaying the openings around the edges of windows or skylights can significantly enhance visual comfort. At Lester B. Pearson International Airport in Toronto, Canada, the skylight openings are splayed, which minimizes the contrast between the glazed surfaces and the inner ceiling. This design results in naturally soft light transitions and good daylight distribution throughout the terminal hall. Despite the relatively small roof glass areas in relation to the size of the hall, electric lighting is turned off during the day. Figure 9.34 shows a similar approach used at the Bois-Genoud School in Lausanne, Switzerland, where the opening is carved into the thick cross-laminated timber construction.

The same strategy was employed in a daylight simulation study for the extension of the clothing store La Maison Simons in Sainte-Foy, Quebec, Canada. In this (unbuilt) project, various ceiling shapes around the roof windows were analyzed using the Ecotect-Radiance program. The simulations demonstrated that splayed openings beneath the skylights significantly enhanced illuminance uniformity throughout the mall (see Figure 9.35).

9.1.6 Window glazing properties

9.1.6.1 Spectrally selective glass

In buildings where the energy balance is dominated by internal heat loads, such as offices or classrooms, daylight is necessary, but solar heat gains are often undesirable, as they can lead to overheating and increased cooling demand. To mitigate this issue, the glass industry has developed high-performance glazing assemblies designed to transmit daylight while admitting less total energy than typical window glass[28] (see Figure 9.36). These advanced glazing assemblies are known as spectrally selective glazing. Spectrally selective glass is coated glass that typically has a light transmittance (LT) approximately twice as high as its total solar transmittance.

This type of glass has become common in buildings, as it offers the clear advantage of high light transmittance combined with relatively low solar heat gains. Table 9.1 presents examples of glazing properties

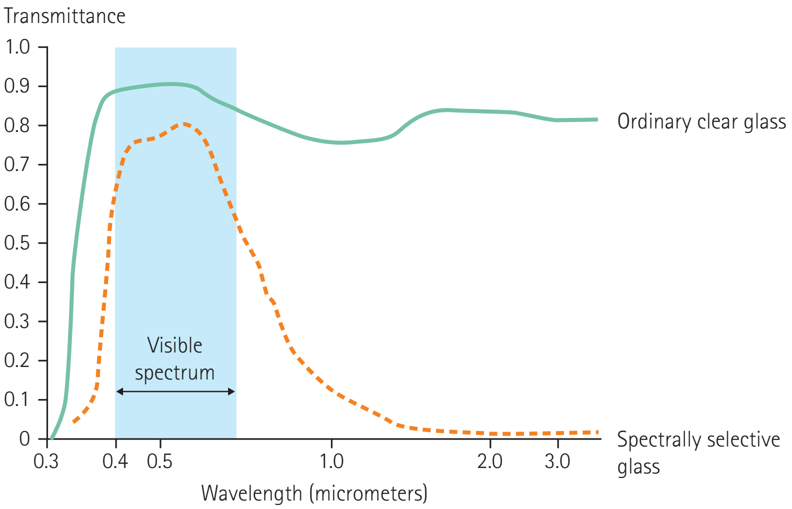


Figure 9.36
Spectral transmittance of spectrally-selective glazing compared to ordinary clear glass. From Carmody & al. (1996)[38].

for various common glazing assemblies available on the market, highlighting one glass that is more spectrally selective than the others.

Table 9.1 Optical and thermal properties of ordinary glazing types, adapted from Carmody & et (1996).[38]

Glazing type	LT	g-value (SHGC)	Light-to-solar gains (LSG)
Double glazing			
Clear	0.82	0.75	1.20
Bronze	0.62	0.60	1.03
Reflective	0.20	0.16	1.25
Spectrally selective	0.70	0.46	1.52

9.1.6.2 Glass colour

A strong architectural trend of the modern era is the use of large fenestration areas. Highly glazed façades, often with inadequate shading, have become quite common[26] and can result in excessive solar heat gains, leading to highly variable heating and cooling loads[24]. One solution to this problem is to use solar-protective glass, which includes reflective or tinted (also known as heat-absorbing) glass.

In addition, modern window glass is often coated with low-emissivity (low-e) coatings to reduce radiative heat losses to the outside and decrease the heating demand of buildings. Solar-protective and low-e coatings applied to contemporary glazing assemblies can distort the natural colour of daylight, thereby modifying the natural radiation spectrum that reaches the eyes and skin of building occupants. This may affect visual performance and perception, as well as the human photobiological response.

The colour of natural light varies constantly from morning to

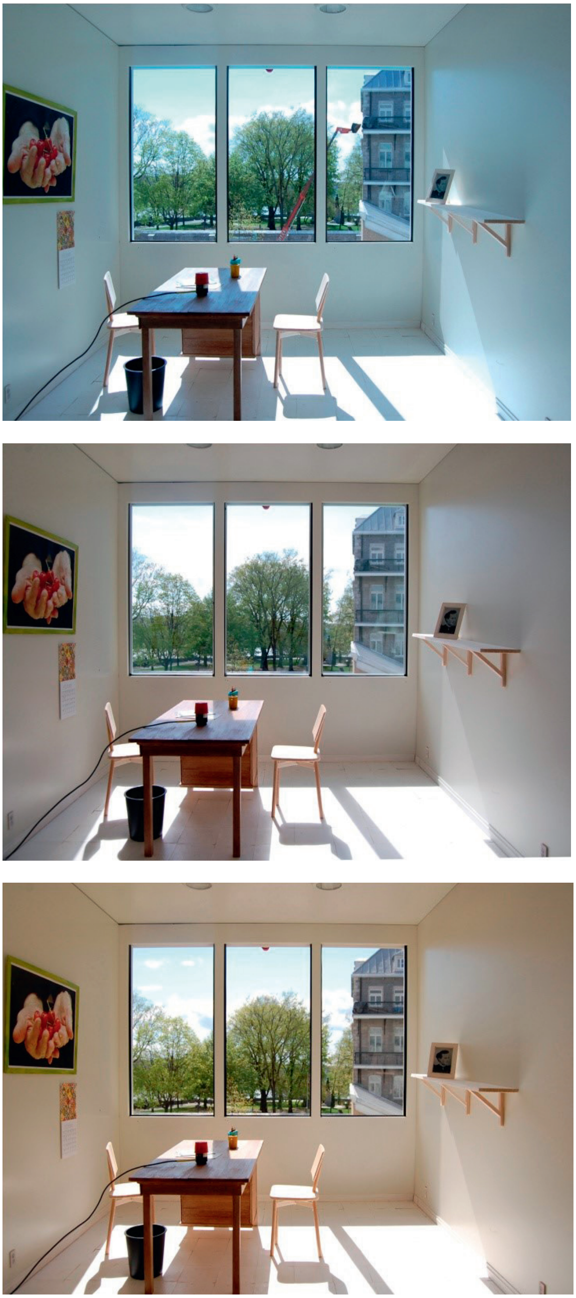


Figure 9.37 Three scaled rooms representing an office room, with three coloured glasses, bluish (top), neutral (middle), and bronze (bottom). Photo: Hélène Arsenault.

evening, and the human eye can adapt to these gradual shifts through a process called *chromatic adaptation*. These variations in daylight colour provide environmental cues about the time of day, season, weather conditions, and more. For example, everyone has experienced the distinctive red hue of a sunset. When architects use coloured glass, the colour information present in the natural world is distorted, resulting in a loss of environmental context (see Figure 9.37). In other words, the human brain receives misleading information about the time of day, season, and weather. One might feel that the workday is almost over when, in fact, there are still two hours left until work ends.

In an experiment[27] conducted at Laval University in Quebec, Canada, human subjects were immersed in a 1:4 scale model of an office room. The participants were asked to assess their perception of daylight and their level of arousal at the beginning and end of the experiment using a self-reported Karolinska Sleepiness Scale (KSS). Three types of glass, all with the same visual transmittance (52%) but slightly different colour shifts, were evaluated in a balanced order of presentation: bluish, neutral, and bronze glass (see Figure 9.37). The initial hypothesis was that the blue glass would help maintain arousal since short-wavelength radiation has been shown to reduce melatonin (the sleep hormone) production[28]. However, the results of the study indicated that the blue glass led to a statistically significant decrease in perception of brightness, pleasantness, and visual comfort compared to the other two types of glass. Additionally, the blue glass produced a statistically significant reduction in the self-reported level of arousal on the KSS scale. In other words, participants felt drowsier at the end of the experiment in the room with the blue glass, while the other window types had no effect on arousal.

This unexpected result can be explained by a few factors:

1. Around noon, when the experiment took place, the melatonin levels of participants were naturally very low and likely not influenced by daylight conditions.
2. All three types of glass transmitted radiation in the blue range, including the bronze glass. The smaller amount of blue light transmitted through the bronze glass may have been sufficient to keep melatonin levels low.
3. The perception of the room with blue glass was less dynamic and less pleasant, and the effect of visual perception likely dominated any measurable biological effects. It is worth noting that the preference for warm colour tones has been documented in the

> literature[13 29]. Some authors speculate that this preference is due to Nordic people's connection to fire, while others[30] claim that warm colours are favoured over cold ones because they affect our limbic system and resonate with our deepest emotional instincts (such as identifying potential mating partners based on reddish skin tones), thereby supporting survival and well-being.

One important conclusion of this study is that although photobiology research indicates that short-wavelength light is more effective at reducing melatonin production, the psychological (visual) perception of an environment may significantly influence the arousal state of building occupants, especially in a typical daytime context. Another key conclusion is that research on photobiology conducted with electric light sources may not be applicable to daylighting. Overall, this research underscores the need to carefully consider glass colour in architectural design.

9.1.7 Visual protection devices

Ideally, an energy-efficient window solution for the Nordic climate consists of highly transparent and spectrally neutral glazing combined with a dynamic or movable exterior solar shading device. When dynamic shading devices are not feasible, an alternative solution is to design a fixed exterior device with an appropriate geometry that corresponds to critical solar angles. However, fixed external blinds reduce indoor daylighting year-round, even under overcast sky conditions. This not only creates dark interiors on overcast days but also encourages reliance on electric lighting. Dynamic shading devices perform better under the predominantly overcast sky conditions typical of Nordic countries. Additionally, it is important to note that in the Nordic context, fixed horizontal shading devices have limited effectiveness in reducing peak loads when the solar altitude is low, and the sun reaches the window at nearly normal incidence. These peak loads are used to determine the size of mechanical cooling equipment.

When exterior solar shading devices are excluded from building design for various reasons, a shading device placed between glass panes, combined with spectrally selective glass, may serve as an energy-efficient alternative. This approach has the added advantage of requiring low maintenance, as the shading device is protected behind a glass pane. This solution was implemented in the Malmö SUS Hospital (see Figure 9.38), where the building program did not allow for either exterior or

Figure 9.38
Malmö SUS Hospital, where a small room in the inner courtyard was modelled (upper right corner). The point daylight factor DFp was doubled by changing the reflectance of inner courtyard's exterior wall and ground surfaces from 50 to 80% and 35 to 50% respectively. Final completed building with highly reflecting exterior material is shown (bottom left). Photo: Stephanie Jenny Angeraini, White arkitekter.

Figure 9.39
Effect of diffusing glass, Campus Laval University, Quebec, Canada. Photo: Marie-Claude Dubois.

interior devices due to maintenance and hygiene concerns. This combination achieved a g-value of 0.21 with the Venetian blinds closed. The glass exhibited the optical properties of spectrally selective glass, with a light transmittance (LT) of 0.69 and a g-value of 0.35.

Fixed exterior shading devices are most often sized according to overheating periods, which primarily occur during the summer and autumn. However, the most significant visual comfort issues typically arise during the winter when solar altitudes are low. As a result, it is often necessary to provide an additional visual protection device, as the exterior device is usually not sized for winter sun angles. Ideally, the visual protection device should be located inside the windows and adjustable by the occupants. This interior positioning allows for the use of some passive solar heat gains during the winter, as the visual protection material absorbs heat, and radiates and convects it into the room. However, certain precautions regarding interior visual protections are worth mentioning:

- White or very bright translucent fabrics may increase glare instead of reducing it (see Figure 9.13).
- Black or very dark screens allow for maintaining a view but create a gloomy interior, necessitating the use of electric lighting.

White, translucent fabrics capture direct sunlight and transmit it diffusely in all directions within the space. Diffusing glass produces the same effect (see Figure 9.39). Ideally, diffusing glass should be located above eye level or away from the occupant's direct line of sight.

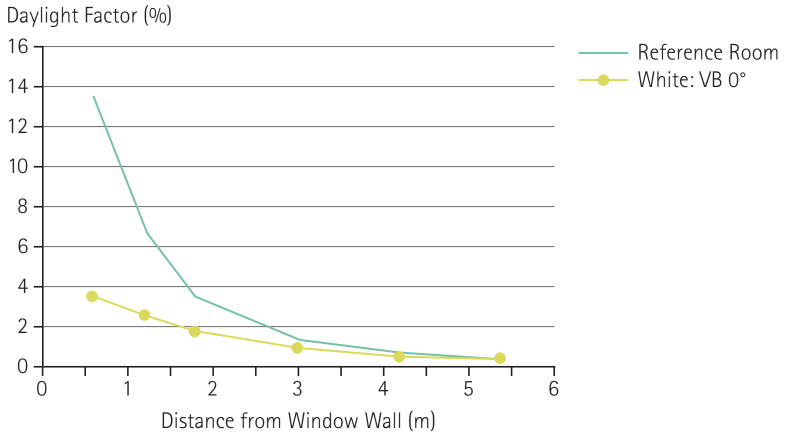


Figure 9.40
Daylight factor under an overcast sky, adapted from Christoffersen (1995)[39].

Black screens are effective for maintaining a view through the window, but they often reduce daylighting to such an extent that electric lighting must be turned on. It is generally advisable to avoid extreme tones; neither white nor black provides an ideal solution for screens.

Research also indicates that Venetian blinds are high-performance shading devices because:

1. They allow variable daylighting levels through the adjustment of the slats, functioning like a dimmer.
2. When the slats are in a horizontal position, they reflect daylight towards the ceiling, which then reflects it back down into the room, thereby increasing daylight uniformity.
3. Even when closed under strong sunlight conditions, Venetian blinds allow enough light to pass through to provide ambient daylighting for work.

Figure 9.40 shows the horizontal daylight illumination profile in a room with and without a Venetian blind. The Venetian blind reduces the daylight factor (DF) near the window while maintaining a high DF at the back of the room, which increases uniformity. It is also worth noting that Venetian blind systems split into two parts are available on the market. In these systems, the lower part can be closed for glare protection while the upper part remains open (horizontal) to provide ambient daylight at the back of the room.

Figure 9.41
Example of high internal surface reflectance, Malmö Opera house. Architects: Sigurd Lewerwntz, Erik Lallerstedt and David Helldén. Photo: Nicholas Wakeham.

9.1.8 Indoor and outdoor reflectances

Using high reflectance values for walls, floors, and especially ceilings is the simplest daylighting strategy and a significant energy conservation measure. As Lechner (2015)[31] expresses, 'white is the greenest colour,' meaning that the use of bright reflective colours is one of the most effective and straightforward strategies in sustainable design, applicable to both indoor and outdoor surfaces.

It is likely not a coincidence that in Nordic countries, where outdoor daylight is generally weak in winter, bright and especially white interiors have been used throughout architectural history. As Miller (2016)[32] states:

> 'There is often a white luminosity present in the interior space of Scandinavian civic, commercial and religious buildings that is a direct response to the arctic climate. The white finish allows spaces to remain lit even in the dark winter with its snow-covered landscapes. White rooms offer a means to stay near the almost elusive aspects of nature, the delicate daylight and unpredictable weather'.

The Bagsvaerd Church in Denmark, designed by Jørn Utzon in 1976, features a white interior that creates a high level of reflection from relatively small openings (see Figure 2.27). The large hall of the Opera House in Malmö (Figure 9.41) also employs this strategy, with even the furniture in the room designed for high reflectance. Despite the relatively deep room, it is possible to read a text in the middle of the space without any electric lights on. In the Stockholm Public Library, the high-reflectance walls of the Rotunda above the main hall help to reflect daylight toward the lower part of the hall (see Figure 2.28).

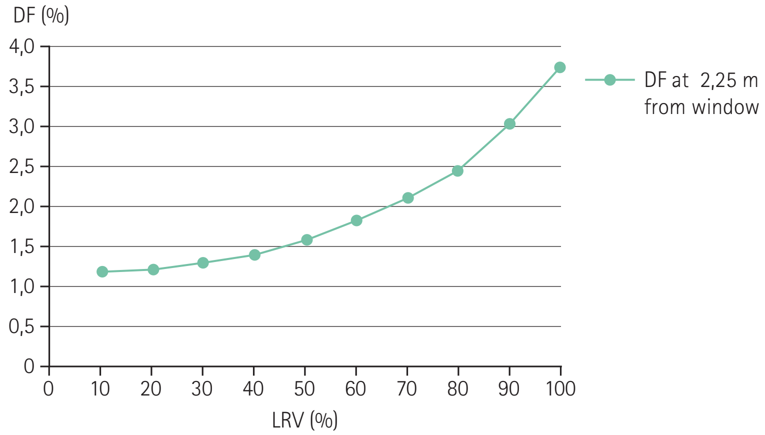


Figure 9.42
Effect of increase in reflectance. Simulations by Stephanie J Angeraini, White arkitekter.

The effect of surface reflectance on interior illumination is not linear but exponential, meaning that as reflectance increases, the relative indoor illumination measured at a point increases exponentially[33]. This can be easily understood by considering each ray of light that falls on a surface. Each time a photon bounces off the surface, its energy is 'multiplied' by the surface reflectance. Since the photon bounces many times before its energy is fully absorbed, very high reflectance values yield a greater number of bounces, resulting in more light being reflected compared to surfaces with low reflectance values. This phenomenon was demonstrated by Sumpner in 1894[33], known as the integrating sphere equation and Sumpner's formula.

$$E = \frac{F}{s(1 - \rho)} \tag{9.4}$$

where

E = Illuminance (lux),
F = Luminous flux (lumens) from a lamp inside an enclosure (an integrating sphere),
s = Surface area (m^2) of the sphere,
ρ = Reflectance (-) of this surface.

Note that the daylight factor equations proposed in Chapter 7 are variations of this formula, as explained by Lynes (1979)[34].

Systematically increasing the reflectance values of room surfaces (floor, walls, ceiling) leads to the findings presented in Figure 9.42, which shows that increasing the reflectance from, for example, 40% to 50% has a smaller effect on the relative daylight factor (DF) than increasing the reflectance from 80% to 90%. In other words, there are significant benefits to using very high reflectances, specifically those above 80%. Light-piping materials used in daylight tubes often have a reflectance of 98%.

Unfortunately, for maintenance reasons, it is not always feasible to have highly reflective white surfaces in buildings. Floors often need to be darker, and white walls can become glaring or dirty, which is why a reflectance of 70-80% is often recommended for walls. The ceiling should preferably have the highest reflectance value (> 85%) whenever possible. Additionally, window frames should also have a high reflectance, as they are the first surfaces that reflect daylight into the interior.

For workspaces, the European standard SS-EN 12464[35] states that

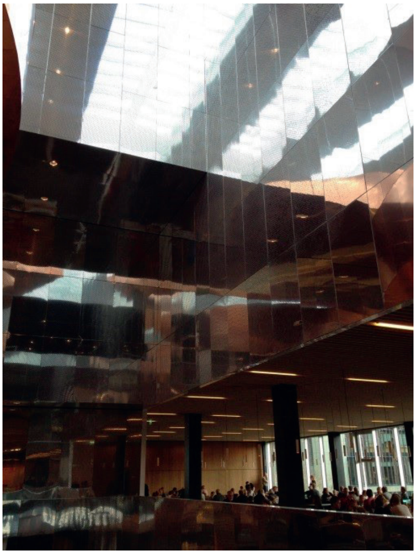


Figure 9.43
Use of specular material surfaces, which give rise to reflections and uncertainty about the definition of the space. Experimentarium, Copenhagen, Denmark.
Photo: Marie-Claude Dubois.

'to avoid gloom and to raise adaptation levels and comfort of people in buildings, it is highly desirable to have bright interior surfaces, particularly on the walls and ceiling.' The following recommendations are also provided:

- Ceiling: 0.7 to 0.9
- Walls: 0.5 to 0.8
- Floor: 0.2 to 0.4

This standard also suggests that the reflectance of major objects (furniture, machinery, etc.) should be in the range of 0.2 to 0.7.

The high reflectance that is recommended should come from diffusing materials to avoid specular reflection. The question of whether reflecting surfaces should be of diffuse or specular character often arises in discussions with architects. Figure 9.43 shows an example where specular material was used at the Copenhagen Experimentarium in Denmark. The result is a complex visual environment, which is justified in this case since it is a science center. However, using the same solution in an office or a medical clinic could be highly disturbing, as the overall impression of the room's boundaries would be more difficult to distinguish. Additionally, highly specular materials can pose problems when visual information is transmitted, leading to disturbances or even privacy issues. For example, a specular ceiling may reflect traffic information from street level when headlights of buses and cars are reflected off it at night. A specular floor may also

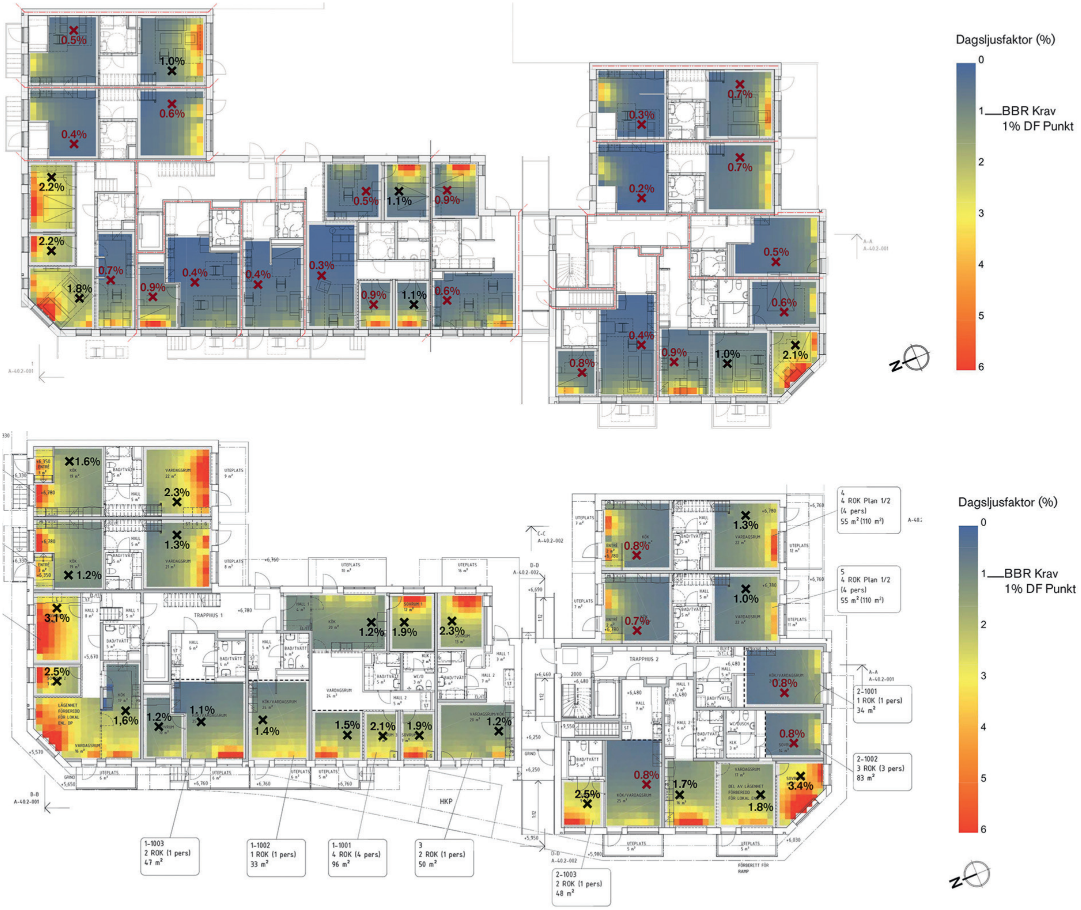


Figure 9.44 Daylight factor (%) calculations for the Sorgenfri apartments in Malmö, Sweden, showing the improvement in DF by increasing the reflectance of inner surfaces. Simulations by Stephanie J Angeraini, White Arkitekter.

create challenges for obvious reasons. Consequently, diffuse surfaces are generally recommended.

Figure 9.44 shows the effect of increasing the reflectance of inner and outer surfaces on daylight factors in a housing project in Sweden. In the top image, the initial reflectance values for the ceiling, walls, and floor were 85%, 80%, and 40%, respectively. These values were increased to 85%, 85%, and 60% by using whitewashed oak as the floor material in some areas. The reflectance of the balcony floor was also raised from 40% to 60%, and the reflectance values of the door and window frames were increased from 70% to 85% and from 30% to 50%, respectively.

Figure 9.45
Daylight distribution at Medborgarhuset in Eslöv (Citizen's house), Sweden. Architect: Hans Asplund. Photo: Nicholas Wakeham.

A white-painted brick surface (with 85% reflectance) was added to the exterior in place of the original green plaster (reflectance of 30%). Additionally, the window glass transmittance increased from 65% to 70%. Note that the combination of these changes made it possible to achieve the required DF_p levels for certification in several rooms.

Figure 9.46
Example of glazed intermediate partitions, Hälsostaden, Ängelholm. The picture clearly shows that daylighting is illuminating the corridor as all electric lighting is switched off. Photo: Marie-Claude Dubois.

Figure 9.47 Intermediate glazed partitions between social space and meeting room at GSK offices in Quebec Canada (photo: Stéphane Groleau; top) and at the Axis Headquarters, Lund, Sweden (photo: Nicholas Wakeham; bottom).

The effect of reflectance is equally important for exterior surfaces, especially in dense urban environments, where daylight primarily originates from the externally reflected component (ERC). In the case of the Malmö SUS Hospital in Sweden, the impact of the external wall and ground reflectances on the inner courtyard surfaces was studied using computer simulations. The simulations revealed that a simple increase in the exterior wall reflectance from 50% to 80% and in the ground reflectance from 35% to 50% doubled the DF_p value in a room at ground level adjacent to the courtyard (see Figure 9.38).

9.1.9 Light distribution

The human eye has an incredible capacity for adaptation (see Chapter 3). However, it can only adapt to a brightness range of about two orders of magnitude at any given time by varying the size of the pupil's aperture, a process that takes less than one second. In other words, although the human eye enables adaptation to very different light conditions at different times, simultaneous adaptation to varying brightness levels is impossible.

Given the limited simultaneous adaptation capacity of the human eye, it follows that while total light uniformity should be avoided, large contrasts should also be eliminated, as they may create adaptation problems. A certain degree of light uniformity is thus desirable within the built environment, particularly in spaces where functional illumination is the main design goal. One way to ensure relatively good uniformity is by positioning windows high up near the ceiling to allow for deeper daylight penetration, thereby avoiding dark corners (see Figure 9.22). Splitting a window into two or three separate units on a facade also contributes to increased light uniformity[6].

Placing openings in different walls or areas of the ceiling also contributes to distributing daylight within a space. An example of this is the library of the Nordic House by Aalto in Reykjavik, where daylight enters through facade and roof windows (see Figure 2.25). Another

Figure 9.48 Intermediate glazed partitions, Children hospital, Lund, Sweden. Photo: Marie-Claude Dubois.

Figure 9.49 Intermediate glazed partitions, Experimentarium, Copenhagen, Denmark. Photo: Marie-Claude Dubois.

Figure 9.50 Example of sand blasted intermediate glazed partitions, different hospital buildings, White architects image bank..

example is the Citizen's House (Medborgarhuset) in Eslöv, Sweden (see Figure 9.45), where Asplund incorporates high-placed windows on one wall and a skylight near the ceiling on the opposite side of the room, creating uniformity and visual comfort in the room.

9.1.10 Glazing in intermediate partitions

The use of glass in intermediate partitions allows for the transport of daylight from the facade to core spaces, especially in circulation areas, which require a lower light level (150 lux in corridors). Figure 9.46 shows a corridor in the administrative section of the new Hälsostaden in Ängelholm, Sweden. Daylighting, combined with high surface reflection, illuminates the corridor space through intermediate glazed partitions. The electric lighting system must be planned accordingly so that it switches off when the illumination in the corridor is sufficient.

Intermediate glazed partitions can also be used between a conference room and the circulation area, provided that a curtain is installed for privacy or to darken the space during screen projections (see Figure

Figure 9.51 Example of intermediate partitions above head height, CTBO Pavillon, Laval University, Québec, Canada. Photo: Marie-Claude Dubois.

9.47). Another application of intermediate glazed partitions is between common areas in inner courtyards or between office spaces and adjacent atria, as seen in large museums or airports. In the healthcare sector, which often demands deep building plans, glazed intermediate partitions are useful for separating different spaces and functions without blocking natural light or contact with the outside (see Figures 9.48 and 9.49). When privacy is required, diffusing glass can be used (see Figure 9.50).

In educational buildings, intermediate glazing above head height is commonly used to allow for functional wall use for storage while minimizing distractions from the corridor. In the Kathleen Grimm School (see Figure 9.29), daylight is transmitted through the transom above the lockers.

The use of transoms (glass above head height) may not provide much daylight from peripheral rooms to adjacent corridors, but it allows for views of daylight or sunlight incident on lateral walls. The subtle colour shifts of daylight patches can be observed by people walking in the corridor; this provides information about the time of day and weather conditions. This type of environmental information is important for connecting building occupants to the natural environment. This relatively inexpensive daylight strategy can enhance the indoor environment in deep spaces such as hospitals and university campuses (see Figure 9.51).

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CHAPTER 10

Design strategies for top lighting

MARIE-CLAUDE DUBOIS

'Light is not so much something that reveals as it is itself the revelation.'

JAMES TURRELL

'Space and light and order. Those are the things that men need just as much as they need bread or a place to sleep.'

LE CORBUSIER

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Atrium, well index (WI), plan aspects ratio (PAR), section aspect ratio (SAR), skylights, cut-off angle, light wells, daylight tubes, light pipes, tubular daylighting devices (TDDs), mirrored light pipe (MLP), optical redirecting system (ORS), fibre optic lighting, Fresnel lens.

This chapter focuses on daylight that enters through the roof. In deep buildings, such as hospitals or large office buildings, it is not possible to illuminate the building core with daylight from the facades. Instead, atria, covered courtyards, skylights, daylight tubes, or more advanced rooftop daylighting systems must be utilized.

Top lighting is often the most suitable strategy for illuminating large spaces, such as factories and warehouses, as it provides a uniform distribution of daylight across the area, making it ideal for ambient lighting. The potential energy savings from top lighting are significant and likely underutilized. Since top lighting systems face the zenith while side-lighting systems face the horizon, top lighting from skylights can be more efficient than side-lighting on overcast days. Additionally, top lighting offers the advantage of providing the most exposure for longer periods throughout the day.

The main advantages of top lighting are:

1. The ability to capture zenithal illumination, which is particularly effective under overcast skies, allowing smaller glazing areas to achieve high illumination levels compared to vertical windows.
2. The capability to provide natural illumination over large areas, as opposed to side-lighting.
3. The potential to achieve high illumination uniformity across the room, making it ideal for ambient lighting.
4. The ability to illuminate the top floors of buildings in dense urban environments without shading from adjacent structures.

The disadvantages of top lighting systems are:

1. No view.
2. An even daylight distribution that may result in a monotonous rendering of space and people if not designed well or used in conjunction with side-lighting.
3. Limited applicability in multi-storey buildings, mainly for top floors and atria.
4. Higher radiative heat losses from glass facing the ‘cold’ night sky.
5. Unless well planned, daylight may only reach the floor and be absorbed there, failing to provide perceptible illumination in the room (see Figure 10.1).
6. A high risk of overheating and glare on hot days unless appropriate shading or glass orientation is provided.

Figure 10.1
Atrium, main university building (Universitetshuset), Lund University, Sweden. Photo: Nicholas Wakeham.

In general, the same aspects discussed in the previous chapter on sidelighting need to be considered regarding climate and site, orientation, glazing size and properties, light distribution, and so on. However, some additional factors must be considered depending on whether illumination is provided through one of the following systems:

1. Atria
2. Skylights
3. Light wells
4. Tubular daylighting devices
5. Fibre optic lighting

The following sections discuss some of these top lighting systems in detail.

10.1 Atria

The atrium was the central open area of a house in ancient Roman architecture, admitting light and air to the surrounding living spaces[1]. According to several authors[2 3], the atrium has become one of the more widely used architectural forms in large-scale buildings over the last 40 years. Daylight utilization in an atrium is particularly beneficial, as natural light can illuminate potentially dark core areas and decrease reliance on electric lighting. Atria usually connect different task-intensive parts of complex building programs and are common in large hospitals, offices, campus buildings, etc. (see Figure 10.2). Atria may become increasingly important in the future for providing restorative

Figure 10.2
Atrium, Axis Communications headquarters, Lund, Sweden. Photo: Nicholas Wakeham.

spaces that have the character of semi-outdoor environments. This relevance grows in the context of high urban density and unpredictable climate conditions.

However, when conditioned to the same level as ordinary interior environments, covered atria can increase the building's energy demand and peak loads because they typically involve a large air volume that requires heating, cooling, and ventilation[4]. Energy use is not consistently reduced by the presence of an atrium, as spaces can become too hot in the summer, and there may be glare problems from bright roof elements compared to darker interiors farther from the atrium[5]. Air stratification can also be an issue. Therefore, it is important to consider the atrium as part of a holistic design concept, where ventilation, heating, and cooling demands are minimized as much as possible. This entails reducing the glass area whenever feasible, which often contradicts the design goal of creating a bright space with the character of an outdoor environment[6].

The general design recommendations for energy-efficient buildings also apply to atria:

- Select energy-efficient glazing (low U-value, low g-value, high LT).
- Minimize glass area to reduce heat losses and high solar gains during hot days.

- Provide effective additional shading (dynamic, exterior when possible).
- Use thermal mass to store passive solar heat gains and maintain a constant temperature.
- Minimize the envelope-to-volume ratio to reduce heat losses.
- Minimize thermal bridges.
- Use natural ventilation when appropriate (not during winter).

Considering daylighting only, the atrium can be exploited to achieve three objectives, each with an increasing level of difficulty[7]:

1. Provide sufficient levels of illumination within the atrium.
2. Provide sufficient illumination to maintain plant growth (which requires 750 to 2 000 lux for twelve hours a day[8]).
3. Provide sufficient illumination to displace electric lighting in spaces adjoining the atrium.

Considering daylighting only, the key features for illuminating the atrium as well as the spaces adjoining it are:

1. The geometry of the atrium well.
2. The reflectance of the well's surfaces.
3. The roof fenestration system.[9]

The most studied effects of atrium design include daylight levels at the atrium ground floor, vertical daylight levels (VDF, VSC) on the well's surfaces, and the horizontal daylight factor in adjoining spaces. The literature on atrium design is abundant, making it impossible to review it thoroughly here; see Aizlewood (1995)[7] and Sharples & Lash (2007)[9] for details. Some of the important aspects outlined in these reviews and other articles are summarized below.

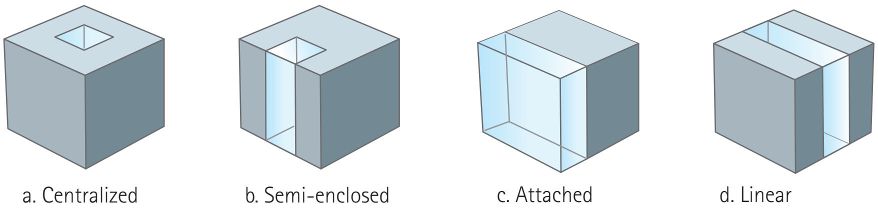
a. Centralized
b. Semi-enclosed
c. Attached
d. Linear

Figure 10.3 Different atrium typologies.

10.1.1 Atrium well geometry

Atria can be classified according to how many sides are surrounded by the building mass (see Figure 10.3). Note that the three-sided atrium is sometimes considered an attached glazed space or greenhouse. The atrium can thus be top lit only or lit from one or several sides. Consequently, there is an almost infinite number of configurations to analyze.

Most previous studies investigated only one specific type of atrium (square, rectangular, or linear), and their geometries were altered by adjusting the atrium well height[10]. However, atria are not limited to square or rectangular shapes. Willbold-Lohr (1989)[11] found that circular atria provide the highest illumination levels, followed by square, equilateral triangle, rectangular, and then linear shapes. The higher volume-to-surface area ratio of the circular form creates fewer reflections and, thus, less light flux absorbed by the surfaces. More recently, Erlendsson (2014)[12] found—through simulations—that the circular shape offers a distribution of daylight autonomy in adjoining rooms that is quite similar to the square shape, but triangular atria performed more poorly (see Figure 10.4).

Saxon (1983)[13] indicated that if an atrium has a specific area of glazing and building height, the daylight factor (DF) on the floor of a square atrium is 7% higher than that of a rectangular atrium. Matusiak & Aschehoug (1999)[6] claimed that the linear street-type atrium has an even greater potential for effective daylighting compared to square or rectangular geometries.

The well geometry and surface reflectances are two key features of an atrium that have a direct effect on the vertical daylight factor (VDF) on the atrium walls[9 10 14]. According to previous reviews[7 15], the daylight levels in rooms adjacent to atria are significantly influenced by the VDF on the well wall and the properties of the rooms (size and surface reflectances). Littlefair (2002)[15] proposed equations for the calculation of the average daylight factor (ADF) in rooms adjoining atria and the VDF at the facade center of each floor:

$$\mathrm{ADF} = \mathrm{C} \cdot \mathrm{DF}_w \tag{10.1}$$

where

$$\mathrm{C} = \frac{2A_{glazing}\,\tau_{vis}}{A_{total}(1 - R^2_{mean})} \tag{10.2}$$

where

Figure 10.4
Inner courtyard at the Guggenheim Museum, New York, designed by Frank Lloyd Wright. Photo: Jouri Kanters.

ADF	Average daylight factor in adjoining rooms (%),
DF_w	Vertical daylight factor at the window (%),
$A_{glazing}$	Net glazing area (towards the atrium, m^2),
τ_{vis}	Window glazing transmittance (-),
A_{total}	Total area of the room surfaces including window (m^2),
R_{mean}	Area-weighted reflectance of the room surfaces (-).

Equation 10.1 expresses that the average daylight factor (DF) in the room has a linear relationship to the vertical DF at the window, which has been confirmed by other research[14]. Du & Sharples (2011)[14] showed that data obtained from simulations agree with these equations, especially for rooms with balconies. However, when unobstructed windows are used on the well side, the calculated results from the equations should be multiplied by 0.8, as the equations tend to overestimate the average daylight factor (ADF) in the adjoining rooms compared to simulations.

The atrium well geometry can be described by its well index (WI), which is a function of well length (l), width (w), height (h), and well index depth (WID), considering the distance from the top edge of the atrium well (y). The equation for the well index is presented in Aizlewood (1995)[7], see Figure 10.5.

$$WI = \frac{h(w + 1)}{2wl} \tag{10.3}$$

$$WID = \frac{y(w + l)}{2wl} \qquad \text{(rectangular atrium)} \tag{10.4}$$

$$WID = \frac{y}{w} \qquad \text{(square atrium)} \tag{10.5}$$

The well index (WI) expresses the relationship between the light-admitting area of the atrium (l·w) and the surface area of the atrium walls (h(w + l))[16]. The WI allows for a comparison between several atrium shapes associated with a specific building height[17]. For a square atrium, the WI is the height divided by the width, meaning that a high WI corresponds to a deeper atrium[12]. The well index depth (WID) is the main parameter describing the geometric characteristics of atria in terms of vertical daylight levels[18]. Samant & Yang (2007)[16] noted that variously shaped atria with the same WI can have different light-admitting areas. To address this, Bednar (1985)[19] introduced the plan aspect ratio (PAR) and the section aspect ratio (SAR) to express the geometric character of the atrium, where:

$$PAR = w/l \tag{10.6}$$

$$SAR = h/w \tag{10.7}$$

Liu et al. (1991)[20] used computer simulations to study how the daylight factor (DF) varies across the atrium floor as a function of the plan aspect ratio (PAR). They also described the variation of DF in relation to the section aspect ratio (SAR). The PAR and SAR values were then compared to the well index (WI), and they concluded that the WI was a good predictor of the DF.

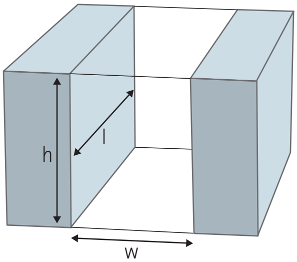

Figure 10.5
Well geometry. Adapted from Sharples & Lash (2007).

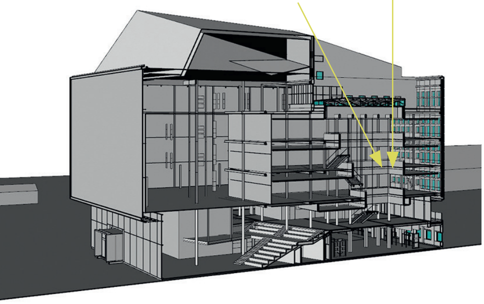

Figure 10.6
Studenthus Valla, Linköping, Sweden by White arkitekter.

Du & Sharples (2009)[10] studied the effect of well index (WI) and surface reflectance through computer simulations for a square atrium with no roof under the CIE overcast sky. They found that the vertical daylight factor (VDF) decreased with an increase in WI, indicating that shallower wells present higher VDF than deeper wells. The VDF followed an exponential function of well index depth (WID), which was also noted in other studies[7 14 21]. The VDF is higher at the top and drops dramatically along the depth in a non-linear fashion, following an exponential decay. This indicates that there are relatively greater advantages to preferring shallower atria.

Du & Sharples (2009)[10] also investigated the impact of well geometry on VSC on the walls of square and rectangular atria under a CIE overcast sky. The well had no roof, glazing, or structural system. They noted that daylight incident on vertical surfaces significantly affected daylight levels in spaces adjoining the atrium. They showed that the central area of vertical surfaces (from the center line to a line at 30% of the well width) was the principal area for daylight applications. Additionally, they demonstrated that as the WID increased, the VSC decreased, further indicating that shallower atria are preferable. In line with these results, Canadian design guidelines[22] recommend maintaining the atrium's width-to-height ratio at 1:1 whenever possible.

Du & Sharples (2011)[14] then investigated the horizontal daylight levels in spaces adjoining atria and the vertical daylight levels on atrium well walls for a four-storey square atrium under overcast sky conditions. They found that the daylight levels in adjoining rooms along the center of the room exhibit an exponential decay from the window to the back wall on each floor, which was expected and consistent with previous results[17] [23]. However, they also discovered that as one moves toward the base of the atrium, the exponential decay is not as steep, indicating that daylight uniformity is higher on lower floors compared to higher floors.

Other aspects, such as high inner surface reflectance or opening the atrium toward the zenith, can help achieve high daylight levels at ground level and on vertical walls, especially in deep atria. Neal & Sharples (1992)[24] investigated the effect of splaying the atrium using scale models of a square atrium. For a relatively wide atrium with a SAR of 1, they observed an increase in DF of 40% at a 10° splay, rising to 80% at a 30° splay angle. For a narrow atrium (SAR > 4), the increase in DF at the base of the atrium was significant, with a 300% increase at a 10° splay and a 1 000% increase at a 30° splay angle. Erlendsson (2014)[12] also found that making the atrium wider at the top than at its base leads to a significant increase in daylighting autonomy on all floors of adjoining rooms, as it allows for greater access to daylight. This strategy was implemented in Studenthus Valla, Linköping, Sweden, where the atrium was shaped to open toward the zenith, allowing daylight to reach the bottom (see Figure 10.6).

Canadian design guidelines[22] also recommend using a greater number of smaller atria instead of a single large one. A simulation study conducted in the context of the NSM hospital in Malmö supports this statement. This study compared large U-shaped and H-shaped hospital layouts and showed that the H-shaped configuration, which included two inner courtyards instead of one, provided a higher average daylight factor (DF) on intermediate and upper floors. Additionally, the H-shaped building resulted in a smaller floor area with DF < 1% and, conversely, a larger area with an acceptable DF of 1-6%.

10.1.2 Surface reflectance of atrium well

Using measured data of horizontal illuminance in the adjacent rooms of a square atrium, Baker, Fanchiotti & Steemers (1993)[25] found that the rooms near the ground were primarily illuminated by light reflected from the walls and floor, while the upper rooms received most of their daylight directly from the sky. As a result, the upper part of the atrium typically suffers from excessive illumination, whereas the bottom part experiences the opposite effect. The same observation applies to rooms facing an urban canyon on the street. Old towns were intuitively planned in response to this phenomenon by decreasing glazing size with increasing height. Aschehoug (1986)[26] also noted that smaller windows on the top floors allow more light to be reflected by the atrium façade toward the lower levels.

Obviously, the use of high surface reflectance aids in bringing daylight from the roof to the ground level and adjacent rooms. As expected, the effect of atrium wall reflectance on the VDF on the atrium walls is not linear; it follows an exponential function, which is a direct consequence of Sumpner's law. In other words, selecting very high reflectances for the atrium walls offers significant advantages when possible. Du & Sharples (2009)[10] also found that increasing the reflectance of the floor in an atrium could enhance the daylight levels on the walls.

Some studies[17 23 27] recommend that the window areas on each floor be proportionally increased from the top to the base of the atrium to compensate for the diminishing daylight with depth. Norwegian researchers (1999)[6] tested both increasing the glazing size towards the ground and increasing the glazing transmittance as compensatory measures for the daylight loss along the atrium's height. They showed that both solutions effectively improved the balance of lighting within the adjoining spaces.

While this is a potentially brilliant idea, it results in more glass at the bottom level and thus fewer opaque walls to reflect light. A simulation study[17] was conducted using Radiance under overcast sky conditions to measure the daylight factor at a single point in the adjoining room on the ground floor of atria with various wall reflectances and WI values. This study indicated that when window areas on each floor

Figure 10.7
Large skylight at the MKB offices in Malmö, Sweden. Photo: Marie-Claude Dubois.

were proportionally increased from top to bottom, the wall reflectance could not dramatically increase the daylight levels in ground floor rooms. This is because the fully glazed wall surface on the ground floor could not reflect more light toward opposite or neighbouring rooms. However, measurements from another study[28] proved that increasing the floor reflectance at the edges of the well did improve light levels in adjoining rooms.

10.1.3 Roof fenestration system

A carefully designed roof fenestration system can prevent glare, mitigate passive solar heat gains, and provide adequate daylighting while minimizing direct sunlight[29]. Regarding roof shape, there are almost infinite possibilities for configurations and sizes[30].

The atrium fenestration system serves two main purposes: 1) to admit as much diffuse daylight as possible and 2) to control direct sunlight to prevent glare and overheating[9]. While extreme glare and overheating can ruin the ambiance, it is important to note that the scale and lighting levels typically found in atria often create a feeling that lies somewhere between an indoor and outdoor space, which may make higher levels of sunlight more acceptable. Additionally, while daylight in a sidelit space is directly in the line of sight of occupants, it is usually above the line of sight in atria, where occupants are typically engaged in non-vision-critical tasks such as walking and talking. Nevertheless, since glare and overheating can still pose potential problems, they should be carefully considered.

Under Nordic skies, it is logical to orient the glass towards the zenith as much as possible to collect zenithal daylight, since overcast sky conditions are dominant. However, a flat roof will transmit less daylight on sunny days, especially due to the low solar altitudes, as shown by Matusiak & Aschehoug (1998)[31]. We can speculate that an optimal solution for Nordic climates is to use sloped glass with a large reflector, allowing skylight to enter from the zenith during overcast conditions, as well as low-angle sunlight on sunny days, as illustrated in Figure 10.5.

Studies of real atria[32] suggest that 30–60% of incoming daylight can be blocked by the atrium roof, which can also affect the distribution of daylight inside the atrium. Navvab & Selkowitz (1984)[33] studied the DF measured with an azimuth of 0° at the center of a well with high reflectance (86%). They investigated fourteen roof structures with different glazing options under varying sky conditions. Sawtooth and monitor configurations showed the highest sensitivity to solar altitude compared to pyramids, vaults, and A-frames. Later, Sharples & Shea (1999)[34] studied the effect of roof obstructions on daylight levels in atria through 1:25 scale model studies exposed to unobstructed real skies for 4–6 weeks. They examined a square atrium with a WI of 2.0 covered by a flat roof, a south-oriented mono-pitched roof, and an A-frame double-pitched roof. The atrium roof structure systematically reduced vertical illuminance on the well walls, exhibiting a similar pattern of loss for the three roof types. The south-sloping mono-pitched roof had the least impact on daylight levels in the atrium well, although all three roofs performed similarly under overcast sky conditions.

Boubekri (1995)[35] showed that the atrium roof structure has a significant impact on daylighting. Using an artificial overcast sky, he studied the VDF on the well walls under three roof types (flat top, monitor, sawtooth monitor) of a seven-storey atrium. The flat top roof produced the highest daylight levels, while the sawtooth roof exhibited the strongest directional properties, mainly transmitting light toward the wall facing the glass. The monitor roof admitted the least daylight but resulted in the most uniform daylighting. Later, Calcagni & Paroncini (2004)[17] obtained results through computer simulations showing that the atrium roof (a double-sloped steel frame with a side grid of 2 m and commercial solar control glass) reduces the DF by about 45% in the area adjacent to the atrium.

In Norway, Matusiak & Aschehoug (1998)[31] studied atrium roofs under direct sunlight and found that horizontal glazing performed the poorest, as it blocked the low-altitude sun when it was most needed in winter. A mono-pitched roof oriented to the north outperformed a south-facing slope by allowing in low sun (even increasing it through reflection from the internal sloped surface of the roof) while controlling rays from higher angles on the south side.

In Canada, Laouadi & Atif (2001)[36] found that domes were the best roof configurations for admitting the low winter sun. Later, they investigated the daylight performance of barrel-vault skylights and found that they were more effective at transmitting daylight than flat skylights with similar glazing attributes[37]. Sharples & Shea (1999)[34] studied the effect of roof structure on daylight within the atrium well under real overcast sky conditions. They found that the south-sloping mono-pitch roof had the highest transmittance, while the flat and A-frame roofs performed similarly. A study[38] conducted in the climate of Malaysia also showed that, under overcast skies, the flat roof provided the highest daylight ratio (measured on the atrium floor at the center, corner, and central edge) compared to pitched roofs, pyramidal-gridded roofs, and sawtooth configurations.

More results are discussed in Sharples & Lash (2007)[9]. However, it is evident from their review that there is no consensus, as different studies arrive at varying conclusions depending on factors such as location (latitude and climate), daylight conditions studied (sunny or overcast), methods used (measurements or calculations), and daylight metrics considered (horizontal DF, VDF, etc.). It is challenging to provide general advice, and more research is clearly needed in this area.

10.2 Skylights

Skylights are light-transmitting fenestration systems placed on the roof. The transparent part of skylights is often clear, but diffuse materials are also used. Unlike atria, skylights are typically designed with the primary goal of illuminating the top floor of low-rise buildings. Additionally, skylights aim to provide uniform lighting for commercial and industrial applications[39]. They have even been used successfully in large factory spaces (see Figure 10.8) to reduce reliance on electric lighting and create a more visually pleasing atmosphere with good colour rendering.

Figure 10.8
Factory building on the Vitra Campus, Basel, architects SANAA. Photo: Marie-Claude Dubois.

Typical buildings that use skylights include retail stores, shopping malls, grocery stores, schools, single-story office buildings, manufacturing and agricultural buildings, warehouses, and distribution centers. Laouadi (2010)[40] found that potential lighting energy savings for a retail store located in Ottawa, Canada, may reach up to 50% with a roof moderately glazed with skylights.

Surveys[39] of occupants in retail spaces with skylights indicated that they found the skylit areas to be more attractive than non-skylit spaces. Additionally, the skylit spaces were described as having better light quality, improved uniformity, increased sales, and higher customer satisfaction compared to the non-skylit spaces.

Since the mid-20th century, skylights have been sold as off-the-shelf manufactured products, offering a wide variety of systems in different shapes and sizes (Figures 10.9–10.11). Even 'bubble' shapes protruding from the roof construction may be used, as seen in the Citizen House in Eslöv by Hans Asplund (Figure 10.12).

Skylights can provide both daylighting and ventilation. Due to their location on the roof, skylights can lead to unwanted summertime solar

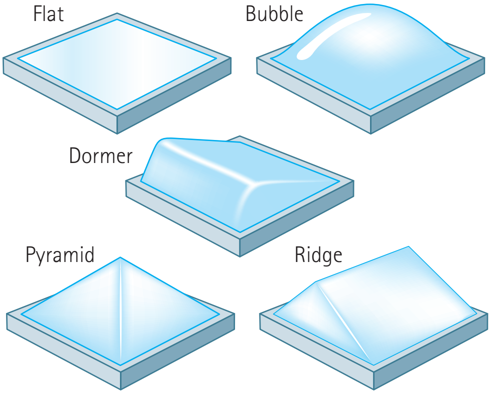

Figure 10.9
Different off-the-shelf skylights products. Adapted from Heschong & Mahone (2014).[39]

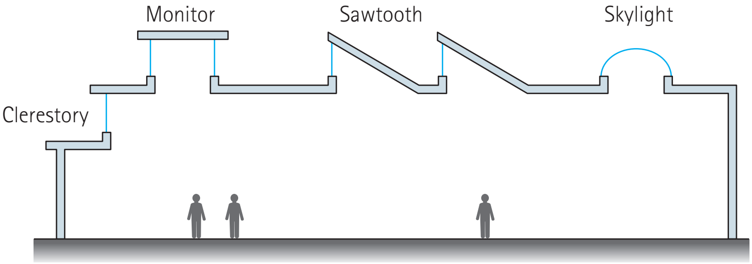

Figure 10.10
Skylights come in a variety of shapes, adapted from PWGSC (1989).[22]

Figure 10.11 Sawtooth configuration, skylights above an atrium, children hospital, Lund, Sweden. Photo: Marie-Claude Dubois.

Figure 10.12 Skylights at the Citizen House, by Hans Asplund, Eslöv, Sweden. Photo: Nicholas Wakeham.

heat gains and higher wintertime heat losses. Conventional window technologies, such as heat-absorbing tints in the glass, insulated glazing, and low-emissivity coatings, can be employed to control heat gains and losses. More advanced skylight designs may include sun-tracking mechanisms, open-sided cylinders, large lens-like elements, or even mirrored reflectors mounted next to conventional skylights to enhance daylighting without increasing daytime heat gain or nighttime heat losses. However, these advanced systems are rarely economically justified in the Nordic climate, which is dominated by overcast skies.

The key aspects to consider for skylight performance are listed below:

1. Shape and slope of transparent parts,
2. Orientation of transparent parts,
3. Size of opening,
4. Space between skylights,
5. Material of transparent parts,
6. Design of well (the space between the transparent part and the ceiling),
7. Relationship of the skylight to room surfaces and integration with the electric lighting system.

The following subsections provide general recommendations for each of these aspects, as found in design guidelines[22 39 41] and scientific articles. Other aspects related to skylight design, such as visual and thermal comfort, seasonal shifts in daylight availability, heat losses and gains, etc., are not addressed here. The reader is invited to consult the Skylighting Design Guidelines[39] for detailed information.

10.2.1 Shape and slope of transparent parts

Skylights come in various shapes and sizes, such as rectangular, circular, oval, diamond, triangular, multi-sided, tubular, and more. Laouadi (2000)[42] demonstrated that skylight shape significantly affects daylight transmission. He developed equations to predict the diffuse transmittance of skylights with different shapes under three sky conditions in Ottawa, Canada (latitude 45°N). His findings indicated that skylight shape does not produce significant differences in equivalent diffuse transmittance under overcast skies. However, under clear skies in winter, the equivalent diffuse transmittance of non-flat skylights was up to 56% higher than under CIE overcast skies and up to 27% higher than that of flat skylights, particularly for hemispherical domes. This is because non-flat skylights capture more circumsolar light at low sun altitudes in winter compared to flat skylights.

A flat glazed skylight on a flat roof receives very little sunlight when the sun is low in the early morning and late in the day. In contrast, a skylight with sloped sides (e.g., bubble, pyramid, or other raised shapes) receives substantially more sunlight at these low sun angles, increasing illumination by 5% to 10% at the start and end of the day[40] (Figure 10.13).

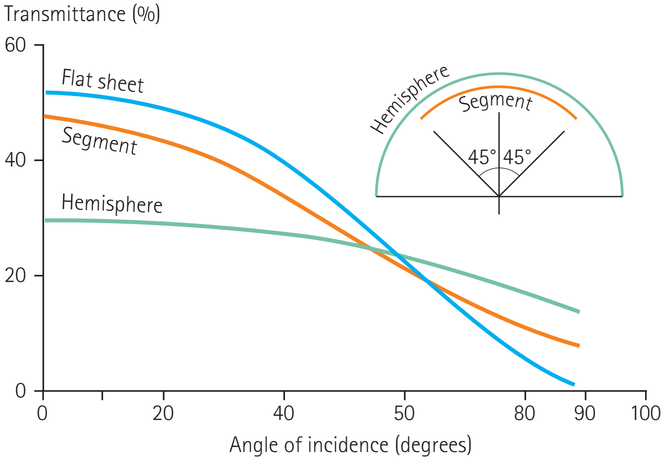

Figure 10.13 Transmittance of skylights of different shapes. Adapted from Heschong & Mahone Group (2014).[39]

Later, Laouadi (2010)[40] also demonstrated that high-profile clear domes transmit substantially more daylight than flat skylights with similar glazing, particularly on winter days with low sun altitude. Diffusing domes, however, transmit up to 50% less daylight than flat skylights when considering the entire year. This is likely due to their performance under overcast and uniform sky conditions.

Sloped glass performs better than vertical glass under Nordic skies, which are often dominated by overcast conditions. Daylight collection through vertical glazing, commonly used in commercial buildings, does not achieve the same illumination levels on overcast days (see Figure 10.14). While flat glass collects zenithal light, it transmits less daylight under sunny conditions. Therefore, a sloped skylight is an optimal solution in Nordic climates, as it admits skylight on overcast days and captures low-angled sunlight on sunny days.

The slope of a skylight impacts solar heat gains. A low slope allows more solar heat in the summer and less in the winter, which is the opposite of what is desirable for energy efficiency.

Perhaps the two most important aspects of skylight design are:

1. Sloped glass, which captures both zenithal and low-angled sunlight;
2. Glass that directs light toward a large reflector with high surface reflectance (see Figure 10.15).

Figure 10.14
Skylight at the shopping centre Nova Lund, Lund Sweden. Photo: Francisco Ortega.

Sloped glass combined with a large vertical reflector is effective in directing daylight downwards, as seen in the MKB office renovation in Malmö, Sweden (see Figure 10.7). In this case, the roof daylighting system successfully brings daylight to the ground floor, three stories below. Note that the reflector is large, highly reflective, and vertical.

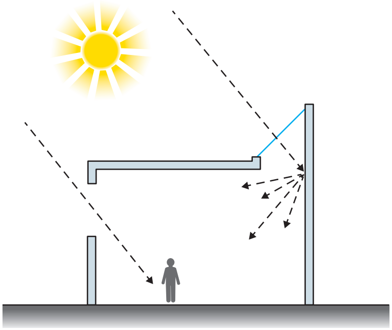

Figure 10.15
Principle of sloped glass catching zenithal luminance and low angle sun and reflection by the adjacent wall.

10.2.2 Orientation

South or north orientations are preferable, as direct sunlight is easier to manage: it can be effectively shaded on the south side and is almost completely avoided on the north side. Skylights on north-facing roofs provide constant but cool illumination, making a north orientation ideal for buildings with high internal heat gains to prevent overheating. North-oriented skylights may also be sloped to avoid all sunlight if necessary; see Equation 7.1 for calculating exact sun angles.

Skylights on east-facing roofs provide maximum light and solar heat gain in the morning, while west-facing skylights provide afternoon sunlight and heat gains, which is rarely desirable in buildings that accumulate heat throughout the day. South-facing skylights offer the greatest potential for desirable passive solar heat gain in winter, but they can also allow unwanted heat gains in summer. The decision to slope a skylight toward the south or north depends largely on the building's energy balance. In some cases, the roof structure dictates skylight orientation.

10.2.3 Spacing

When skylights are installed to provide uniform daylight distribution in large open spaces, careful attention to skylight spacing is a key design consideration. Fewer large skylights are generally more economical than numerous smaller, closely spaced ones; however, the latter option may provide more uniform ambient daylighting.

In large spaces, the distance between skylights should be approximately equal to the floor-to-ceiling height. Guidance from the Lawrence Berkeley Laboratory (1988)[43] provides an unattributed rule-of-thumb that square skylights should be spaced 1.0 to 1.5 times their height above the floor. This advice is reiterated in the more recent Skylighting Design Guidelines (2014)[39] (see Figure 10.16).

However, the scientific literature offers differing recommendations regarding skylight spacing. For example, McHugh et al. (2002)[44] conducted photometric measurements of intensity distribution for several white skylights and well combinations, finding that skylight spacing should be less than 1.4 times the mounting height. Dewey and Littlefair (1998)[45] found that a spacing-to-height ratio of 1.5 met the CIBSE ratio for illuminance uniformity of 0.8 for flat, shed, vertical sawtooth, and dome skylights. They reported a spacing-to-height ratio of 2.0 for north light (sloping sawtooth) and 3.0 for vertical monitors. Much earlier, Lynes (1968)[46] provided spacing recommendations for circular domes with and without wells, concluding that for domes without wells, the spacing-to-height ratio should be 1.25.

More recently, Laouadi (2010)[40] proposed a skylight spacing criterion called surface area coverage (SAC). The SAC refers to the surface area beneath the skylight that receives an illuminance equal to or greater than the recommended task illuminance. Using the SAC method, he determined that the skylight-to-ceiling height ratio for diffusing domes was 1.63 for a ceiling height of 3 m and 0.96 for a ceiling height of 6 m, in order to meet a target task illuminance of 200 lux under CIE clear sky conditions.

In summary, the rule-of-thumb stating that skylights should be

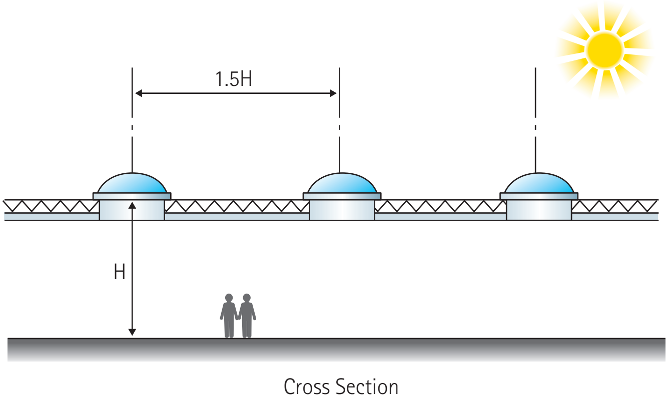

Figure 10.16
Spacing between skylights adapted from Heschong & Mahone Group (2014).[39]

spaced at a distance equal to 1.0 to 1.5 times their height above the floor appears to be justified during the early design phase. The exact spacing should be verified through computer simulations as the design progresses. Additionally, the skylight position should take advantage of window placement; if there is a window on one side, the skylight should be placed on the opposite side to achieve an even distribution of daylight (see Figures 2.25 and 9.45).

10.2.4 Size of opening

Skylights typically provide high indoor daylight availability, offering two to three times more light than windows, as they capture the powerful zenithal daylight. As a rule-of-thumb, the skylight size should never exceed 5% of the floor area in rooms with many windows and should not exceed 15% of the total floor area in spaces with few windows. Some calculation examples are provided in the Skylighting Design Guidelines[39], most of which result in a skylight-to-floor area ratio of 4% to 6%, depending on factors such as energy costs, geographical location, building usage, and illuminance targets.

Note that a correctly sized skylight with appropriate lighting controls can provide significant energy savings, while an undersized skylighting system does not justify the investment in electric lighting controls and fails to create the desired effect of a well-daylit space. Conversely, an oversized skylighting system may result in overheating and significant heat loss in winter. The goal is to size the skylight system with precision, considering all relevant parameters.

10.2.5 Material of transparent parts

Some skylight products use plastic instead of glass because it is typically less expensive and less likely to break than most other glazing materials. The most common plastic materials include acrylics, polycarbonates, and fiberglass[39]. These materials are available in a variety of colours (clear, translucent, bronze, and gray) as well as in different thicknesses and numbers of layers. Naturally, more layers, tints, or coatings result in reduced daylight transmission.

Compared to glass, plastic surfaces scratch easily and may become brittle and discoloured over time. Additionally, many plastics allow most ultraviolet (UV) rays to pass through, increasing the risk of fading damage to furnishings. However, the presence of UV radiation can be beneficial for occupants' vitamin D production, so it may be desirable for health, provided there is caution against overexposure. More expensive skylights are typically made of glass, which is more durable than plastic and does not discolour. Glass used for skylights must be classified as 'safety glazing,' which includes both tempered and laminated glass.

The material's transmittance and transparency are not directly related; it is possible to have a material that scatters light while still allowing a high percentage of light to pass through. Merely specifying the light transmittance (τ_{vis}) and g-value of the material is insufficient. It is necessary to include a description of the material's diffusing properties, as more diffusive materials typically produce a more uniform daylight distribution. However, diffuse materials will also block the view of the sky. Typical optical properties for glass and plastic materials are presented in the Skylighting Design Guidelines[39].

A slope or curvature in the glazing or plastic helps prevent moisture issues and the accumulation of leaves or snow. These skylight designs do not typically require the additional framing needed to slope a flat skylight for proper drainage on flat or low-slope roofs.

10.2.6 Design of the skylight well

Once daylight has been admitted through a skylight's transparent material, it can be scattered and diffused by the shape and surfaces of the light well, by shading devices beneath the light well, and even by the room surfaces. The design of skylights also requires careful consideration of the light well space (the area between the roof and the ceiling) (see Figure 10.17).

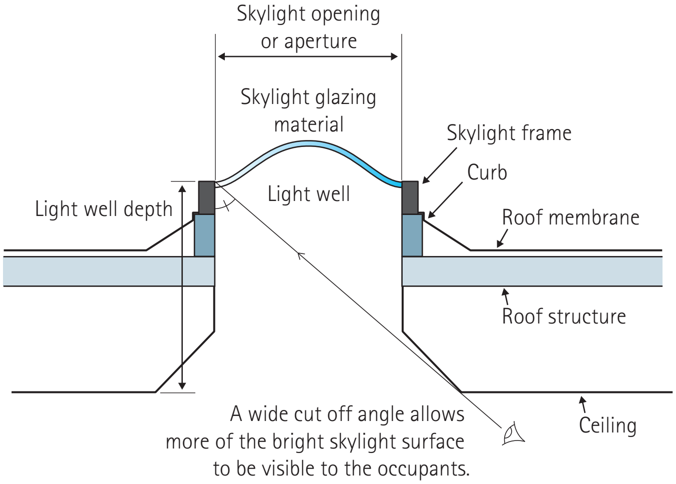

Figure 10.17
Skylight section showing the light well. Adapted from Heschong & Mahone Group (2014)[39].

The well space may reduce the amount of daylight and solar heat gains entering the area. Deep wells provide a significant opportunity for controlling daylight distribution beneath skylights. A careful design of the light well can prevent a direct view of the bright sky while allowing for good daylight distribution, which is described by the cut-off angle (see Figure 10.17). This angle is also used to describe the shielding effect against glare from lighting fixtures. For lighting fixtures in offices with computers, the IESNA recommends a minimum cut-off angle of 55° from vertical, although less stringent angles (45° to 55°) are usually sufficient in buildings with less critical visual tasks, such as warehouses and retail spaces[39].

Splayed well surfaces reduce contrast when looking directly at the skylight (see Figures 9.34-9.36). Splayed surfaces also help distribute daylight more evenly in the room, which is beneficial for visual comfort and lighting energy savings. However, Laouadi (2010)[40] found that splay angles lower than 60° do not significantly improve the well's efficiency.

Finally, Laouadi (2010)[40] developed a computer program called Skyvision, which analyzes the optical characteristics of skylights of various shapes and types and predicts their energy and daylight performance. Skyvision considers the lighting and shading controls, skylight shape and glazing type, curb and well geometry, building location and orientation, and prevailing climate. Additionally, a simplified analysis tool called SkyCalc[47], developed as an Excel

Figure 10.18
Bon Lait Sports Hall, Dietrich, Untertrifaller Architekten. Photo: Rickard Nygren.

spreadsheet, is also available to estimate energy savings from skylighting based on various inputs.

The surface reflectance of the light well is another important parameter to consider. A highly reflective and diffusing surface (e.g., white paint) provides a broadly distributed light pattern beneath the skylight, while a specular reflective surface (e.g., reflective foil) may create an image of the sun and sky on a limited area below the skylight. Coloured surfaces may distribute light evenly, but they will tint the light, as shown in the example of La Tourette in Figure 2.22. In general, for applications where uniform light distribution is the goal, a matte white reflector is a good solution. Table 10.1 presents reflectance values for typical building materials.

Table 10.1 Typical surface reflectance of materials, adapted from Heschong & Mahone Group (2014)[39].

Material	Reflectance
White plaster	0.93
Aluminium foil	0.85
White paint	0.80-0.90
White enamel	0.65
Red brick	0.45
Granite	0.45
Concrete	0.40
Galvanised steel	0.35
Medium grey paint	0.25
Flat black pain	0.04

10.2.7 Skylight in relation to room surfaces and integration with electric lighting system

As mentioned before, the best solution is to combine a skylight with a large vertical reflector (a wall) indoors to diffuse light rays towards the space (see Figure 10.7). The ceiling height is another important aspect to consider in the overall design. As the ceiling height increases, the light transmitted by the skylight is distributed over a larger floor area and working plane, resulting in more uniform lighting. Conversely, lower ceiling heights lead to less uniformity, with bright areas directly beneath the skylight and darker areas in between[39].

The electric lighting system should be designed to supplement illumination from the skylights. Additionally, it should provide sufficient lighting for the evening, for maintenance, or during dark overcast conditions. Figure 10.18 shows an example of electric lighting integrated with the skylight design at the Bon Lait Sports Hall, designed by Untertrifaller Architekten. It is also important to note that daylight is generally of a cooler colour than light from artificial systems, so designers typically select lamps with a cool colour temperature to complement daylight.

When the skylight is placed centrally in the room, it is necessary to illuminate the walls to avoid large contrasts. Various solutions can be employed, but it is important to avoid directing electric light rays towards the skylight, as this could contribute to light pollution.

10.3 Light wells

Light wells are vertical spaces architecturally built within the building structure, featuring a skylight at the top that transports daylight (and sometimes ventilation) into the building core. The space occupied by light wells requires heating or cooling, which contributes to increased energy use. This technique was common in the past, but a few relatively recent examples can be found in Nordic climates, such as the National Gallery of Canada in Ottawa, Ontario, designed by architect Moshe

Figure 10.19 Light wells of the National Gallery of Canada, Ottawa, Ontario, Moshe Safdie, architect. The image on the left shows the highly reflective surfaces used inside the light wells.

Figure 10.20
Tubular daylighting device under a sunny (left) and an overcast (right) climate. The picture on the right side shows a scene mainly illuminated by electric lighting.

Safdie (see Figure 10.19). In this case, the light wells are linear, and the climate of Ottawa is substantially sunnier than that of Scandinavia.

Fontoynont (2009)[48] compared the costs of various daylighting and lighting techniques over long time periods for a building located in France. His cost calculations included the initial construction costs and operation/maintenance expenses (electricity costs in €) for the expected lifetime of the building, assuming annual illumination (expressed in Mlmh) delivered to the work plane. He demonstrated that daylighting systems designed to bring daylight deeply into a building are generally not cost-effective unless they utilize off-the-shelf industrial products with advanced optical performance and low maintenance, while collecting daylight directly from the building envelope. Consequently, it is more economically justified to use advanced tubular daylighting devices (TDDs) than architecturally built light wells; thus, this technique is not explored further here. Since light wells were not cost-effective in France in 2009, they are unlikely to be cost-effective under the predominantly overcast sky conditions of Nordic countries.

Figure 10.21
Light pipe from Solatube.

10.4 Tubular Daylighting Devices

Tubular Daylighting Devices (TDDs) are sometimes referred to as 'light pipes' or 'daylight tubes.' TDDs operate on the principle of light piping, with surface reflectance typically exceeding 98% inside the pipe. Figure

Figure 10.22
Fiber optic system, from Parans. Illustration: Parans Solar Lighting AB.

10.20 shows a picture of indoor illumination under a daylight tube in the sunny climate of Granada, Spain (left), compared to the same type of system under an overcast sky at the Lighthouse in Copenhagen (right). The system under the overcast sky performs poorly, as most light in this room at that moment comes from the electric lighting system.

On a more positive note, TDDs can bring daylight to deep spaces without producing glare or increasing cooling demands. They are especially valuable in retrofit projects or applications requiring excellent colour rendering. However, their performance is dependent on sky-clearness[49]. They are efficient under direct sunlight but produce significantly lower illumination under overcast skies[50], making them more suitable for climates with an abundance of clear skies[51]. Additionally, their use is typically restricted to the top two floors of buildings. The website of Solatube, one of the main manufacturers of TDDs, states that the light pipe should not be located more than 9 meters from the rooftop.

TDDs typically include three parts: a collector, a mirrored light pipe (MLP), and a diffuser (at ceiling level), as shown in Figure 10.21. The collector may feature an optical redirecting system (ORS), which reduces the number of light bounces within the pipe. These ORSs are optically complex, making it difficult to predict their illumination output using simple simulation tools. This lack of predictability hinders their widespread use and effective implementation[52] [53].

10.5 Fibre optic lighting systems

The second most commonly used roof-based daylighting transport devices are lens- and fiber optic systems. Fiber optic lighting systems consist of a collector connected to small, flexible cables that embed plastic or glass fibers, along with a diffuser at the end (see Figure 10.22). The collector, which is typically located on the roof, can be either passive or active. Passive systems are fixed at a specific angle and orientation optimized for sunlight collection, while active systems have a tracking device that continuously orients the collector towards the sun[53]. According to Oh et al. (2012)[54], active fiber optic systems are more suitable than light tubes at low solar altitudes (less than 50°) since it is easier to harvest sunlight with a solar tracking system than with a passive system.

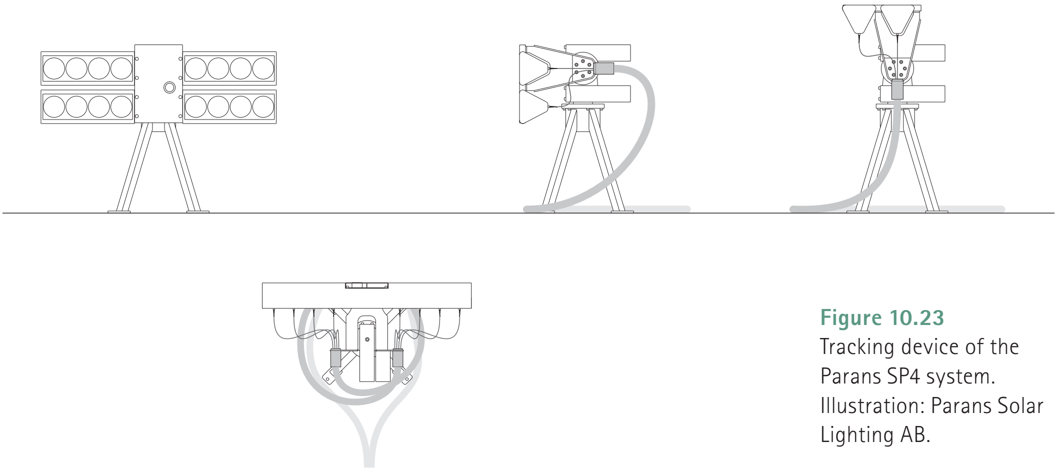

Figure 10.23
Tracking device of the Parans SP4 system. Illustration: Parans Solar Lighting AB.

Figure 10.24
Optic fibers embedded in flexible cable. Photo: Parans Solar Lighting AB.

Both collector and diffuser may include a series of Fresnel lenses, which are thin transparent materials with prismatic circular indentations or a chain of prisms. Due to the limited acceptable angle of the lenses, these types require a tracking system to orient them towards the sun and locate the position of the focal point[55]. Figure 10.23 shows an active tracking device that contains the collector and Fresnel lenses of the Parans system from Sweden.

A recent study[55] investigated the performance and energy savings of a fiber optic lighting system in a study hall interior. The system provided intense white light with a high luminous flux of 4 500 lumens under 130 000 lux of direct solar radiation, with a perceived colour temperature of 5 800 ± 300 K at 10 meters from the sun-tracking collector. The study showed that annual lighting energy savings were 19% for Uppsala, Sweden, and 46% in southern Europe for a study hall interior. For an interior illuminated 16 hours per day throughout the year, the savings were 27% and 55%, respectively.

A Master's thesis[56] conducted through simulations and measurements investigated the Parans fiber optic system (SP4), which utilized glass instead of plastic fibers with longer cable distances (100 meters). This allowed light to be transmitted several floors down, with a colour shift towards red occurring after 75-100 meters. The findings showed a good agreement between measured and simulated values, as well as no perceptible risk of glare. A simulation study was conducted using climate data from Copenhagen, Paris, Washington, and San Francisco. The authors concluded that fiber optic systems are more suitable for locations such as San Francisco, while at higher latitudes (like Copenhagen), the energy-saving potential decreases significantly.

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CHAPTER 11

Integrating daylighting and electric lighting

NIKO GENTILE

'The General Assembly of United Nations regognizes "the importance of light and light-based technologies in the lives of the citizens of the world and for the future development of global society on many levels, [...]" and considers that "light-based technologies contribute to the fulfilment of internationally agreed development goals, including by providing access to information and increasing societal health and well-being, [...]"'

THE GENERAL ASSEMBLY OF UNITED NATIONS, ON THE MOTIVATION OF PROCLAMING 2015 THE INTERNATIONAL YEAR OF LIGHT AND LIGHT-BASED TECHNOLOGIES

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Luminous efficacy, tungsten filament, halogen, incandescent, fluorescent lamp, CFL, LED, OLED, plasma, luminaire efficacy, LOR, ballast factor, lighting controls, manual dimming, occupancy detection, presence detection, absence detection, daylight harvesting, energy efficiency, energy saving, energy for lighting, energy for illumination, energy for parasitic use, maintenance factor, circular economy applied to lighting technologies.

11.1 Electric lighting systems

An electric lighting system includes three components:

- a light source providing the actual illumination;
- a luminaire, or light fixture, holding the light source and improving the light extraction and re-direction from the light source;
- a control system operating on the light source (Figure 11.1).

These three components are briefly described in this chapter. In addition, since electric lighting uses energy, the last part of the chapter illustrates some effective strategies to save lighting energy.

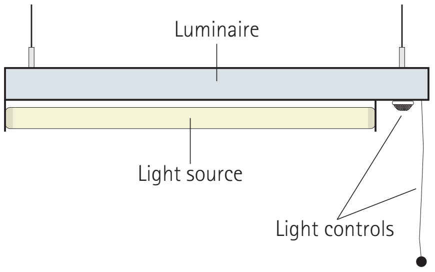

Figure 11.1
The three components of a lighting system.

11.1.1 Electric light sources

Combustion-based artificial light sources such as fire, candles and oil-lamps, have been the alternative to daylight for millenniums. They had obvious downsides: they were dangerous, costly and difficult to control. It was just in 1871 that Thomas Edison patented the first fully functional light bulb based on the incandescent technology, paving the way for the first revolution in lighting: the birth of electric lighting.

It is common belief that we are experiencing today a second revolution in electric lighting: the light-emitting diode (LED) revolution. This technology brought to society an efficient, economical and versatile light source, making it possible for an even greater impact of lighting on future society.

LED will become the main light source globally, considering the phasing out of other technologies. In Europe, the so-called Eco-Directive imposed a gradual phase-out of incandescent bulbs starting from March 2009. The ban concerned filament tungsten first and non-directional halogen later, and it is now also including the more efficient fluorescent T5 technology – from August 2023, under the Restriction of Hazardous Substances (RoHS) Directive.

11.1.1.1 Properties of light sources

Luminous Flux

The luminous flux or luminous power is the total perceived power of light delivered by the lamp, measured in lumen.

Power load

The power load is the power in Watts required to run the lamp.

Luminous efficacy

The energy performance of a light source is provided by its luminous efficacy K, which is the ratio between luminous flux and power load (lm/W). The physical limit of luminous efficacy is 683 lm/W. Indeed, one Watt of a hypothetical light source emitting monochromatic light at 555 nm – wavelength with maximum human eye sensitivity in photopic conditions – emits 683 lumens.

Luminous efficacy should not be confused with luminous efficiency, as efficiency is a dimensionless quantity. Luminous efficiency is the ratio between the luminous efficacy of the light source and the theoretical maximum luminous efficacy (683 lm/W).

Correlated Colour Temperature (CCT)

The correlated colour temperature of a titular white light source is the temperature of a Planckian radiator (black body) which irradiates light of the closest colour to that of the light source.

Spectral Power Distribution (SPD)

SPD is the radiant power emitted by the light source at each of the visible wavelengths.

Colour Rendering Index (CRI Ra)

The CRI Ra or general CRI index shows how well, on a scale of 1–100, a light source renders colours.

Lifetime

For traditional light sources, the lifetime was defined by the number of hours after which 50% of test samples would have broken. LED sources, however, may burn for a high number of hours without failure, but their light output will still degrade over time. Lumen depreciation indicates the percent reduction of luminous flux over time, due to ageing of the light source combined with environmental factors. The term 'lumen maintenance' is often used in lighting products. With lifetime, the lighting market refers today to lumen maintenance L_{70} for LEDs, which is the time after which the light source delivers only 70% of its initial luminous flux.

Dimmability

Not all light sources are dimmable. Certain technologies, such as incandescent lamps, are naturally dimmable. Others, like fluorescent, require some technological expedients to be dimmable (controllers combined with appropriate ballasts or drivers).

Temporal Light Modulation (TLM)

TLM is a fluctuation in luminous flux. Visible TLM, typically below 80 Hz, is generally called flicker, but TLM can also give rise to other light artefacts such as stroboscopic effects and phantom array, see Chapter 3 (3.2.9).

11.1.1.2 Incandescent and halogen sources

The traditional incandescent (or tungsten filament) light bulb consists of a metal tungsten filament wire placed in evacuated glass bulb. Electrical connections from the socket provide current directly to the metal filament, which heats it up to high temperatures and makes the filament glow. The vacuum in the bulb prevents the wire to burn instantaneously because of oxidation. The heated filament emits radiant energy on a broad range of wavelengths, including the visible ones. A considerable portion of this energy i.e., about 90%, is emitted in the infrared range, making this type of lamp rather inefficient. The infrared energy that is released, namely heat, makes the bulb hot even for short burning times. Therefore, in an energy design perspective, incandescent bulbs provide considerable internal heat gains in a space.

The spectral emission of an incandescent lamp is continuous over the visible spectrum, and higher at longer wavelengths (Figure 11.2). This contributes to both low CCT (2000–2700 K) and high CRI. In fact, CRI is maximum (CRI = 100) for incandescent lamps, as they are used as reference source for CRI calculation. The exact spectrum of incandescent lamps depends on the temperature of the tungsten wire. For very hot wires, more radiation is emitted at shorter wavelengths and the luminous efficacy of the lamp is higher. If lower voltage is applied, the wire temperature is lower, the radiant energy is higher around the red wavelengths, and the luminous efficacy is lower. For extremely low voltage, the incandescent bulb may not emit energy at all in the visible spectrum and all the radiation may be in the infrared range. High voltages, however, will reduce the lamp lifetime, since the filament will break earlier due to higher temperatures. For example, standard 30 W incandescent bulbs have a luminous efficacy of around 9 lm/W and roughly 2 000 hours of lifetime, while the 100 W versions have an efficacy of about 13 lm/W and roughly 1 000 hours of lifetime. Very powerful incandescent lamps, such as those that were used in photography, could reach 35 lm/W, but they barely had 40 hours of lifetime.

One way to extend the lifetime of incandescent bulbs is to enclose the filament into an environment filled with an inert gas and a halogen element. Such technology is called ‘tungsten halogen’, ‘incandescent halogen’ or, simply, ‘halogen’ lamp. In a traditional incandescent lamp, due to the high temperature, some particles of tungsten will evaporate. In a halogen lamp, these particles react with the halogen element, and they are deposited again on the filament. In such conditions, the tungsten filament temperature can reach higher temperatures, leading to higher luminous efficacy. A 30 W halogen bulb delivers more than 500 lm (18 lm/W), and its lifetime is higher than 3 000 hours. Because of the higher wire temperature, tungsten halogen bulbs also have higher CCT, generally around 3 000 K.

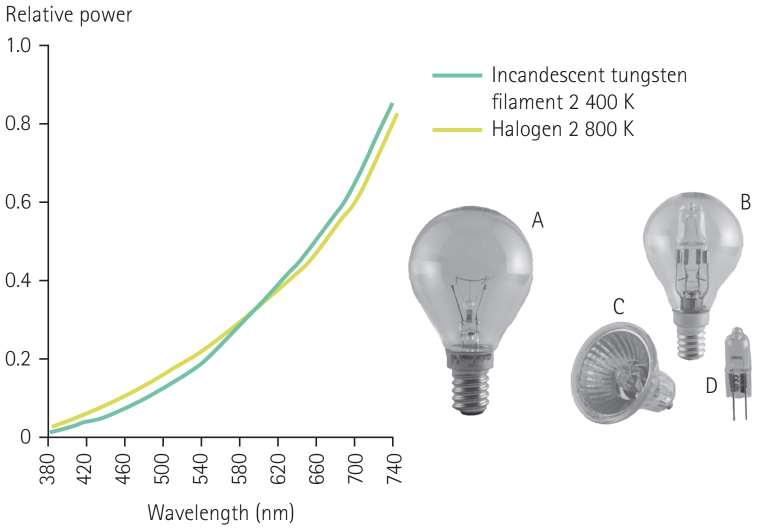

Figure 11.2
(Left) Typical SPDs for tungsten filament and halogen lamps. Note that the halogen lamp emits more at shorter wavelengths, raising both luminous efficacy and CCT. (Right) Incandescent light sources: A) Tungsten filament, B-D) Halogen in different formats.

Differently from traditional incandescent, the luminous source in halogen lamps is relatively small. Therefore, halogen technology could introduce directional lamps in the market, such as spotlights (Figure 11.2); halogen lamps have been extensively commercialized starting from 1959, when General Electric patented the first functional halogen bulb. Incandescent and halogen lamps have been sold in different sizes and powers. European traditional bulbs were usually provided with E27 and E14 type screw sockets. Halogen lamps have been popular in spotlight versions, with bayonets or bi-pin socket types.

A benefit of incandescent lamps, both traditional and halogen, is that they do not require any additional device to operate; it is enough to let the current flow through the wire. This translates in very low production costs and relatively easy disposal. In addition, they can run on both direct and alternating current. Flickering is reduced even with alternating current since the glowing filament guarantees thermal and luminous inertia.

11.1.1.3 Fluorescent and compact fluorescent sources

Fluorescent and Compact Fluorescent Lamp (CFL) are members of the same family of gas-discharge technology. A glass tube is filled with mercury vapours, and electrons are allowed to travel through the tube. The electrons excite the mercury vapours, which emit radiation in the ultraviolet (UV) range. A phosphor coating on the tube starts to glow when receiving the UV light; it then releases visible light outwards. Due to the excitation at different energy states, the light is released at singular wavelengths, providing the characteristic SPD with peaks (Figure 11.3).

Electricity cannot flow directly into the tubes in this type of technology. Fluorescent lamps need a starter and a ballast to operate, and two electrodes at the extremities of the tube. Starter and ballasts are assembled into the light fixture for fluorescent tubes. In CFLs, they are instead compacted into the lower part of the bulb (Figure 11.3).

Fluorescent lamps are much more efficient than incandescent lamps, with luminous efficacy typically higher than 100 lm/W. The lifetime of lamps is also extended to around 10 000 hours or more. Different mixtures of phosphor layers make it possible to produce lamps with different CCTs and CRIs, the latter being potentially as high as 90. The CFL version, which was considered an easier replacement of existing incandescent bulbs, usually has a lower CRI (around 80) and lower luminous efficacy (around 70 lm/W) in comparison with standard fluorescent tubes.

On the other hand, fluorescent tubes and CFLs also introduced a few new issues. For example, starter and ballast introduce complexity and energy losses in the system. Ballasts, which are typically used to convert 220 VAC 50 Hz to a suitable current, require additional energy to run and have their own energy losses. Additionally, the light output is affected by the ambient temperature. Finally, the disposal can be expensive and potentially more impactful on the environment, mostly because of the electronics of the driving devices and the mercury content of tubes. Regarding the latter, the EU Restriction of Hazardous Substances (RoHS) directive restricts the use of hazardous substances in electronics, which effectively initiates the phase out of fluorescent lamps from August 24, 2023.

Another issue is that the delivered luminous power and dimmability of the light source depend on both the light source and the ballasts characteristics. In practice, a ballast-lamp combination have a specific power-to-lumen curve, making replacements quite difficult. Light output of fluorescent technology is also highly dependent on ambient temperature, and, depending on the specific lamp, it can easily fall by 10–20% for just a few degree Celsius deviation from the optimal ambient temperature[8]. Finally, the disposal is more expensive and potentially more impactful on the environment, mostly because of the mercury content and the electronics of the driving devices.

11.1.1.4 Light-Emitting Diode (LED)

Light-Emitting Diodes (LEDs) or Solid-State Lighting (SSL) are the two names indicating the same light source. The LED technology probably represents the biggest revolution in lighting after the invention of the incandescent light bulb. The success of LED is driven by its value for money, efficiency, and versatility. The very short investment returns of LED-based lighting retrofit[9], makes switching to LED one of the most favourable energy conservation measures in buildings. Considering the foreseen 47–55% cost decrease of LED in the next two decades[1], it is expected that LED penetration in developed countries will increase from the current 20-30% to over 80% of the total installed electric lighting in 2035[2] [3].

Electroluminescence, the phenomenon on which LEDs are based, was discovered as early as 1907, while the first LED was invented – and largely ignored – already in 1927[4] [5]. Their commercial breakthrough

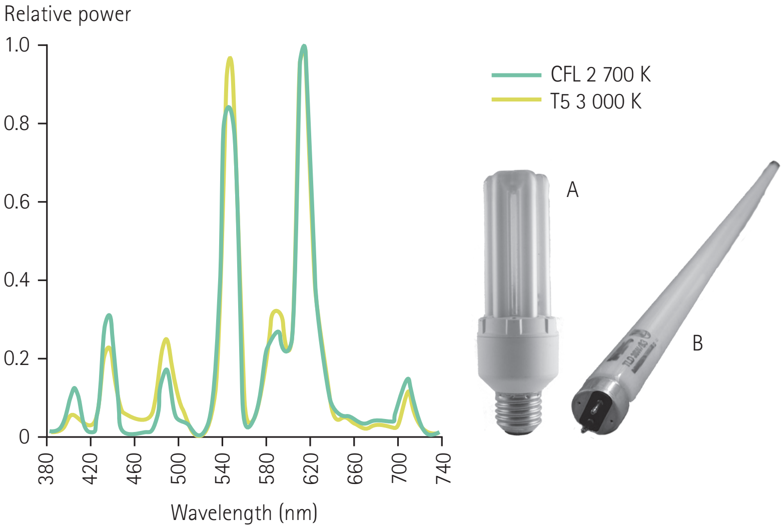

Figure 11.3
(Left) Typical SPDs for CFL and a fluorescent T5 tube. (Right) Fluorescent light sources: A) CFL and B) Fluorescent tube.

came only around 1970. At that time, LEDs were producing radiation in the infrared or red part of the spectrum. The red LED was used for electronic displays or indicators. Research on semi-conductor materials led to a breakthrough in 1994, when Japanese researchers were able to produce high-brightness blue LED[6]. From that point, the production of white LEDs was just a step away. Part of the blue light could be converted into yellow light by using phosphor layers, in a process like the one used in fluorescent technology. This way, the light source produced a continuous emission of radiation over the visible spectrum. Blue light and phosphor coating are responsible for the typical spectral power distribution of LEDs, which is characterized by two peaks, one in the blue and one in the yellow range (Figure 11.4). Ratio and location of the two peaks partly determine the characteristics of the emitted light in terms of CCT, CRI, etc.

Qualities of LED light sources degrade if they heat up, hence they must be provided with heat sinks behind the chip. A practical consequence is that the LED will dissipate heat at the base of the light source, which is opposite to what happens for incandescent light sources. Therefore, existing sockets, optimized for front dissipation of incandescent light sources, may not be optimal for LEDs.

The LED itself is very small and extremely bright (Figure 11.4), therefore glaring. The diode needs a plastic shell that improves the light extraction and diffuses the light. However, this is not enough, and commercial lamps are also provided with light diffusion systems, as opaque acrylic or polycarbonate covers.

LED technology uses direct current (DC), which is different from the alternating current (AC) of the electricity network. Therefore, LEDs need a driver – a device to some extent analogous to the fluorescent ballast – to convert the incoming AC current. Like ballasts, drivers add some complexity and energy use to the LED circuit. Today's LED driver efficiency is above 90%[7].

One of the mainstays for LED market penetration is its high luminous efficacy. Nowadays, ordinary LEDs are sold with efficacies ranging anything between 80 and 150 lm/W, while the 200 lm/W threshold in the market was passed already in 2016[8]. The theoretical efficacy limit for LED with CRI > 90 is estimated to be around to 250 lm/W.

The innovation brought from LEDs includes much more than higher luminous efficacy. For example, LEDs can provide a wide range of CCTs, while keeping the CRI high. The CCT can be easily tuned, which paved the way to commercial lamps that are both dimmable and adjustable in CCT, although keeping the output quality throughout the luminous and CCT range is still critical. In a daylight and electric lighting integration perspective, CCT tuning also prompts the realization of so-called integrative lighting schemes, namely lighting systems providing electric lighting with variable intensity and CCT, resembling daylight to regulate the biological rhythms of users. Finally, LEDs have a very long lifetime; 50 000 hours lifetime is expected for most LEDs, but this number refers to L_{70}, while the diode may continue illuminating for more than 100 000 hours before failure.

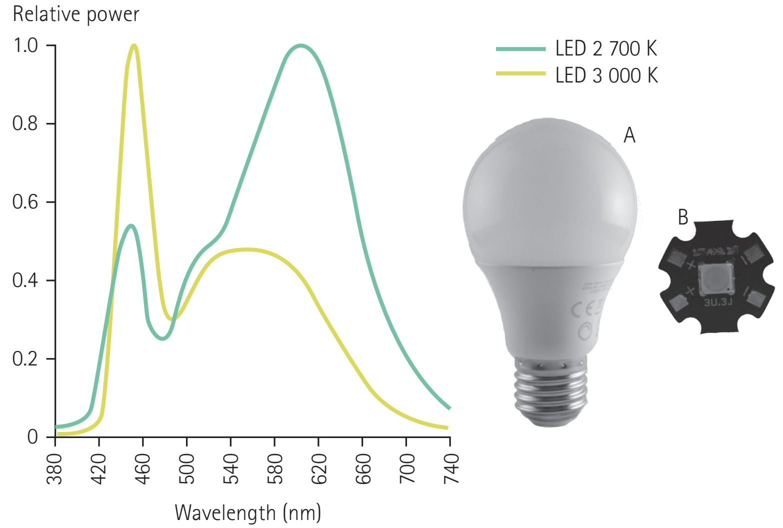

Figure 11.4
(Left) Typical SPDs for LED lighting. The peak in the blue region is higher for higher CCTs. (Right) A) a commercial replacement bulb with E27 socket and B) a single diode without driver and optics.

11.1.2 Luminaires

One or more light sources are connected to a luminaire. The main function of the luminaire is to redirect light according to the design, but it can also host the necessary driving gears for running the light source (starters, ballasts, and drivers).

The luminaire shape and hanging position provide the main direction of light. Some examples of light re-distribution by luminaires are provided in Figure 11.5. The optical system – reflectors and/or diffusers – is generally used to diffuse, redirect or increase the angle of view of the light source. For example, reflective lamellas are placed perpendicularly to fluorescent tubes, while diffusers are mostly used for punctual light source like LEDs.

Polar diagrams are used to represent the light distribution of the luminaire. They are normally found in the product datasheet. To build a polar diagram, two C-planes measure the luminous intensity around the luminaire, see Figure 11.6.

The luminaire affects the efficiency of the lighting system, since some lumens delivered by the light source are absorbed by the luminaire's optical system. The light output ratio (LOR) defines the fraction of light absorbed by the luminaire optics:

$$LOR = \phi_{\mathrm{lum}}/\phi_{\mathrm{lamp}} \tag{11.1}$$

where ϕ_{lum} is the initial luminous flux released by the luminaire and ϕ_{lamp} is the initial luminous flux released by the lamp. Modern luminaires typically have a LOR above 90%.

On the driving gears side, modern high-frequency ballasts and LED driver efficiency is above 90%[27] [28]. Focusing on ballasts only, a specific lamp produces the nominal luminous output only if coupled with a specific ballast. Other ballasts will reduce/increase the lamp output by a factor called Ballast Factor (BF), which is the ratio between the luminous flux of certain ballast-lamp combination and that from the same lamp using a reference ballast. BF is usually, but not necessarily, lower than one. BF higher than one indicates that the lamp will deliver more lumens than the nominal total luminous flux, at the cost of the lamp lifetime.

The overall efficiency of the luminaire and light source system is measured by the luminaire efficacy. The luminaire efficacy is the ratio between the power in input to a system and the output in lumen. This definition considers losses in the overall lighting system, including the fraction of absorbed light, losses in ballast, drivers, etc.

$$K_{lum} = \frac{\phi_{lum}}{P_{system}} \left(\frac{lm}{W}\right) \tag{11.2}$$

The luminous efficacy of luminaires is useful for quantifying the energy efficiency of the luminaire itself, but it does not address the issue of architectural applications. A certain lighting design can waste energy by delivering light where not needed, despite using efficient luminaires. Recently, Durmus and colleagues[9] [10] have proposed a framework to describe the lighting application efficacy (LAE) defined as

$$LAE = \eta_{lum} \cdot \eta_{spatial} \cdot S_{visual} \tag{11.3}$$

where η_{lum} is the luminaire efficiency (analogue to the luminaire efficacy but related to the maximum possible lumen output of 683 lm/W), $\eta_{spatial}$ refers to spatial efficiency, indicating the fraction of light from the luminaire(s) that bounces off visually significant surfaces and eventually reaches the occupants' eyes, and S_{visual} represents the sensitivity of the visual system, factoring in spectral luminous efficiency along with other visual processes, such as adaptation and contrast perception. The LAE framework can be seen at different levels of complexity, and although it does not yet have a practical application, it might change energy efficient lighting design in a foreseeable future.

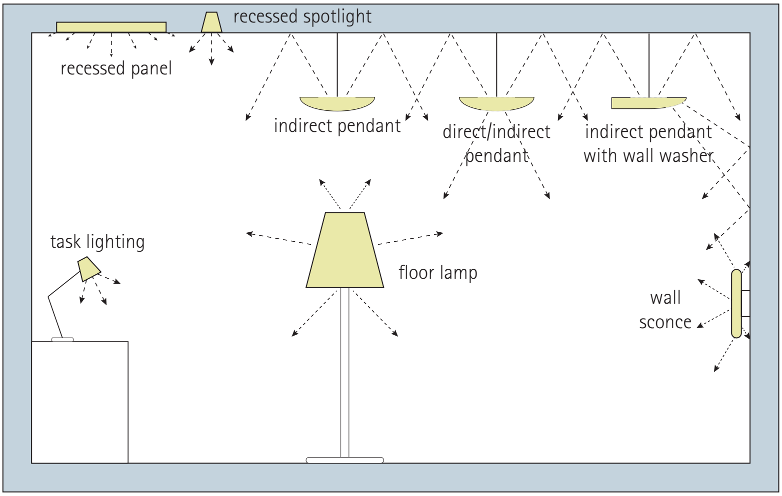

Figure 11.5
Qualitative classification of luminaires.

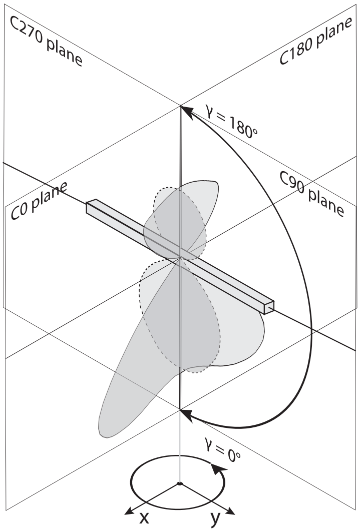

Figure 11.6
C-Planes building a polar diagram.

11.2 Daylighting and lighting control systems

A Lighting Control System (LCS) can switch on/off, dim and/or tune the CCT of a light source (Figure 11.7).

A LCS includes four main elements:

- a sensor detecting environmental information;
- a controller, which elaborates the sensor information;
- an actuator, which operates on a light source according to commands provided by the controller;
- the light source (Figure 11.8).

This four-element structure even applies for simple LCSs like manual switches at the door. In this case, the human eye would be the sensor, the human brain would be the controller, while the actuator for the light source would consist of hand, switch, and the ballast/driver (Figure 11.9)[11].

LCSs in indoor spaces are typically used to save energy, although the emerging trend is to focus on well-being, e.g. by using CCT tuning to stimulate the circadian rhythm (integrative lighting). Regardless of the purpose of the LCSs, occupants have strong opinions about them and the designer should follow the general recommendations provided below[12]:

- Occupants behave differently with centralized controls, namely they care less about lighting if the control is central.
- Occupants' requirements and preferences are different for different ages and abilities.
- Frequency of occupancy varies widely, and this is a fundamental design criterion for LCSs.
- Occupants want the LCS to behave predictably.
- The LCS should change the lighting conditions gradually (not abruptly).
- Blinds and shading devices may affect the LCS response, which requires extra care when designing LCSs for daylighting and electric lighting integration.
- Occupants must be trained, since some LCSs do not have obvious affordances[13 14].
- LCSs are usually more efficient if integrated in the Building Management System (BMS).
- The energy consumption of the LCS itself should be carefully accounted for when designing the lighting system[13].
- Training of designers and installers, as well as budget for monitoring and verification plans should always be considered.

Figure 11.7 Typologies of LCSs. Icons from www.freepik.com. Illustration: Niko Gentile.

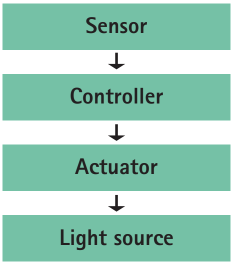

Figure 11.8 Main elements of a lighting control system.

Figure 11.9
Manual switch control: the simplest LCS. Illustration: 'Light Man' by Kevin Zanni.

11.2.1 Manual controls

Although there is a general tendency to provide a higher degree of automation for LCSs, it is desirable that occupants can control their own environment. More control educates occupants to use lighting consciously and helps them learn about their own space. In addition, manual controls are widely appreciated by users[15] [16] [17] [18] [19].

Manual controls are an easy and the preferred option for integrated daylighting and electric lighting schemes. The occupant's eye, indeed, is probably the most reliable photosensor. Research has shown that occupants tend to switch electric lighting on only when daylighting is insufficient. However, they tend to forget to switch lights off even when plenty of daylight is available[20] [21] [22] [23]. This suggests that an automatic switch off would reduce the energy use for lighting[24]. But not all occupants are the same; some tend to actively switch lights off (active occupants), while other occupants neglect switching lights off (passive occupants)[25] [26] [27]. Switch on-off patterns for active and passive occupants are included in some simulation tools, such as Daysim[28] [29].

It is of course desirable that a majority of active occupants inhabits a space, as this will greatly reduce energy use. Disciplines like environmental psychology helps develop effective ways to promote energy efficient behaviours. This is further explored later in this chapter.

People show a wide range of individual preferences when it comes to lighting[30]. Therefore, adding manual dimming to a simple switch, for example, by means of individual desk lighting, may enhance both satisfaction and energy savings. This is mostly beneficial when daylight is also provided, since occupants tend to choose lower illuminance in such cases[15].

11.2.2 Occupancy strategies

While active energy-efficient behaviour of occupants should be promoted, the designer should still make sure that lighting is switched off when the space is unoccupied. Occupancy strategies are solutions foreseeing the occupancy of a space, which operates lighting consequently.

Time scheduling is maybe the simplest occupancy strategy, since it just requires a timer. The lights are kept off during a predefined unoccupied time, for example nights or weekends.

During occupied hours, an occupancy sensor actuating an on-off switch can be used. The occupancy sensor detects: presence (automatic switch on-off) or absence (or vacancy, automatic switch off). Presence detection is desirable in common spaces, which are occupied often but irregularly. Absence detection works best in private spaces (individual offices, bathrooms, etc.), especially if plenty of daylight is available.

False switch events, i.e. lighting switching on or off independently from the occupancy, are both well-known reasons for complaints and a source of poor energy performance[31]. False switch-off may depend on sensor technology, sensor positioning, and short switch-off time delay.

Passive-InfraRed (PIR) is by far the most common technology used in occupancy sensors, due to its low cost and reliability[32]. Yet other technologies exist – like ultra-sound or pressure-based sensors – and they may be preferable for some specific applications. Innovative applications may improve detection – and minimize false switch on-off – through a combination of different sensor technologies. Innovative strategies include detection of computer mouse movements or chair pressure sensors[33 34 35].

It is important to check whether some obstacles obstruct the sensor views. A wall is an obvious obstruction, but even glazing could block detection when using PIR sensor, since glass is opaque to infrared radiation. The sensor position should also account for the sensor's field of view and its sensitivity at different distances. The data sheet of any commercial occupancy sensor provides this information. One common mistake is to check only whether the considered space falls into the field of view of the sensor, ignoring the remaining areas. Therefore, lights may undesirably turn on due to people passing nearby. The field of view can be limited by applying tape to specific sections of the sensor; the tape is often included in the sensor package.

The sensor switches lights off when it does not detect presence for a certain time. This time delay can be set to 5–10–15–20 minutes for most commercial sensors. Choosing the optimal time delay is a trade-off between energy saving and false switch on-off events. Shorter switch delay times will increase energy savings, but also the number of false switch events. If people move often in the space, a 5-minute delay can be acceptable. For desk-based tasks, where there can be little movement, research indicates that 7 minutes is the lowest acceptable time delay[31]. Since 7 minutes can seldom be selected for commercial sensors, a time delay of 10 minutes is a more usual selection. The time delay can be reduced by triangulation from a network of sensors. In a pilot case, this solution led to negligible false-off events with just 1-minute time delay[36]. As a trade-off, the triangulation needs a higher number of sensors, which increases the design complexity, installation costs, and likely the energy use for sensor and control devices[13].

11.2.3 Daylight-linked systems

The electric lighting can be switched on-off or dimmed according to available daylight. The first strategy is commonly called daylight on-off, while the second is called daylight harvesting system (DHS).

The effectiveness of daylight-linked systems is high when the space is sufficiently, but not excessively daylit. As rule-of-thumb, daylight zones with a DF between 2% and 5% are generally suitable for daylight-linked systems.

A traditional daylight-linked system requires a photosensor for measuring illuminance in the space. The design and commissioning depend on three aspects:

- technical robustness,
- architectural integration, and
- questions related to the occupants[37].

Technical robustness mainly refers to reliability of the spectral ($V(\lambda)$ curve) and spatial response of the photosensor. Difference in measured illuminance can be as high as 118% between two sensors with different spectral responses[38]. Under unstable weather conditions, the photosensor may frequently switch or dim the lighting. Some photosensors are provided with dead-band switching to avoid such issues. It may also be useful to partially shield the photosensor in order to minimize fluctuations, although this affects its spatial response[39]. A typical problem in common practice is that current lighting simulation software cannot account for the exact response of commercial photosensors, which represents a shortcoming when evaluating the potential energy savings of systems[40].

Architectural integration mainly concerns the position of the photosensor. The sensor may see:

- daylight only (open loop), with sensor typically positioned outdoor or looking at the window,
- daylight and electric lighting (closed loop), with sensor located indoor.

Open loop is unaffected by changes in the interior space. Closed loop may lead to over- or under dimming due to local indoor lighting conditions. A combination of open loop and closed loop would be ideal, but more costly.

Most applications use a closed loop solution. In this case, positions affected by direct sun should be avoided for the sensor. The optimal positioning is normally facing slightly towards the wall opposite the window, for the sensor to be naturally shielded.

Finally, the set-up of DHSs is often critical, since installers are typically neither trained nor equipped to install and calibrate the system[41]. Therefore, care should be taken in contracting the installation, and budget for monitoring and verification of the systems should always be allocated.

Technical robustness and architectural integration aim to have a constant illuminance on the workspace over time. If this is not achieved, occupants may report dissatisfaction. Several studies reported occupants sabotaging systems because they were not properly working[42 43]. On the contrary, well designed and installed DHSs are well accepted and can lead to significant energy savings[44].

DHSs would perform best if combined with dynamic shading devices, but the installation and maintenance can be tricky[45], and, just as for any automatic system, it is beneficial to always provide a manual override[46].

11.2.4 Colour tuning

A colour tuning system changes the colour of the light source according to determined rules. For ordinary applications, colour tuning refers to tuning between different CCTs. Colour tuning is a relatively new control technology, as it developed almost in parallel with white tuneable LED technology. This strategy mainly aims to improve visual comfort, for example in combination with a DHS to have both a constant illuminance and a constant CCT in a mixed daylight/electric lighting space. A particular application of colour tuning is the so-called integrative lighting, see further down in this chapter.

11.2.5 Solar and daylight controls

Solar and daylight controls govern the operation of solar shading devices and other daylighting systems, e.g. electrochromic glazing. These controls are designed to maximize daylight, reduce glare, control solar heat gain, and maintain visual comfort, while minimizing electric lighting use. Controls and control logic for shading devices and daylighting systems are best designed if integrated with electric lighting controls. However, shading controls operate on different logics than electric lighting[46]. Typically, solar and daylight controls are activated to reduce glare and heat gains.

While manual shadings do exist and are generally efficient and appreciated, here the focus is on automatically controlled systems. Early, simple time-based strategies relied on fixed schedules for adjusting shading devices, e.g. lowering them during sun peak hours. Such strategies would certainly reduce the daylight provision even at times when shading is not really needed. Modern logics are based on environmental sensors operating on real-time data of irradiation or indoor illuminance. For solar heat controls, vertical outdoor sensors typically take the shading devices down when solar irradiance increases above 180-200 W/m^2, despite a wide variety of suggested target thresholds from the literature[47]. For glare protection, a photosensor should be placed indoors. The reading of illuminance is used as a proxy for glare. There are at least two ways to predict glare with this strategy. The first one consists of placing the photosensor horizontally on the desk. Research has shown that people in offices are likely to lower shading if daylight illuminance on the desk is around 2 000-3 000 lux[48] [49] [50], and these values or a lower one could be used as threshold for triggering the shading device. The second strategy consists of measuring the vertical illuminance at the eye, which is a good predictor of glare. Vertical illuminance around 2 000 lux would likely result in glare[51] [52], and target values of 1 000 lux or below are preferred to trigger shading.

Since glare depends on absolute illuminance at the eye and contrast in the field of view, more accurate luminance-based camera sensors calculating DGP in real-time have been proposed[53] [54], but they are difficult to implement in practice.

More advanced control methods may use so-called 'adaptive shading', where the shading operation is governed by several sensors, like radiation, light, temperature, and occupancy[55] [56]. Adaptive shading has the advantage of optimizing all indoor comfort variables at once, providing ideal solutions for both visual and thermal comfort.

Recently, research has been increasingly oriented towards sensorless techniques, like predictive control systems[57] [58] [59]. Predictive control systems use historical data and weather forecasts to regulate shading operation. There are both technical and economic advantages in avoiding sensors. Predictive controls work best in environmental conditions having a certain time inertia, like temperature. This is the case of shading devices, whose operation affects solar gains and thus indoor temperature. Modelling predictive controls have been proven to positively affect energy efficiency and thermal comfort[60]. However, predictive controls are less suited for lighting control, where changes are immediate, which makes real-time sensor-based technology still the preferred choice.

11.2.6 Integrative lighting

The International Commission of Illumination (CIE) opted for the term 'integrative lighting' to describe lighting designed to support psychological and physiological functions of humans[61]. This is a general definition which includes any type of solution that would address visual and non-visual aspects, like visual performance, visual preference, non-visible flicker, and the like. However, the term 'integrative lighting' is commonly associated to the specific function of promoting circadian entrainment, and it is often confused with the widespread commercial names of 'human centric lighting', 'biocentric lighting', etc.

Circadian entrainment depends at least on intensity, spectrum, timing, duration, and adaptation state of the observer. However, real integrative lighting schemes are today simply realized by adopting white tuneable LED that can be adjusted in luminous output and spectrum (or CCT).

We observe today a great increase in interest for integrative lighting systems, with standards and certification schemes starting to include circadian considerations in their verification methodologies, see for example WELL[62], UL 24480[63]. The role of lighting in circadian regulation is even cited by the latest European standard for lighting of workplaces[64]. This growing interest relates to the increase body of knowledge demonstrating the key role of light in regulating sleep-wake cycles and consequently health and wellbeing. However, it was the publication of consensus-based circadian metrology[65] what made it possible to bring circadian recommendations into design requirements. In particular, the metrology defines a new circadian metric – the melanopic Equivalent Daylight Illuminance (mEDI) – that describes the impact of light stimuli on melanopsin production, which is measured in lux. The metric is officially adopted by the CIE, therefore making its use more common than other existing circadian metrics, like the Equivalent Melanopic Illuminance (EML), and the Circadian Stimulus (CS). The definition of consensus-based mEDI targets by Brown and colleagues (2002)[66] has further accelerated the large scale adoption

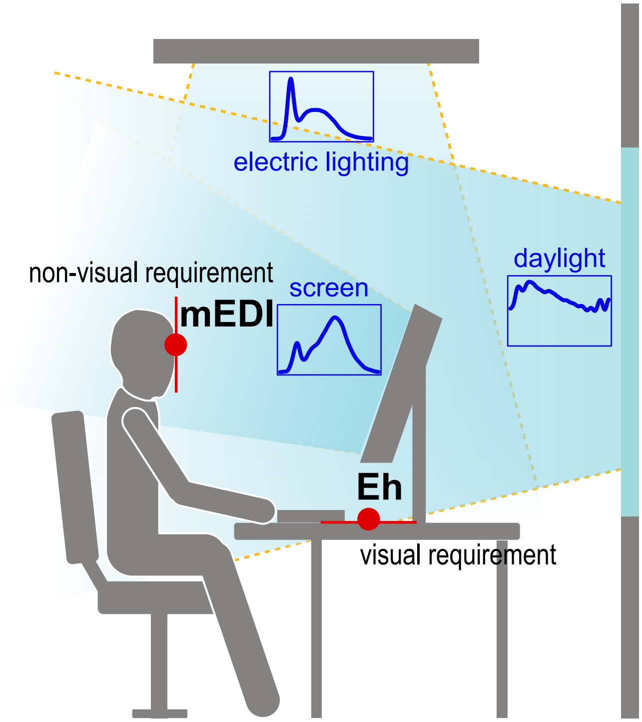

Figure 11.10 Integrative lighting should satisfy both visual (mainly horizontal, task-based) and non-visual circadian (vertical, user-centered) requirements. Image by Niko Gentile adapted from the original[67].

of integrative lighting. These targets are: 1) mEDI ≥ 250 lux during daytime, 2) mEDI ≤ 10 lux before going to sleep, and 3) mEDI ≤ 1 lux during nighttime. The consequences are obvious: light during the day is as important as darkness during nights.

In an architectural perspective, it must be noted that mEDI describes the radiation reaching the eye. Therefore, mEDI is normally measured on the vertical plane, at eye position. This approach differs quite dramatically from the traditional lighting design focused on visual requirements, which adopts the horizontal work plane to measure light. The two approaches are also conceptually different. While visual requirements are typically focused on the built environment (the plane for which the task is concerned), non-visual requirements are focused on the occupants and the radiation reaching their eyes (Figure 11.10).

It is important to keep in mind that integrative lighting can be realized with daylighting, electric lighting, or a combination of both. Since daylight is our evolutionary time-giver, it is easy to conclude that daylight should be the preferred source in integrative lighting schemes. However, the 'human centric lighting' has been largely embraced by the electric lighting industry, and notably many integrative lighting schemes are solely based on electric lighting[67].

In a technological perspective, the control activation of electric integrative lighting is, most of the time, based on predefined schedules defining the CCT and luminous power to the luminaire[68]. In an energy perspective, it must be noted that reaching the mEDI requirements at the eye during daytime can require as much as three times more luminous power (300% increase in energy use) than reaching the ordinary visual requirements on the horizontal task plane – typically, 500 lux[67 68 69]. This calls for a better integration of daylighting in the built project. Research has shown that including proper daylighting design for integrative lighting increases energy for lighting of just approximately 5% compared to traditional systems[70], with respect to the 300% aforementioned. Also, further room for savings is offered by daylight-linked controls based on visual and non-visual targets[71]. Indeed, in most practical cases, well daylit spaces can guarantee target mEDI for a large part of the year, leaving the duty to the electric lighting system for only few days during winter months.

11.2.7 Control networks and integration in the BMS

The lighting and daylighting controls, or part of them, may be included in a network. Possibly, such network is integrated in the Building

Management System (BMS). A networked lighting control, especially when integrated in the BMS, is preferable over a single stand-alone control for several reasons:

- It is more accurate, since sensors and controllers may drive luminaires in a more harmonious way.
- It is rational, since the same sensor may provide input to different building services, like lighting and HVAC.
- It is more reliable, since more sensors can provide feedback and self-detect failures.

Networks can be either cabled or wireless. Implementation of wireless networks is usually cheaper than the cabled ones, especially for retrofit projects[72]. Wireless networks are also easier to be scaled and upgraded. However, wireless networks are sometimes difficult to switch off completely during non-occupied hours, which increases the parasitic losses for control gears. Another issue with wireless connection is safety[73], since hackers can potentially enter the network and take control of the light.

Modern wireless connectivity based on Visible Light Communication (VLC) reduces the safety concerns. VLC technology transfers data through high frequency modulation of the light source, which puts sensors or even smartphones into communication. VLC allows faster and greater data exchange compared to Wi-Fi, but it cannot pass opaque surfaces, the latter being an advantage in view of the aforementioned safety issue.

Summing up, the design of LCSs may follow the steps in the flowchart in Figure 11.11.

11.3 Strategies for saving electric lighting energy

A few years ago, a paper on efficient building design strategies was titled: ‘Buildings don’t use energy: people do’ [74]. Indeed, it is a common belief that the use of efficient light sources can automatically lead to energy savings, but reality is much more complex. It would be more appropriate, yet not enough, to focus on the entire lighting system, including energy use for auxiliary devices. The truth is that the way in which the system is used has the greatest impact on the final energy use. In other words, the energy demand for lighting is driven by both technological and non-technological factors. Some authors have proposed a semantic distinction to describe the effects of these two factors[75].

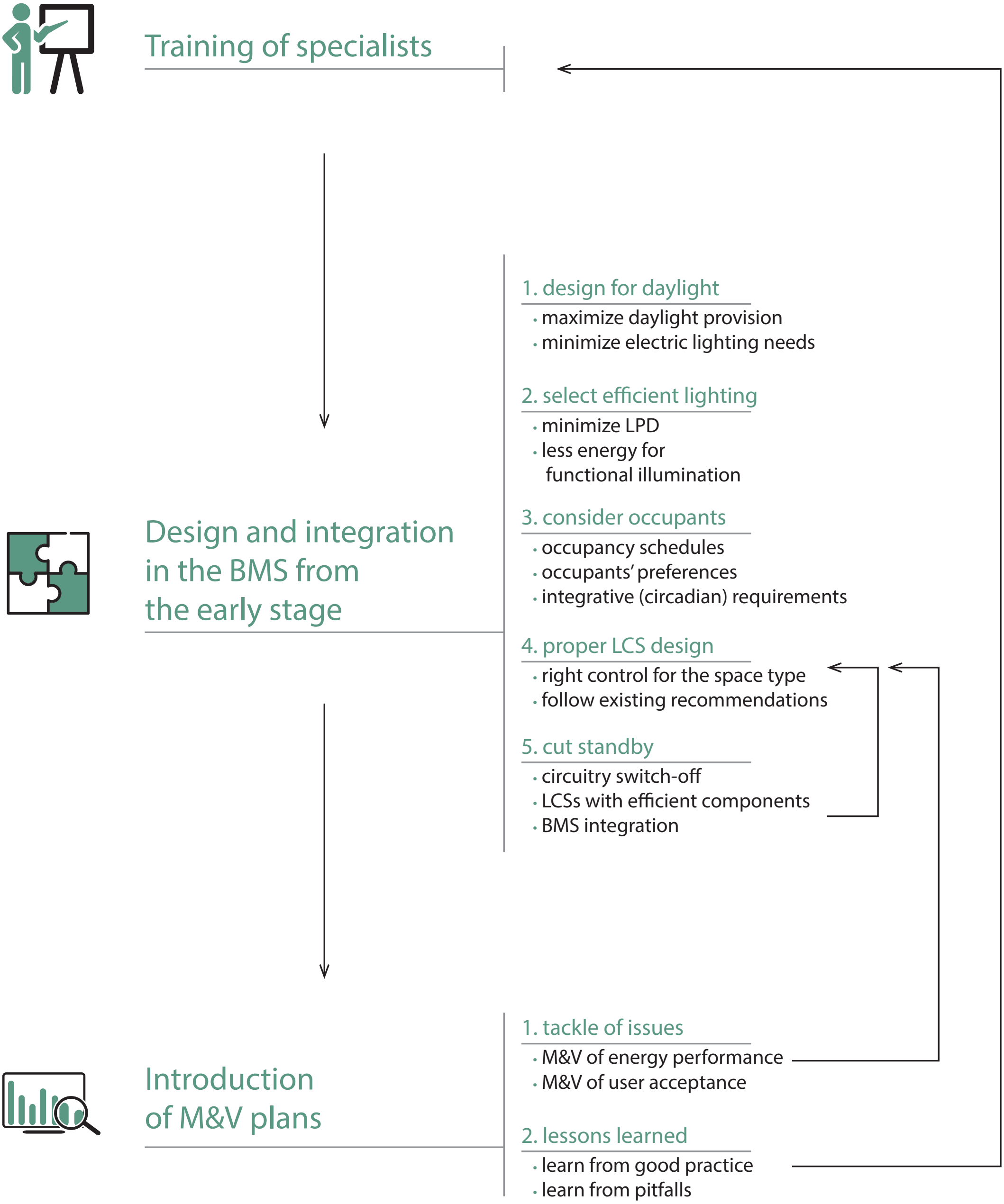

Figure 11.8 Ideal steps when designing LCSs. Illustration: Niko Gentile.

- Energy efficiency, as the fraction of useful energy delivered in relation to the primary energy provided to the system. Energy efficiency is a technological factor, usually measured by means of the efficiency η.
- Energy saving, as the effects on the final energy use of a technology including the behaviours of investors, consumers and end-users, prompted by psychologic and economic analyses. Therefore, energy saving adds the non-technological factor to the energy efficiency of a system.

Efficiency gains are usually beneficial, but they might be offset by behavioural factors. The rebound effect for lighting is an example of behavioural effect. The rebound effect is the fact that increasing efficiency of light sources boosts their affordability, and a higher number of light sources will be used for longer time. Researchers have shown that a rebound effect of 100% can be observed for lighting over the past 100 years, which is a complete offset of potential savings[76]. However, this has also led to beneficial side-effects, such as the overall increase of communities' access to lighting. Rebound effects have been recently observed for household lighting. In Germany, old and inefficient incandescent bulbs have been replaced by LED bulbs, but, on average, they deliver more lumens (luminosity rebound) and they are switched on longer (burning rebound), leading to a rebound of about 6%[94]. The example of rebound effect shows that any effective energy saving strategy should consider both technological and non-technological factors. Aligning with these observations, energy policies should be shaped taking both energy efficiency and energy saving criteria into consideration[75].

Another important definition concerns the total energy use for lighting, which is the sum of the energy that goes to illumination only and the energy for parasitic uses, i.e. the energy feeding the non-illuminating or auxiliary devices in a lighting system. Recent developments in lighting are decreasing the energy loads for illumination, while the massive introduction of controls is raising the energy demand for parasitic uses.

Given the previous definitions, this subchapter explores the *energy saving* strategies for *lighting*, with emphasis on office buildings and where the user, rather than technology, drives the energy saving.

11.3.1 Improvement in lamp and luminaire technology

Lamps with luminous efficacies higher than 90 lm/W, like fluorescent T5 lamps, have existed for more than 20 years. Nevertheless, statistics show that many existing installations still use highly inefficient lamps like fluorescent tubes type T8 or T12[77]. About 75% of lighting installations in industrialized countries will face retrofit in the next future[78], and switching the lamp technology is the most remunerative way to save energy[79]. It is no surprise that this is often the first measure undertaken by ESCo companies[80].

Savings of about 40% and 70% compared with existing installations are estimated for switching to fluorescent T5 and LED respectively, the latter being the only possibility in Europe in the near future, following the ban of T5. Decreasing cost and increasing efficiency of LED lamps make the 're-lamping' a very convenient efficiency strategy. Sometimes bare re-lamping may be difficult, because newer light sources require different driving gears and sockets. Today, the market offers a number of LED replacement kits for existing luminaires. These kits are cheap and effective solutions, but changing the whole luminaire is still recommended.

An additional consideration for re-lamping is that savings with newer lamp technology should not be taken for granted. For example, commercial LEDs have a wide range of luminous efficacies, and not all LEDs are actually that efficient.

Some additional areas for savings are provided by an optimized SPD of the light source. There are two ways to save energy by optimizing the SPD:

- by providing more radiation where the human eye is more sensitive;
- by providing radiation where the illuminated surfaces reflect more.

Following the first logic, an ideal light source would be at maximum efficiency when it emits visible radiation only in the visible range and following the $V(\lambda)$ sensitivity curve of the human eye. In such case, none of the radiation is lost and yet the objects are perfectly illuminated. Such light source does not exist, but LEDs' spectral power distribution is partially tuneable. An investigation in a real building showed, for instance, that the 6 000 K LED panels were perceived as brighter than 2 700 K fluorescent lamps, despite providing the same illuminance on the workspace[14]. As logical conclusions, the 6 000 K LED may be dimmed and still provide the right perceived 'quantity' of illumination. However, it is questionable whether the higher brightness and higher CCT would be appreciated by users, but this is an issue digressing from the mere energy saving perspective.

According to the second logic, over 40% of energy for lighting can be saved with theoretical spectral distribution and objects[81]. In a real-life scenario, a study showed that 15% can be saved by using optimized spectrum of commercially available LED illuminating ten objects across five different hues[82], while preserving the colour rendering in the range of acceptability.

Moving from the lamp to the luminaire, savings of about 10% have been achieved in the recent past, when electronic high frequency ballasts replaced old electromagnetic ballasts. One of today's challenges is to improve the power factor (PF) of dimmable LED drivers; this issue does not deal exactly with energy savings, but lower PF are detrimental for the electricity network and the electricity company may charge more for using low PF.

Finally, with the growing luminous efficacy of light sources, there is a growing concern for the 'hidden' or parasitic energy use of luminaires. In Europe, for example, there is a limit of 0.5 W standby for luminaires – to decrease to 0.3 W in 2027[83], but it is technically and economically feasible to aim for a 0 W standby standard[84].

11.3.2 Use of lighting controls

Previous subchapters concerned the design of LCSs. However, their potential for energy savings has not been quantified.

Limited research has looked at the energy saving potential of manual controls. However, it has been seen that well designed systems (interface, position, etc.) coupled with training of the occupants can actually lead to energy savings, although they may be difficult to predict. Coupling manual dimming and/or absence detection to manual switches is also beneficial. The addition of a manual dimming contributes to saving 7–25% energy compared to relying only on on-off switches. Most interview studies report on a high appreciation of manual dimming systems.

Occupancy detection can provide energy savings of about 30% compared to manually controlled systems[85]. The saving potential is in partly linked to the switch-off time delay, ranging from about 26% with 20-minutes delay to 35% with 5-minutes delay [86]. Most importantly, the occupancy detection should be correctly set to either ‘presence’ or ‘absence’ detection, coherently with the space type.

For small individual spaces and/or with abundant daylight, the use of presence detection may actually lead to more energy use than a simple manual switch on-off, and as much as 75% more energy use compared to a simple absence detection[19 41]. In such cases, the electric lighting would often be on even when daylight provides enough illumination, causing energy wastage and annoyance to the occupants.

Adding daylight harvesting to an absence detection would raise the energy savings up to 60% compared to manual controls, given that systems are properly designed and commissioned. A number of sensors in network may achieve a perfect dimming of the lighting system, maximizing the savings for illumination. At the same time, the energy for peripheral components will grow. A complete switch-off of the system, including controlling gears and devices, should be designed from the beginning. Without a complete switch, in cases with abundant daylight, very efficient electric lighting sources and low occupancy rates, the energy for lighting with advanced controls may be higher than manually controlled systems[13].

Finally, occupancy control also includes timers and institutional shut-off. Shut-off during unoccupied hours is extremely important for limiting energy use. It is worth mentioning that in some cases, higher energy use has been observed during non-working hours than during working hours[87]. Nowadays, some office buildings are left with electric lighting on during entire nights or weekends, seldom for safety concerns. This enormous energy waste is not acceptable, and a simple occupancy lighting control would be of great help.

11.3.3 Use of Task/Ambient Lighting

Using general lighting, either electric or from daylight, mixed with task lighting is a strategy used at the beginning of the electric lighting age, when electric lighting was expensive. This is beneficial for both user and energy, as previously seen.

The electric lighting is usually designed to provide 500 lux on the desk, and current LED task lamps require only around 6 W to provide that illumination. In this case, the electricity for lighting would be reduced by more than 25% in comparison to a case relying only general lighting, with increased satisfaction of occupants. In addition, people are more likely to accept lower illuminances if this is provided by daylight. Therefore, visual comfort, satisfaction, and energy use are optimized by using a combination of general lighting and dimmable task lighting.

While it is true that people do not like too uniform lighting, a task/ambient approach may sometimes lead to high contrast in the field of view. High contrast reduces visual comfort and brightness perception, and it increases the visual fatigue. This is especially a risk during mornings, afternoons and overcast winter days at high latitude. In such cases, daylight may not give enough illumination to provide acceptable contrasts. Therefore, an intelligent, general lighting system, based on daylight harvesting, may be considered. A combination of task and ambient lighting has also been mentioned as a suitable strategy for energy-efficient design of integrative lighting schemes[88].

11.3.4 Improvement in Maintenance Factor

The initial design criteria of a lighting scheme should be maintained over time. The Maintenance Factor (MF) is the ratio of the average horizontal illuminance at a certain time (E_t) and its initial value (E_{in}).

$$\mathrm{MF} = E_t / E_{in} \tag{11.4}$$

The MF considers the lumen depreciation of lamps, ageing and dirtiness of luminaire optics, as well as maintenance of room surface reflectance. The MF can also be applied to daylight systems, taking into account, for example, the reduction of glazing transmission due to dirtiness. MF should be related to the planned maintenance time. A MF = 0.9 for a planned maintenance (e.g. cleaning, or cleaning and lamp substitution) of two years, means that after two years, the luminous flux is expected to be reduced by 10%.

The derivation of the MF is made by the designer, which should follow reasonable assumptions and general guidelines[89]. MF, and therefore the planning of system maintenance, has a large impact on the efficiency of the system. Even in non-critical applications such as offices, shops and schools, the luminous output can be reduced by up to 5% per year. In critical applications, such as animal barns, the accumulated soiling on luminaires and surfaces can reduce the illuminance by 60% in just one week[90].

It is suggested that an efficient lighting installation should have a MF > 0.75. As rule of thumb, an intensive plan of maintenance for offices considers a yearly cleaning of the luminaires, cleaning of the room surfaces every third year, and lamp replacement every 10 000 hours of burning time, the latter largely variable according to the lumen depreciation of the lamp.

11.3.5 Capitalizing on user response

Occupants, while sometimes unpredictable or inefficient – referred to as having a 'dark side' [87]– can also act as energy-efficient 'machines' when lighting systems leverage predictable energy-saving behaviours. Although some occupant behaviours are random, others are consistent and explainable[91]. Light-related behaviour is generally driven by:

- environmental changes (adjustments to address over- or under-illumination, glare, overheating, etc.) or
- psychological processes (influenced by social norms, previous experiences (heuristics), or individual perceptions).

Behaviour in response to environmental changes is well studied, even at individual levels. However, behaviour shaped by attitudes, emotions, or perceptions is less understood. For instance, users often adjust lighting to meet individual preferences, and studies have explored energy-efficient strategies to accommodate these needs. Additionally, behaviour can stem from evaluations of personal and social contexts, beyond direct lighting preferences. Strategies promoting these energy saving behaviours are often referred to as 'nudges'. A nudge is an intervention, generally consisting of a positive reinforcement, that influences people's choices or behaviours without restricting options or imposing significant incentives[92].

Energy-saving behaviours are crucial, with potential savings of 5–30% in non-residential buildings[93]. As lighting technology nears maximum efficiency, further energy gains will likely depend on deeper insights into user behaviour.

Gentile (2022)[94] identified four categories promoting energy saving behaviours for lighting, that can be used in the design of daylighting and lighting systems.

The first strategy focuses on dimming extent and speed. Gradual adjustments in lighting levels, particularly reductions up to 20%, are often imperceptible to users. When combined with natural light, such changes can lead to substantial energy savings, reducing electric lighting output by as much as 60%. This approach ensures energy efficiency without compromising user comfort or satisfaction.

A second key area involves behavioural heuristics, which shape how users interact with lighting systems. The heuristics are: availability, anchoring, and default settings. The concept of anchoring demonstrates that starting with lower initial light levels encourages users to maintain lower settings, while availability indicates that limiting the range of available light levels can also save energy. Furthermore, default settings – such as lights automatically turning off or shades automatically rolled up at the end of the day – are highly effective in reducing energy use.

The third strategy addresses the design of the lighting and shading control interfaces. User-friendly and intuitive controls play a critical role in shaping energy-efficient behaviours. Co-located controls for shading and lighting, designed with familiarity and simplicity in mind, make it easier for users to interact with systems as intended. Standardized, tactile interfaces reduce confusion and enhance usability, promoting consistent engagement with energy-saving features.

Lastly, feedback and prompts are essential tools for sustaining energy-efficient behaviours. Informative cues, such as visual indicators showing energy consumption, provide users with actionable insights that encourage them to make energy-conscious decisions. Well-

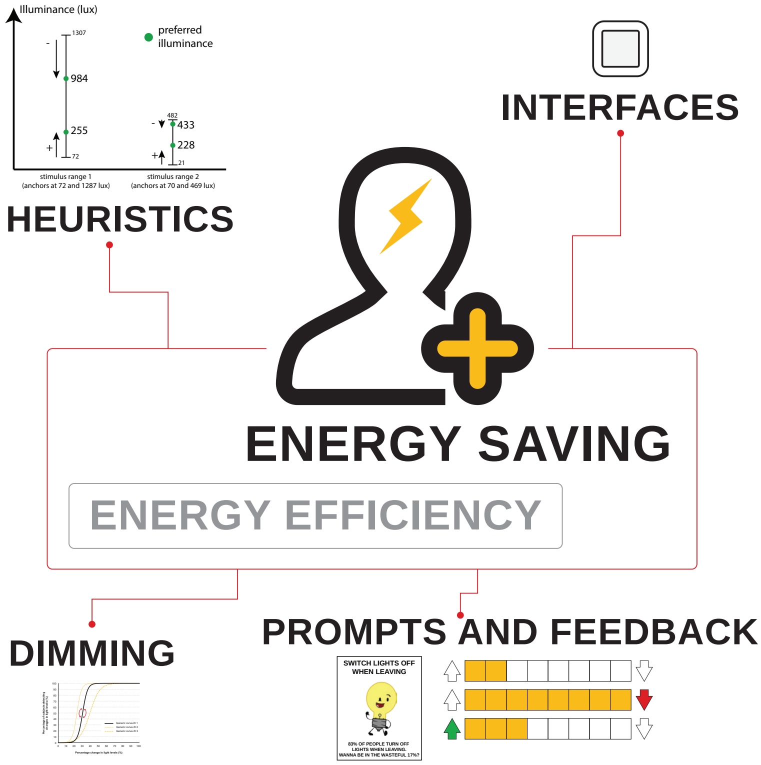

Figure 11.12
Saving electric lighting energy using nudges.

designed feedback mechanisms not only reinforce desired behaviours, but also increase user trust and understanding of automated systems.

A better developed discussion of the different strategies is provided in the original publication[94] to which the reader is referred.

Together, these strategies highlight the importance of integrating behavioural insights with technical advancements in lighting design. While the potential to significantly reduce energy use is evident, the need for multidisciplinary research remains crucial for developing robust methodologies. By combining engineering, social sciences, and behavioural psychology, future innovations can increase the energy-saving potential of lighting systems by exploiting user behaviour.

11.3.6 Rebound effect in lighting

Between 2012 and 2016, artificially lit outdoor areas globally increased at an annual rate of 2.2%, with radiance rising by 1.8% annually[95]. The shift to efficient, low-cost LED lighting has reduced energy use in already well-lit areas but has also expanded lighting in previously dark regions[95]. This is an example of rebound effect, a phenomenon where increased efficiency and affordability lead to greater consumption[96]. For example, fuel-efficient cars often encourage longer trips. In extreme cases, such as Jevons' Paradox, the rebound can fully offset efficiency gains[97].

Over the past three centuries, expenditure on artificial lighting consistently averaged 0.72% of GDP, regardless of location or technology, suggesting a 100% rebound effect[98]. This trend, equating to steady per-capita growth in lighting consumption, reached 130×10^{15} lumen-hours in 2005[98]. This pattern is projected to continue with LED adoption under the following uncertainties: potential rebound reduction due to demand saturation, possible increases due to LED features, and the influence of policies.

Rebound effects are evident in indoor lighting. Borenstein (2014)[99] estimated a 43% rebound in U.S. lighting when replacing incandescent bulbs with LEDs. Hicks and Theis (2013)[100] modelled scenarios ranging from ‘light saturation’ (limited hours of use) to outcomes influenced by LED costs and incentives. They found high energy savings under saturation conditions but backfire effects with cheaper, long-lasting LEDs. A refined model incorporating additional variables, such as bulb quantity, yielded similar results[101].

Real-world data indicates milder rebounds. A study of 6 409 German households (Schleich et al., 2014)[102] found a total rebound of 6% when transitioning from incandescent to LED bulbs, where 60% of this figure is due to higher luminosity in replacement LEDs. Notably, LEDs in this study delivered 24% more lumens, a market-driven factor rather than a consumer choice. Even so, this modest rebound coincided with a 500% efficiency improvement (from 15 lm/W to over 100 lm/W).

Future trends, such as increased lighting needs from ageing populations and larger homes, as well as design trends leveraging cheap, versatile LEDs, could amplify rebounds. Such factors might raise per-capita lighting needs, while new design possibilities, like strip- and full-color lighting, could further drive lumen output[103]. Research on these effects remains limited.

The rebound effect poses risks to energy savings but should not discourage efficiency gains. Rebound should inspire energy-focused policies[104]. Some rebounds, such as those enabling innovation and productivity, can lead to welfare benefits[105]. For developing regions, increased access to electric lighting, replacing hazardous alternatives, contributes to equality, democracy, and justice, aligning with broader societal goals[76].

11.3.7 Increase savings through business: Light-as-a-Service (LaaS)

A circular economy (or closed loop economy) is a regenerative economical system ('cradle-to-cradle'), where resources' input and waste are minimized by producing efficient, long-lasting, repairable, reusable, refurbishable and upgradable products. A circular economy opposes to the current traditional linear economy, which is based on a 'take, make and dispose' business model (cradle-to-grave)[106]. Circular economy principles do not reject the development and growth paradigm, yet reshape it in a world of finite resources.

As our current economic system largely follows a linear economy approach, the transition to circular economy business models is still quite slow. However, considering the increasing demand of resources and energy, there are currently no other alternatives for the future. A circular economy is already on the political agenda. In 2012, the European Commission released a first position paper 'Manifesto for a Resource Efficient Europe' [107], and, in December 2015, it issued a policy and regulatory framework for circular economy[108]. So far, Europe has invested resources for the practical implementation of circular economy. A number of these efforts are today available on the European Circular Economy Stakeholder Platform[109]. Among those relevant to buildings, lighting, and daylighting, it should be mentioned the Circular Economy

Action Plan as part of the European Green Deal[83] and the 'Right to Repair' (R2RD) directive[110].

Circular economy principles can be successfully applied to lighting, and they lead to both innovation and energy savings. An example is to design lighting products for serviceability, which is the ability to prolong the lifetime of products. This certainly includes the use of more reliable hardware, but also of individually replaceable components. For example, a sealed LED desk lamp is a non-serviceable product: if the LED driver fails, the whole luminaire needs to be replaced. Serviceability also includes modularity, connectivity and programmability, as they enable future upgrades of the lighting product[111].

Another example of circular economy is the so-called Product-Service System (PSS) business model applied to lighting. This is commonly referred as 'Light as a Service"' (LaaS). In LaaS, a lighting producer sells 'lumens' rather than lighting systems. The lighting producers own the lighting system, while the costumer pays a fixed fee for service and warranty, as well as the electricity costs. Such approach has several advantages. For the lighting producer, it leads to a decrease of production costs and increase in profits, due to optimization of the production chain. For the customer, it guarantees better lighting design, lower costs and safer return on investments. On a global scale, the producers are stimulated to produce more long-lasting, repairable and upgradable lighting products, while the energy performance is secured by contractual provisions. Several built examples of LaaS exist and have brought significant energy and economic savings, according to the companies involved: the Praxis and Brico stores (Maxeda) in the Netherlands and Belgium, the industry buildings of ArcelorMittal Sagunto in Spain, or the Amsterdam Schipol airport.

11.3.8 From energy savings to resource efficiency

As energy efficiency increases and energy production becomes greener, the environmental impact of producing daylighting and lighting products increases in importance. In older constructions and in a life cycle perspective, the operational phase is generally the main energy consumer and carbon emission source in buildings[112], but figures are inverted for new buildings[113]. The design or retrofit of daylighting systems can be costly[114] [115] and it might result in consistent environmental impacts[116] [117] [118]. After decades of increased attention to improving energy efficiency during the operational phase, the paradigm is now changing, and Life Cycle Assessment approaches are being introduced in regulations. Denmark has introduced limits on CO_2 emissions for new larger buildings since 2023[119], while in Sweden, building permits are released only after providing a climate declaration since 2022[120]. In Europe, the latest Energy Performance for Building Directive (EPBD) targets zero-emission for new and existing buildings by 2050[121].

Electric lighting only contributes to 5% of global CO2 emissions and represents 15% of electrical energy use. Despite significant increases in the energy efficiency of light sources, the operational stage continues to be the most environmentally intensive[122]. LED lighting does require materials for production but it generally performs better than its predecessors in terms of environmental impact[123]. Indeed, they limit the use of hazardous substances compared to the case of fluorescent technology, and they have long expected lifetime, leading to up to 60% lower environmental impact compared to other technologies[124]. In this perspective, it is imperative to focus on serviceability and right to repair, on top of adopting more sustainable materials for production, especially for the LED-package itself[125].

When considering daylighting, instead, the status of knowledge is still limited. Also, the environmental impact is largely dependent on the context. Daylighting systems, indeed, do not simply affect energy use for lighting, but also for heating and cooling. The environmental impact depends on the system, e.g. the window, but contextualized in a specific building. Generally, smaller windows tend to provide a lower environmental impact at the expense of lighting or view quality. More daylight with low carbon facades increases the whole life carbon[117]. To compare designs, daylighting systems should be compared on the premises of the same provided daylight[126]. Also, adding investment costs for different daylighting solutions would lead to potentially different optimal design solutions[127]. Focusing on environment only, research shows that it is possible to meet both daylight and environmental demands in buildings today, but it will be more and more difficult as our global carbon budget runs out[117].

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CHAPTER 12

Technical Daylighting Assessments

NIKO GENTILE

> ‘There is no physical instrument functioning like vision. [...] These (*instruments*) measure radiant energy, not light in its visual sense. Relating visual conditions to photometrical units can be done only most approximately.’
>
> ANDERS LILJEFORS

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Technical Environmental Assessments (TEAs), Observed-Based Environmental Assessments (OBEAs), professional lighting measurement equipment, illuminance meter, luminance meter, measuring daylight factor, measuring daylight illuminance, measuring luminance, high dynamic range (HDR) imaging, field evaluation of glare, measuring reflectance, measuring transmittance.

This chapter provides practical instructions about performing Technical Environmental Assessments (TEAs) of daylighting in actual built spaces. TEAs are objective or 'place-centred' assessments, in contrast to subjective or 'person-centred' Observed-Based Environmental Assessments (OBEAs) (questionnaire, surveys, …, see Chapter 14). TEAs and OBEAs are complementary, and they should be both performed for a complete evaluation of the daylit space.

This chapter briefly explains how to perform basic TEAs in a simplified fashion. The chapter is divided in three sections:

- Perform and verify your first daylight simulation. The goal is to measure daylight in a real space and use this information to build a relatively accurate 3D daylight model of such a space for subsequent simulations. This section explains simplified methods to measure optical properties of materials in a space (visible reflectance and transmittance) that needs to be fed in the simulation. Subsequently, it explains how to measure the Daylight Factor that can be used for verifying your model.
- Assessing glare. The goal is to have a first introduction to glare assessment in real spaces. This section provides a simplified method to create luminance maps with a traditional Digital Single Lens Reflex (DLSR) camera (High-Dynamic Range Imaging).
- Measuring circadian lighting. The goal is to introduce the reader to the assessment of circadian metrics in real built spaces. This section provides basic knowledge on the topic, with a focus on melanopic Equivalent Daylight Illuminance as target metric.

This Chapter presents a first introduction to technical daylight assessments. Most of the procedures illustrated here are simplified to balance accuracy and time. Further explanation is provided in the text.

For a full evaluation of lighting quality, the reader is referred to existing standards, e.g., in Europe, 'EN 12464-1 Light and lighting – Lighting of work places – Part 1: Indoor work places' [1] for electric lighting and 'EN 17037:2018+A1 Daylight in Buildings' [2] for daylighting. For post-occupancy evaluations of integrated daylight and electric lighting, the reader may refer to other available sources, e.g. the guides offered by the International Energy Agency (IEA) - Solar Heating Cooling programme (SHC) Task 50[3] or the more comprehensive and updated one from Task 61[4].

12.1 Run and verify your first daylight simulation

The instruction refers to the modelling and verification of a real built space. Running and verifying your first simulation requires two steps. The first one is to retrieve geometries and the optical properties of materials (walls, glazing, …) of the investigated space. This information is required as input for the simulation. The second step is to verify the quality of the modelling by comparison with field measurements. In this simplified approach, this is achieved by measuring the daylight factor in the real space.

This process requires:

- 2 surveyors working together,
- 2 calibrated illuminance meters,
- 1 calibrated spot luminance meter,
- 1 calibrated reflective reference plate with known reflectance R_{plate},
- Measuring tape,
- Tape,
- Ideally, even a tripod,
- Paper, pen, and a way to communicate (phone, …).

12.1.1 Measuring reflectance and transmittance

Visible diffuse reflectance and direct visible transmittance can be estimated in the field. Two surveyors and the following equipment is needed:

- 2 calibrated illuminance meters,
- 1 calibrated spot luminance meter,
- 1 calibrated reflective reference plate with known reflectance R_{plate},
- Paper and pen.

12.1.1.1 Reflectance

The following procedure holds valid only for diffuse (Lambertian) surfaces. Masonry materials with matte finishing diffuse incident light in all directions. Reflectance of specular materials – e.g. whiteboards

- cannot be measured following this method. For the latter, the reader is referred to available databases of optical properties for specular materials[5], or use of advanced equipment (e.g. a spectrophotometer or a goniophotometer).

First, the main diffuse surfaces of the room should be identified. Lighting conditions must be steady for the duration of the measurements. For reflectance $R_{surface}$ of Lambertian surfaces (values range 0-100%):

1. Surveyor A holds the luminance meter and Surveyor B holds the reflective reference plate on the surface
2. Surveyor A points the luminance camera perpendicularly to the surface, without shading it
3. Surveyor A measures the luminance of the surface on a given spot, $L_{surface}$
4. Surveyor B places the reference plate on the same spot
5. Surveyor A measures the luminance on the reference plate, L_{plate}
6. The reflectance of the surface ($R_{surface}$) is calculated using:

$$R_{surface} = \frac{L_{surface} \cdot R_{plate}}{L_{plate}} \tag{12.1}$$

7. Steps 2–6 are preferably repeated several times, and the average $R_{surface}$ is determined. This process should improve the quality of the assessment.

12.1.1.2 Transmittance

Visible transmittance can be estimated for transparent elements providing direct transmission. This holds true for ordinary glazing assemblies. However, the visible transmittance of shading devices, including those made of fabric, cannot be assessed with this method. For transmissivity tn of transparent surface (values range 0-100%):

1. The two surveyors hold a lux meter each
2. A lux meter is held on the outside surface of the glass
3. A lux meter is held on the inside surface of the glass
4. The surveyor makes a simultaneous measurement of illuminance
5. The ratio between indoor and outdoor illuminance is the visual transmittance

6. Since simulation software generally use visible transmissivity, the transmittance should be converted using the formula

$$tn = (sqrt(.8402528435+.0072522239*Tn*Tn)-.9166530661)/.0036261119/Tn \tag{12.2}$$

where tn is the transmissivity and Tn the transmittance.

12.1.2 Measuring daylight factor

Illuminance is measured with an illuminance meter (also called lux meter). Professional lux meters are quite expensive devices. Ordinary lux meters typically have a sensitivity range between 0 and 200 000 lux, although it may differ among models. The response of professional lux meters is calibrated according to the human eye's spectral sensitivity curve $V(\lambda)$, and their spatial response is cosine corrected, namely it does not depend on the incidence angle of light. This way, a professional lux meter can guarantee accuracy in the range ± 3%.

Light sensors are included in today's smartphones. Several apps turn the light sensor into a lux meter, but the accuracy depends heavily on the type of sensor. Usually, this does not have neither a spectral nor a spatial correction. The measuring range is narrow, and it is suitable only

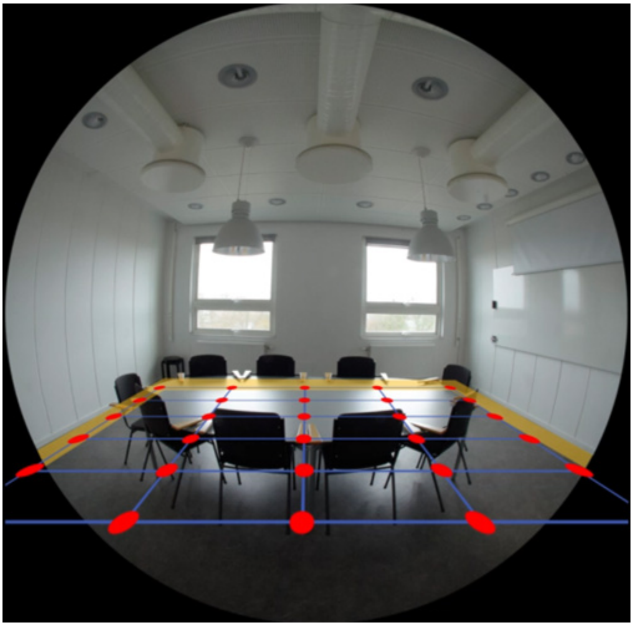

Figure 12.1
An example of a convenient rectangular grid of points with 50 cm distance from the walls. Image: Niko Gentile.

for indoor use. In addition, the apps are ‘universal’, while the sensor is different for any phone model. As a result, illuminance readings with errors of ± 60% in comparison to calibrated lux meters are not an exception. In definitive, smartphone-based lux meters are usually not a good solution for professional measurements. An improved procedure for illuminance measurements via smartphones is provided by the Swedish Authority for the Work Environment[6], but even in this case the accuracy remains insufficient for professional use.

When evaluating daylight design, illuminance measurements are used to determine the daylight factor (DF). The following guide relates to DF and daylight illuminance measurements using handheld analogic lux meters. Two lux meters and two surveyors are needed.

1. Drawing a grid of points in the daylit space

First, a grid of measured point should be drawn. Illuminance will be later measured at each grid node. If the measurement is conducted according to a regulatory framework, it will be the norm or standard stating the required grid size, see e.g. EN 17037[2].

As for the scope of this chapter, which is about verifying the simulated model against the real built space, the rule is: the tighter the grid, the more accurate is the assessment, but the longer it takes to perform the measurements. Limiting measurement time is essential, since DF should ideally be measured at each grid node under constant daylight conditions, but daylight varies over time. Choosing the grid size is therefore a compromise between accuracy and time.

The grid should thus have a reasonable number of points. It should not be too tight; 30 points for a 60 m² sidelit space is a reasonable option. An efficient way to proceed is to use a non-square grid. For example, in sidelit spaces with symmetrical windows (which is often the case), the grid can be denser perpendicularly to the window (e.g. 1 point per meter). The grid can be less dense in parallel to the window (e.g. 1 point every 2 meters), since daylight penetration will most likely change with depth but not so much in the direction parallel to the window wall. However, if the measurement campaign is supposed to be later compared with simulation results, it is often easier to opt for a square grid, since the simulation software will automatically generate square grids. It is a good norm, which is also typically required by standards, to leave a 50 cm space between walls and the grid. This practice is motivated by the fact that points close to walls are heavily affected by shading and reflection from the wall, making the measurement less reliable (Figure 12.1). This space is also seldom occupied by occupants so it has no relevance for the light experience.

2. Measuring the daylight factor (DF)

By definition, the DF is measured during CIE overcast sky. The CIE overcast sky is a mathematically modelled sky and therefore is not common in reality. However, days with dense and homogeneous cloud cover provide similar conditions of diffuse radiation only. It is often difficult to decide whether the real sky is overcast or not. Many times, there is a dense cloud covering, but the clouds may move fast, and the radiation may not be totally diffuse. As general rule, it is best to first place a lux meter on the outdoor and check whether the illuminance is fluctuating. As rule of thumb, when the fluctuation is less than ± 5%, the DF measurement is reliable. The stricter rule is that the ratio between the vertical illuminance screened from ground reflection and the global horizontal illuminance should be between 0.36-0.44, where the ratio 0.396 represents the ideal CIE overcast sky.

A surveyor with a lux meter is needed outdoors for reading the global diffuse horizontal illuminance. If possible, it is still a good idea to have a second lux meter with a shading ring to block the small amount of direct radiation that might be present in real scenarios. This assures a quality of the DF measurement. The surveyor should always

Figure 12.2 The two surveyors are measuring daylight factors while being in contact through the phone. Left: outdoor measurement of global horizontal diffuse illuminance. Right: indoor measurement of horizontal illuminance, with lux meter positioned on a tripod at 0.8 m height. Image: Niko Gentile.

be aware of potential shading from surrounding buildings, trees, own body, etc., as they affect the global horizontal illuminance even with diffuse radiation.

Another surveyor stays in the building, measuring the horizontal illuminance at each point of the grid, generally at 0.8 m distance from the floor. A tripod may be useful to ensure stability and constancy in vertical position. For the indoor conditions, the surveyor should make sure that: the shading device is not used, the electric lighting is completely off, and that there are no shadows on the sensor, either from furniture or from the surveyor him/herself.

The two surveyors communicate the readings for each point, for example by phone or by handheld transceiver. The indoor surveyor directs the measurement campaign and says when it is time to measure the next point. Indoor (Ei) and outdoor (Eo) illuminance measures should be simultaneous (Figure 12.2). The measures are reported on a paper for later calculation of the DF.

It is a good idea to repeat the measurement several times (2-3 times) for the same point and then average the results. This will reduce errors due to the surveyors.

3. Calculation of the DF

The DF is calculated by means of the known formula DF=Ei/Eo ×100%, see Chapter 7.

For most applications, values may range between 0.1% deeper in the room, to more than 10% close to the window. However, for these extreme points, the values are usually not reliable.

12.1.3 Comparison between measured and simulated values

The same grid of points used in the field measurements should be created in the simulated environment. The digital model should have the optical properties measured in situ. A simple DF simulation is then conducted. The modeller should compare the DF for each point of the grid. Aggregated values in terms of DF average and median, should also be calculated. A difference of ± 30% between measured and simulated values is generally expected and accepted, due to a number of factors related to both the complexity of real environments, differences in sky distribution, and intrinsic limitations in the simulation software. Higher differences are expected for points closer to the windows and walls.

Once the model is verified, the modeller can decide to use a tighter grid of points in the virtual environment for more accurate predictions.

12.2 Assessing glare

Daylight glare is generally assessed via the Daylight Glare Probability (DGP) index. A luminance map is needed to determine the DGP. A luminance map is generated by a luminance camera, which is a costly calibrated professional instrument. However, a normal DSLR camera can be calibrated and used for the same purpose, obtaining luminance maps with a decent accuracy.

The approach involves using an automated algorithm to combine Low Dynamic Range (LDR) images taken with a camera into a single High Dynamic Range (HDR) image, incorporating radiometric calibration in the process. The method illustrated here corresponds to a simplified approach resulting in decent – yet inaccurate – HDR luminance maps. The reader should be aware that the resulting DGP is heavily influenced by the inaccuracy of the generated HDR. The instruction should be used to explore the methodology for the first time. Once the reader feels acquainted with the procedure, the equipment, and the terminology, more accurate procedure should be explored. A comprehensive tutorial by Pierson et al. (2020)[7] outlines the calibration and measurement procedure in detail, offering step-by-step guidance on creating accurate luminance maps for daylight-illuminated scenes using sequences of LDR (JPEG) images.

For this simplified procedure, the following equipment is needed:

- DSLR camera configured according to recommended settings (Table 12.1), possibly with a remote shutter control.
- A compatible circular fisheye lens. Alternatively, a non-fisheye lens may be used, provided it is not a zoom lens, or the zoom remains fixed to ensure consistent positioning throughout the calibration process and subsequent LDR image captures. An illuminance meter should also be used in this case.
- A tripod ensures that the camera remains stable during the sequence of multiple exposures required to capture the LDR images.
- Computer and software including Radiance suite for *evalglare* and the *Photosphere* for photometric adjustments. Although these programs are free, alternative software may also be used.
- A calibrated spot luminance meter and a middle grey target, essential for performing photometric adjustments.

Table 12.1 Recommended DSLR camera settings.

Setting	Value
Film speed	ISO 100
White balance	Daylight (5200K)
Exposure mode	Manual
Light metering mode	Insignificant
Focus mode	Manual
Focus value	Infinite
Image quality	Largest
Image type	JPEG or RAW
Picture style	Neutral
Peripheral illumination correction	Disabled
Colour space	sRGB

The HDR imaging generation process requires several LDR photographs taken under identical conditions to be combined together (Figure 12.3); it is essential that there are neither moving objects in the scene, nor that the camera itself is moving or shaking. For this reason, the camera should be placed on the tripod and the use of a remote shutter controller is recommended. Also, since daylight may change fast, the entire set of pictures should be taken in a reasonably short time.

The sequence of LDR photographs should include the entire range from underexposed to overexposed scenes. Assuming that the sensitivity is fixed at ISO 100, the exposure essentially depends on camera aperture and shutter speed.

The camera aperture, indicated with an f/ followed by a number, regulates the amount of light that goes to the sensor. Lower f-numbers, e.g. f/2.8, indicate that more light is allowed to reach the sensor. The camera shutter speed, expressed in seconds, measures how long the light is allowed to hit the image sensor, e.g. 1/125 s. The combination of aperture and shutter speed defines the exposure. Different combinations of aperture and shutter speed may lead to the same exposure.

One way to change the exposures is to set a fixed aperture, and change the shutter speed at regular steps i.e., from underexposed to overexposed photographs (Figure 12.3). Another, and probably easier, way is to use the Exposure Values (EV) setting in the camera. In most cameras, EV varies between –2 (underexposed) and +2 (overexposed), where EV = 0 represents the 'correct' exposure. At least one photograph per EV step is recommended.

The photographing phase is determinant for the production of a good HDR image. First, the position, the view angle and time for shooting should be carefully determined. It is advisable to place a grey, evenly illuminated reference in the field of view.

As mentioned, playing with the exposure (EV or using the shutter speed), the operator should take several pictures covering the entire luminance range. Long exposure time will provide saturated images (white), while short exposure times will provide dark images. Five to nine pictures covering the entire dynamic range are usually sufficient.

At this time, the luminance at one spot on the diffuse surface should be measured for later calibration of the HDR image.

Finally, if a 180° fisheye lens is not available, e.g. if a classic plain picture is taken, the vertical illuminance close to the lens position should be measured. This last step is needed only if the HDR is later used for evaluation of the DGP.

The pictures are processed by specific software, for example

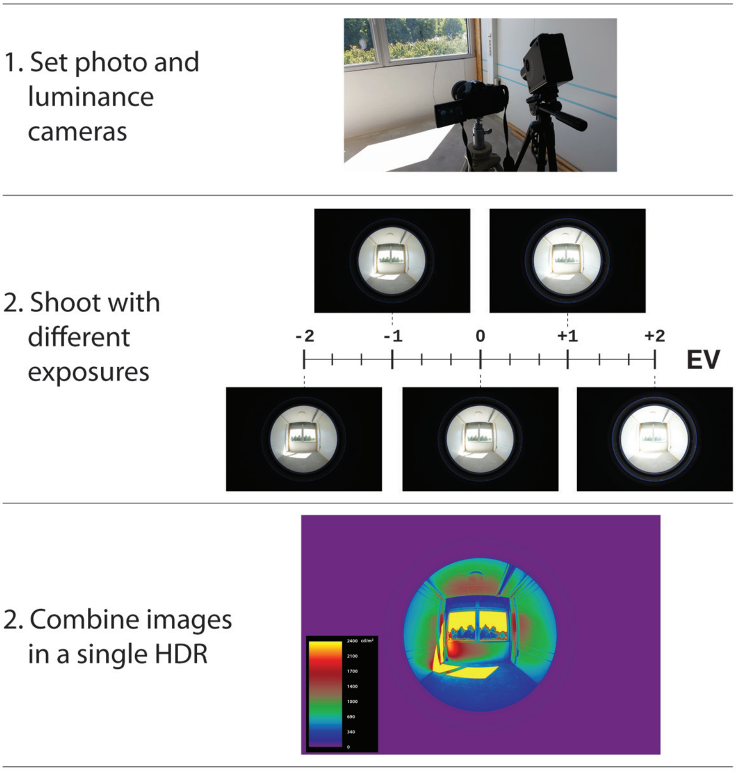

Figure 12.3
LDR images with different exposures are combined together to generate an HDR image providing luminance values. Image: Niko Gentile.

Photosphere. Photosphere, or equivalent software, will combine the LDR pictures in a single HDR image (Figure 12.3). The calibration with the luminance spot meter can be conducted during the HDR generation process. The calibration represents the response of the camera, and it stands valid for further HDR images taken with the same camera. Consequently, the spot luminance measurement on the diffuse surface may be skipped for the following scenes.

The glare evaluation is performed via software. For example, the free software Evalglare provides DGP evaluation of *.hdr image files. The DGP formula requires that both luminance map and vertical illuminance at the eye are known. If the camera used a 180° fisheye lens, the vertical illuminance is automatically derived by Evalglare. For any other view angle, the vertical illuminance should be measured in the field and the value must be entered in Evalglare for a correct DGP evaluation.

12.3 Measuring circadian lighting

Two primary methods exist for assessing the non-visual effects of light[8]:

- Spectral Response of Photopigments. This considers rods, cones, and ipRGCs and includes metrics such as Equivalent Melanopic Lux[9] and Melanopic Equivalent Daylight Illuminance (mEDI)[10].
- Melatonin Suppression. This approach uses the Circadian Stimulus (CS) model[11] [12] [13] [14] [15].

This area is rapidly evolving, and metrics may change over time. Currently, mEDI, introduced by the CIE, is considered the standard, while CS also sees broad application. However, any of the cited metric requires the collection of the same field data and calculation models. The equipment needed consists of:

- A calibrated spectroradiometer covering the 380-780 nm range (preferred). Alternatively, a calibrated illuminance meter may suffice if the space is illuminated by a specific light source only.
- The metric-specific toolbox (e.g., Lucas' toolbox[16], CIE α-opic Toolbox[17], or CS calculators[18], available online).

A spectroradiometer measuring visible irradiance (380–780 nm, 1–5 nm intervals) provides accurate data, including under mixed lighting conditions. An illuminance meter is cheaper and more accessible but relies on approximations, particularly for mixed lighting.

All measurements must be taken vertically at eye level. Follow these steps to perform the measurements:

1. Document the date, time, weather, operating conditions (e.g., shading position, status of electric lighting if any), and take photos for reference.
2. Record vertical irradiance (Figure 12.4) or illuminance at eye level.
3. Download the measured data to a computer for analysis.
4. Process the data using the appropriate toolbox for the selected metric.

The freely available CIE S 026 α-opic Toolbox[17] computes the measured data in mEDI units. Under the Tab '1. Select source of spectral data', select 'User' if you used a spectroradiometer and you therefore measured irradiance. Copy-paste the spectral irradiance values and read the resulting melanopic Equivalent Daylight Illuminance under the Tab 'Outputs' in cell F39. For further exploration and deeper understanding, it can be interesting to look at resulting charts under the Tab 'Charts'.

If you used an illuminance meter, you should select a generic light spectrum under Tab '1. Select source of spectral data'. The spectra are provided by the CIE and they are standardized illuminants. For example, illuminant 'A' represents an incandescent light source, 'D65' is a standard daylight source at 6500 K, 'E' is an equal-energy spectrum illuminant (not useful for practical applications), 'FL11' is fluorescent light, and 'LED B3' is a LED light source with CCT ≈ 3000 K. The user must select a single spectrum assigned to the measured illuminance. The accuracy of the resulting mEDI depends on how the standard spectrum is representative of the real one. In case of daylight only, the approximation is normally acceptable. The case of electric lighting is different. For example, a test conducted on a real LED 4000 K lamp delivering 1870 lux (photopic) results in mEDI ≈ 1430 lux when using the real spectral irradiance, and mEDI ≈ 1182 lux when using the standard spectrum LED B3. For further clarifications, the reader is referred to the users' guide of the CIE S 026 α-opic Toolbox[19].

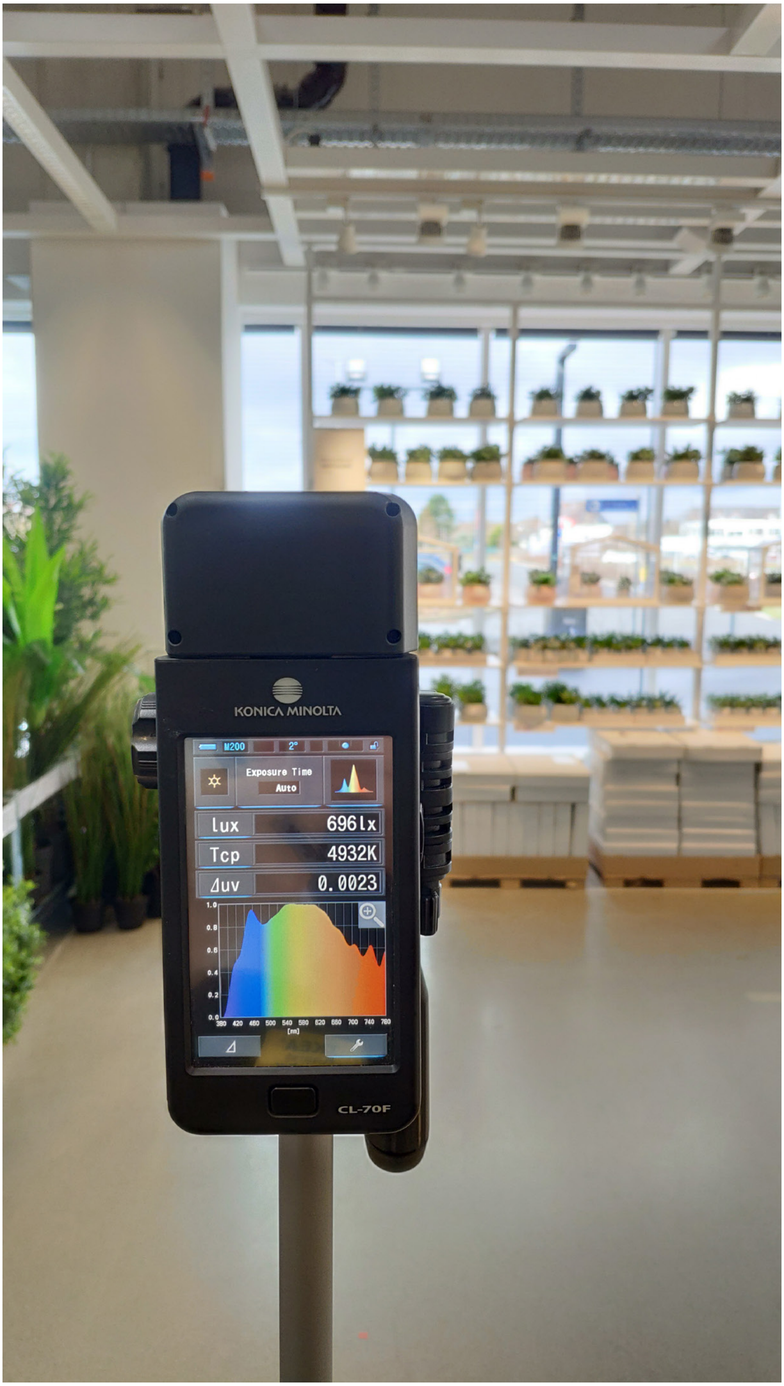

Figure 12.4 A spectroradiometer measuring vertical irradiance. The normalized SPD, the vertical illuminance, the CCT and Duv of the incident light is shown on the screen. The raw data can be saved and used in circadian toolboxes for calculating the relative circadian metrics. Image: Niko Gentile.

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CHAPTER 13

Introduction to daylight simulation

IASON BOURNAS

'Those who fall in love with practice without science are like a sailor who enters a ship without a helm or a compass, and who never can be certain whither he is going.'

LEONARDO DA VINCI

'In most cases, we call an image photorealistic if it 'looks as real as a photograph'. Although this is a laudable goal, there is still a big difference between something that 'looks' real and something that is a good reproduction of reality'

GREG J. WARD, 1998

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Simulation scene, sky model, typical meteorological year, grid-based/image-based analysis, simulation engine, BRE split flux method, rendering equation, radiosity, backward/forward raytracing, photon mapping, daylight coefficients, bidirectional scattering distribution function (BSDF), sky patch subdivision, matrix multiplication methods, Lynes equation, Radiance, Daysim.

This chapter begins with the fundamental elements present in every daylight simulation scenario: the scene geometry, the sky model, the ground, the analysis area, the space usage, and the simulation engine. Next, the reader is introduced to various daylight simulation techniques developed over recent decades, some of which are implemented in current simulation tools. Finally, procedures for conducting annual daylight simulations are presented, along with the implications of different methods and aspects of daylight simulation control.

13.1 Background

Already from the early 1980s, research in computer graphics[1] [2] [3] paved the way for the powerful daylight simulation tools available today. Initially aimed at generating visually appealing images of geometric scenes, computational models have since evolved to achieve higher levels of physical accuracy, leading to the development of daylight simulation for building performance evaluations. Today, architects and lighting professionals can use these simulation tools to (a) predict the quantity and quality of light in a given design and (b) assess whether the lighting conditions are optimal for illumination and visual comfort, according to specific daylight performance metrics.

13.2 Fundamental elements of daylight simulation

Although different software tools may require users to input various parameters through their respective interfaces, a fundamental set of core elements must always be specified to conduct a daylight simulation. Reinhart[4] provided a clear categorization of these elements, along with a schematic map illustrating their interrelationships, as shown in Figure 13.1. These elements are:

- *The scene.* The geometrical model of the three-dimensional space under investigation, where object surfaces have been assigned with materials of specific optical properties.
- *The sky model.* A mathematical model representing the sky luminance distribution, including both direct and diffuse light, coming from different regions of the hemispherical sky dome.
- *The analysis area.* The portion of the scene where daylight analysis will occur. There are two main types of analysis: (1) an image-based evaluation, where surface luminance is assessed for

a particular field of view and (2) a grid-based evaluation where illuminance is calculated for a user-specified grid of points or sensors.

- *The space usage*. Information on space type (office, school, etc.). Depending on space usage, different occupancy schedules apply, and different lighting levels are required.
- *The simulation engine*. The light calculation algorithm merging the scene with the sky model to calculate light (illuminance or luminance) for the analysis area.
- *The results processor*. A post-simulation process where raw illuminance or luminance results are translated into the

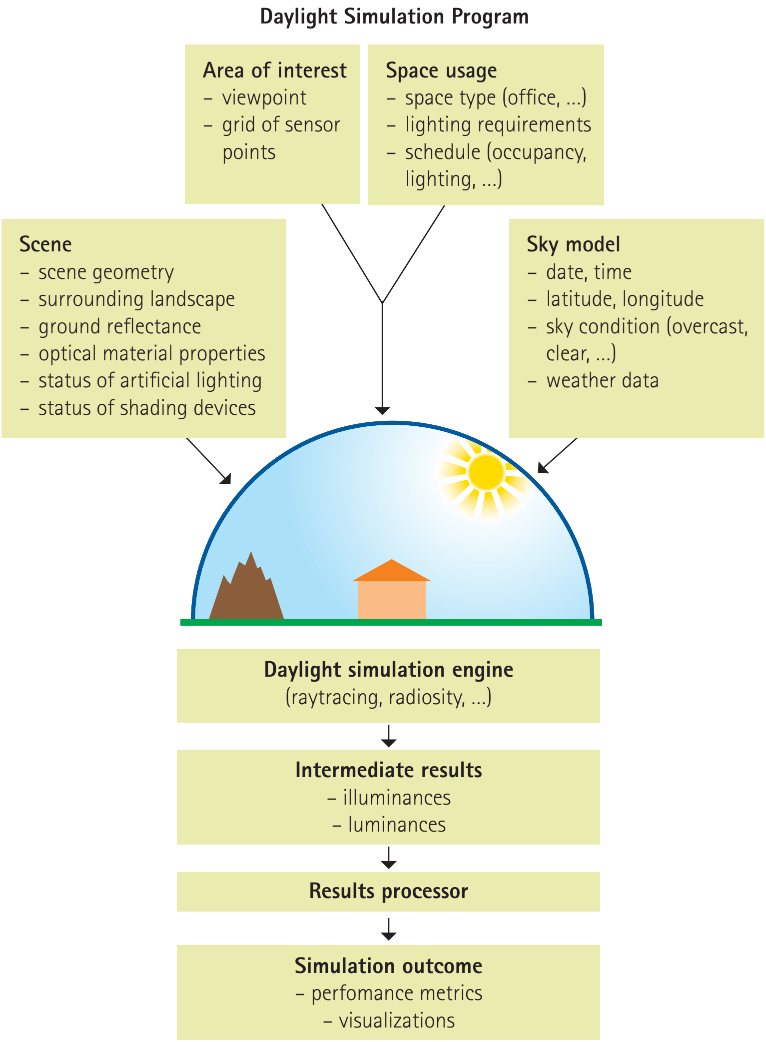


Figure 13.1 Schematic map of fundamental elements of daylight simulations. Source: Reinhart (2011).

format of 'metrics' that can inform the user whether the desired daylight conditions meet the pre-defined criteria. For example, computed illuminance levels can be used to calculate the Daylight Factor metric, while combined illuminance and luminance can be used to calculate a Daylight Glare Probability Index metric using specific formulas. The processor retrieves raw results from the simulation engine and outputs daylight metric values for evaluation in accordance with standards and recommendations.

The *scene,* the *sky model* and the *simulation engine* are elements that the user must carefully design and select, to obtain a realistic result, i.e., one that closely predicts how the real space would appear. On the other hand, the results processing phase is the decision-making element that streamlines the design process. Careful selection of daylight metrics is crucial, as they can influence the results in ways that may lead certain design solutions to be favoured over others deemed 'better performing'.

13.3 Daylight simulation scene

The three-dimensional model required for a daylight simulation includes the building being investigated, its surroundings, and the ground plane. Advances in software interoperability have simplified the process of importing detailed CAD models into daylight simulation tools. However, it is advisable for users to consider daylighting needs when deciding which geometry to include or exclude from a daylight simulation scene. For example, many daylight simulation tools require window glazing to be modelled as a single surface, rather than the multi-pane geometry often found in external 3D modelling software like Autodesk Revit. Such simplifications and considerations are outlined in this subsection.

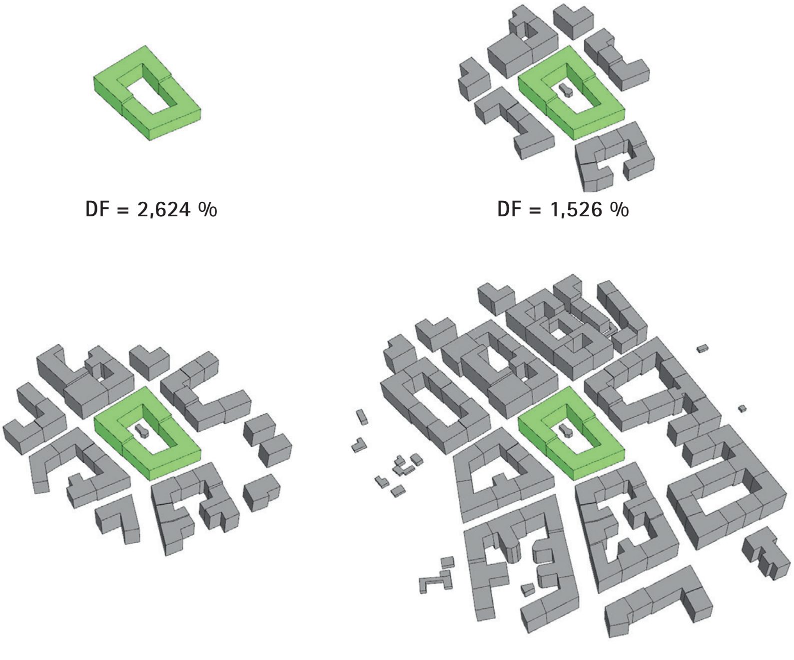
13.3.1 Surroundings

Surrounding surfaces should be modelled, as they can significantly impact the calculated daylight levels by obstructing portions of the sky dome. Spaces on lower floors are particularly affected. Surroundings typically include buildings and trees, which should be modelled based on available data and within a reasonable radius around the analysis area.

Omitting surroundings will lead to an overestimation of lighting levels, especially at the back end of a side-lit room. Over modelling the surroundings, on the other side, may overload the simulation scene, consuming considerable computational resources and increasing simulation time.

Surrounding buildings can be modelled as simplified massing models, as shown in Figure 13.2. In Sweden, building data can be accessed via the Geodata Extraction Tool (GET) by logging into https://maps.slu.se with student credentials. GET is a web-based service that provides geographic data from four Swedish authorities: Lantmäteriet, Statistics Sweden, the Geological Survey of Sweden, and the Swedish Maritime Administration. Municipal planning offices that have surveyed their building stock may also provide data in vector or CAD format. Cities like Stockholm, Gothenburg, Malmö, and others already offer such data upon request.

Surroundings should be modelled to a certain extent. Immediate surroundings must be included, as they obstruct the largest portion of the sky dome. However, obstructions located far from the investigated building may be excluded, unless they are tall enough to impact the analysis area. For each of the four scenes in Figure 13.2, the Daylight Factor of four rooms (one in each orientation) located on the second


DF = 2,624 %

DF = 1,526 %

DF = 1,521 %

DF = 1,520 %

Figure 13.2 The average Daylight Factor (DF) deducted from four rooms (one in each orientation) located in the second floor of the building indicated in green color. The immediate surroundings have the highest impact. Modelling further does not yield a considerable DF decrease. Illustration: Iason Bournas.

floor of the green building was simulated, and the average of the four rooms (DF) is presented. It is obvious that modelling beyond the immediate surroundings has little impact on the simulation results. Some standards recommend minimum distances; for example, the Illuminating Engineering Society of North America (IESNA) Measurement #83 [5] specifies 30.5 m. The author recommends that the simulationist models at least the immediate surroundings in all directions around the investigated building, regardless of their distance.

Surface reflectance for surrounding surfaces can significantly affect the results, especially in denser areas where much of the incoming light is reflected off surrounding objects. Different sources recommend varying values as 'typical surrounding diffuse reflectance'. Values of diffuse reflectance ranging between 0.3 and 0.5 are generally considered reasonable[5 6], when no measured data are available. However, the reader is encouraged to assess the surrounding environment before making any assumptions. A highly glazed building opposite of the analysed structure may exhibit considerable specular reflectance, depending on the type of glazing, which can lead to glare from redirected sunlight. If a visual comfort analysis is to be conducted, the surroundings should be modelled with these aspects in mind; instead of a diffuse material, a specular material should be employed.

Surrounding trees that obstruct the direct view of the sky dome can significantly affect daylight levels. In contrast to buildings, trees are complex and can change throughout the year. A general recommendation from IESNA Measurement #83[5] is to model trees as appropriately sized cones, spheres, or cylinders with an overall visual reflectance of 20%. These methods typically involve measuring the luminance of the tree crown and comparing it to the luminance of the sky behind it. Tregenza and Wilson (2011)[7] provide reasonable approximations of canopy transmittances for different types of trees in cases where measurements of specific trees are not available.

13.3.2 Ground

A daylight simulation will usually run even if the ground is not modelled. Different tools employ various default assumptions regarding the optical properties of an imaginary planar ground surface if the user does not specify these properties. It is important to remember that a ground surface immediately outside a window will reflect daylight toward the room ceiling, which in turn increases uniformity and average daylight levels by directing light to the back of the room. Therefore, it is recommended to assign ground properties that reflect real conditions instead of relying on default settings. When unknown, a commonly used value for ground diffuse reflectance lies between 0.1 and 0.2. In the case of Radiance[8], the most validated daylight simulation engine, omitting the ground surface instructs the software to create a constant upward-facing luminance, as shown in Figure 13.3a. It is crucial to ensure that the luminance source is the sky dome and that obstructions are considered. In a more realistic scene where the ground plane is modeled (Figure 13.3b), the luminance will be lower in areas of the ground that cannot 'see' the sky due to obstruction by the building.

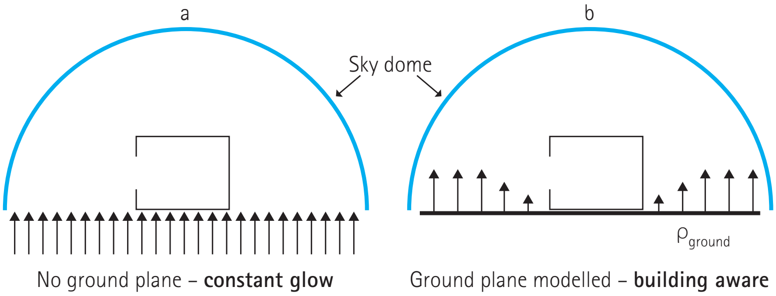


Figure 13.3 a and b Illustration of the ground plane luminance accounted by Radiance in the cases when a) no ground plane is included in the simulation and b) the ground plane is included in the simulation. Illustration: Iason Bournas.

13.3.3 Analyzed building

Modelling surfaces near simulation sensors requires a more detailed design approach. The building envelope should include wall and roof thicknesses, and other surfaces that might obstruct daylight from entering. Room interiors should incorporate large pieces of furniture and interior walls, all reflecting the actual situation. Windows, in particular, are the most challenging to model due to variations in manufacturer details and dimensions, which can significantly affect incoming light (e.g., window mullions). Modelling geometries with adequate spatial resolution can help ensure that results remain within an acceptable margin of error. In general, the dimensions of geometrical objects that affect the simulation should be modelled with a tolerance of 5 cm. For facade details, the tolerance should be 2 cm. Ibarra and Reinhart (2013)[9] recommend that, in the absence of actual geometries of window mullions, a fixed amount of transmittance reduction in the window glazing can be assumed. If window frames and mullions cover

20% of the window opening, one can model the glazing surface with a 20% reduction in its actual visual transmittance. This simplification is acceptable when the simulation aims to provide metrics such as Daylight Factors. However, if the goal of the simulation is to assess potential glare in the space, then window mullions and dividers should be designed in detail, and glazing should be modelled with its actual light transmittance. This ensures that any luminance peaks in the field of view are not underestimated or overestimated. Care should be taken when importing a geometrical model into the daylight simulation software from an external 3D modeler, such as commercial CAD design tools. Ibarra and Reinhart (2013)[9] found that a significant amount of simulation errors made by novices is attributed to inappropriate importing of various geometries, where parts of the building may be omitted (e.g., glazing may not be imported). It should be noted that daylight software expects a geometrical model consisting of surfaces, not volumes. In currently available BIM design tools, a construction element such as a wall might be described as a 'block', rather than a group of surfaces. This distinction can have implications for the assignment of surface optical properties. For instance, an exterior wall of a room has one interior surface (facing the room) and one exterior surface (facing outward). The daylight simulation software will require inputs for both surfaces, especially if they differ in material, which is usually the case. Therefore, it makes sense to separate these two elements when exporting the wall geometry from an external design tool.

Usually, daylight simulation software will 'read' the attributes of the geometric model as specified by the user in a 3D modeler. Specific software may expect numerical inputs in units that are not set by default in the 3D modeler. A good practice is to set meters as the unit of measurements for geometry dimensions. It is also important to consider the location of the geometric model within the 3D modeler. The daylight simulation software may have dependencies on the model's origin point. An imported geometry that retains information about its location (x, y, z) may be placed too far from the origin point, which can affect how the geometry is treated by the simulation tool. Unless the user is aware of how to set the necessary tolerances, it is recommended to model the geometry as close to the origin point as possible.

Another important parameter for geometry modelling in daylight simulations is surface normal. The surface normal direction in physically based rendering algorithms will affect how the interaction of light with this surface will be simulated in terms of light reflection from that surface, according to the 'rendering equation' (see section

13.7.2). Failing to set surface normal for all building surfaces according to real-life expected reflectance will result in over- or underestimation of light levels.

Material properties should ideally be set according to measured optical properties. A useful database of measured surface reflectance for opaque materials can be found at *http://spectraldb.com/*[10]. Most of the available materials were measured by use of a spectrophotometer. A collection of validated optical data for glazing products can be found from Lawrence Berkeley National Laboratory[11]. In the absence of reliable measurements, typical values may be used to generate meaningful results. The European Standard SS-EN-17037:2018+A1:2021[12] includes recommended reflectance values for main surface finishes. Table 13.1 provides a list of these recommendations, along with the previously stated recommendations for ground and surroundings reflectance.

Table 13.1 Recommended reflectance values

Floor [i]	0.2–0.4
Ceiling [i]	0.7–0.9
Interior walls [i]	0.5–0.8
Furniture [i]	0.2–0.7
Surroundings [ii, iii]	0.3–0.5
Ground [iii, iv]	0.1–0.2

Sources:
i. SS-EN-17037:2018+A1:2021[13]
ii. IES lm-83-12[5]
iii. Leder et al. (2007)[6]
iv. Reinhart (2011)[4]

When it comes to Swedish residential spaces, the author has measured surface light reflectance (0-1) with a portable spectrophotometer in a multitude of typical apartment blocks, deriving median values for each surface as follows: interior walls 0.8, floor 0.3, ceiling 0.85 (see Bournas et al., 2020)[14].

13.4 Sky Model

For daylight simulations, the source that provides daylight to the scene is the celestial hemisphere, or sky-dome. The sky's *luminous distribution* (specifically, the amount of daylight coming from different parts of the sky-dome) is defined by mathematical models (sky models) that a daylight simulation tool can process. Sky models differentiate between direct and diffuse daylight quantities and are location-aware, incorporating site latitude and solar altitude depending on the time of year. The International Committee of Illumination[15] has established a classification of 15 different sky types, which belong mainly to three categories: overcast, partly cloudy, and clear. Different models assume different luminance gradations from zenith to horizon, brightness of circumsolar region, and horizon brightness. All models are functions relative to the sky zenith luminance. Applying these models to site-specific radiation measurements is necessary to derive absolute luminous conditions.

A sky model that has been thoroughly validated[16] [17] and is considered the 'gold standard' among simulation experts is the Perez all-weather[18] sky model. Details about the model were previously described in Chapter 7. This model is preferred for several reasons. It can explicitly represent sky brightness by accounting for light scattering through clouds provided the user calibrates five empirical coefficients related to solar altitude, sky clearness, and sky brightness. The size and intensity of the circumsolar region, along with the increased luminance across the horizon, are indicative of the scattering effect (Figure 13.4). The model is also designed to generate luminance patterns for multiple sky occurrences, making it suitable for annual simulations that incorporate time series calculations. In addition, the model can be used in energy simulation tools, allowing for combined daylight and energy analyses with consistent sky models. However, like all existing sky models, it cannot reproduce the unique patterns exhibited in real skies due to random clouds.

Figure 13.4 shows the luminance distribution according to four different models of Stockholm's sky on April 27 at noon time. It is evident that, depending on the assumed sky condition, different results are anticipated. The *CIE Standard Overcast* sky model represents heavily clouded sky and assumes no direct solar radiation (no sunlight). It features a steep gradation of sky luminance towards the zenith and exhibits azimuthal uniformity. This model is used for Daylight Factor simulations that evaluate a 'worst case scenario', assessing the minimum illumination for a given scene. The *CIE Standard Clear* sky model represents the other extreme: a cloudless sky. This model is useful for glare predictions, as it allows for the evaluation of a design assuming the sun's disc can be visible at all times of the day. The *CIE Partly Cloudy* sky model represents a sky with average cloud coverage; however, it is not often used by simulation experts. The *Perez* sky model is beneficial for annual assessments, where the sky luminance distribution needs

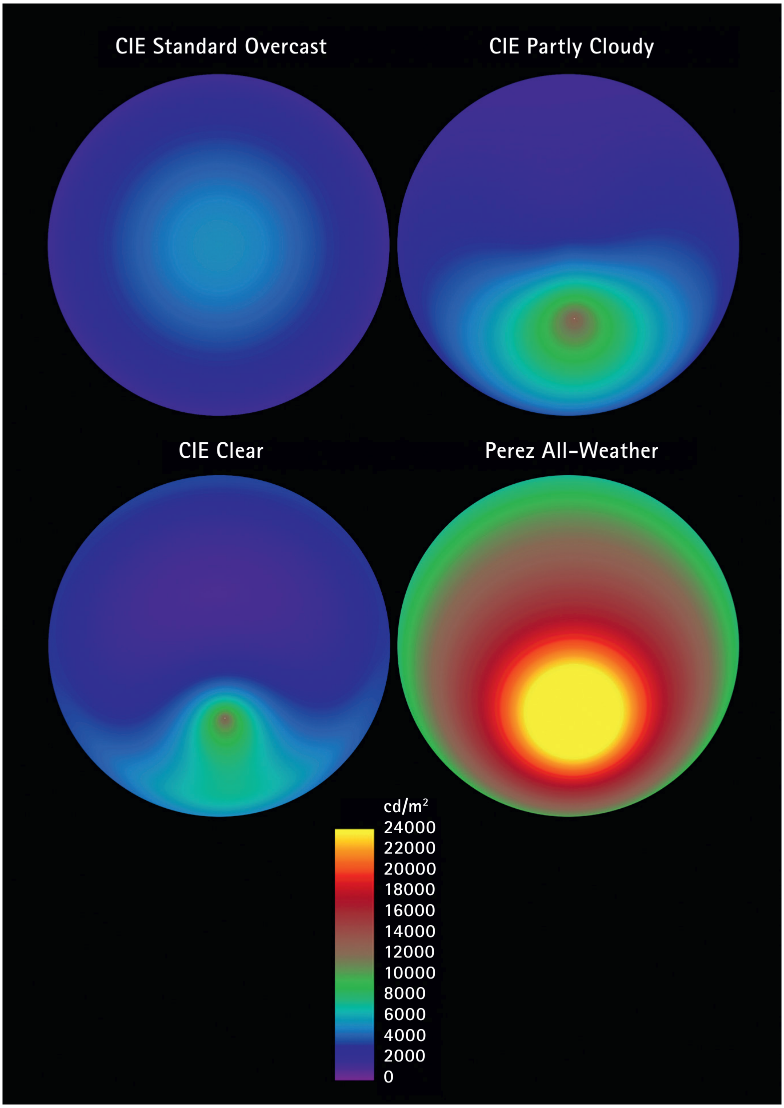


Figure 13.4
Visualizations of the sky luminous distribution in Stockholm, April 27 at noon, according to four different sky models: CIE Standard Overcast, CIE Partly Cloudy, CIE Clear and Perez All-Weather. Illustration: Iason Bournas.

to be iterated hourly or sub-hourly for a particular location according to climatic conditions. The model functions by combining different sky types at each time step to create an annual series of sky types to represent the entire year.

In the absence of measured weather data, any of the aforementioned sky types can be modelled using a *weather file*. A weather file has a standardized format, is location-specific, and contains values for different climatic parameters, such as temperature, humidity, wind speed, and direct and diffuse irradiances, for each of the 8 760 hours of the year. In most cases, these hourly values are derived from historical datasets typically including 20 years of observations, which are statistically processed to exclude extreme weather cases and to compile a *typical meteorological year*, in other words, an 'average year' that represents long-term weather patterns. Weather files are available from different databases. One large database is offered by the US Department of Energy[19], free of charge, which includes more than 2 100 different locations, including Stockholm, Karlstad, and Gothenburg. For more locations, the reader is advised to search for private providers, such as Meteonorm[20], which can provide data at a cost. The US DOE provides a list of recommended private databases[19]. SVEBY (2024)[21] offers weather data for a multitude of locations in Sweden, which is the standard weather data also used for energy simulations in the Swedish building sector. Another repository of weather data that includes multiple locations in Sweden and internationally is climate.onebuilding.org (2024)[22].

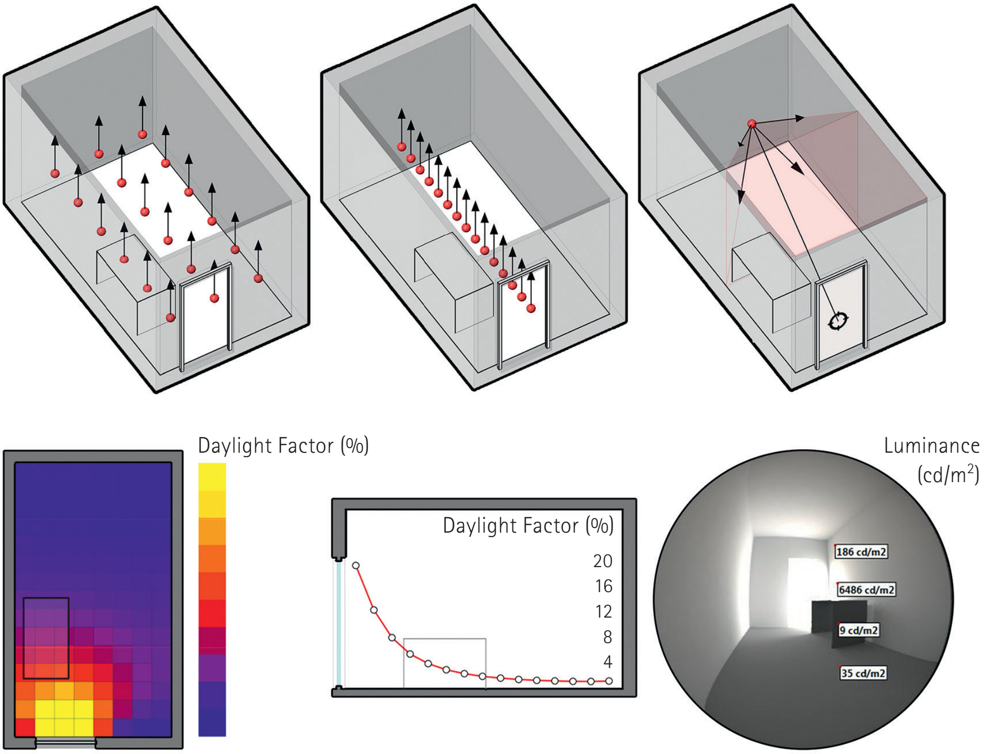


Figure 13.5
Three different analysis areas (top row) for the same simulation scene, and the corresponding outputs (bottom row). Notice that a grid-based simulation is associated with illuminance metrics (e.g. DF) while an image-based simulation provides luminance outputs. Illustration: Iason Bournas.

13.5 Analysis area

A daylight simulation will account for a particular scene and a predefined sky, but the calculation of daylight availability will take place only for specific points within the scene. Two major formats of analysis areas are generally used, depending on the type of analysis and the daylight metric employed: a) measurement points (usually upward facing) that represent daylight sensors and b) selected view perspectives that represent the visual field of the occupant.

Sensor points are usually distributed in a grid over the floor area of the investigated space but can also be a single point inside a scene. The exact placement of sensor points across a given floor area may vary depending on standard or simulation protocol (distance between grid points, vertical distance from finished floor level, no sensors assigned in areas close to walls), thus the assessor is urged to read carefully on the instructions given each time. A variation of this grid-based format is a straight line of sensor points that stretches from the location of an opening to the back of a room. In this case, the reduction of daylight as we move further from the opening can be depicted on a 2D diagram as a trend line. Sensor point simulations calculate the light falling on these points and measure illuminance, and the metrics derived from it (i.e., DF, DA, UDI). Figure 13.5 shows different analysis areas and corresponding outputs.

View perspectives are generally defined by specifying a camera location, a target, and a lens type. The camera location is set at the assumed occupant position (at eye level) and the target can be set according to the task conducted (e.g., computer screen for reading or blackboard for following a presentation). The eye level of a person is 1.20 m above floor level when sitting and 1.70 m when standing. The camera lens used is typically a 180-degree fisheye lens, to mimic the extent of the visual field. View perspectives are generally used to evaluate the visual comfort of the occupant and are thus associated with luminance (cd/m^2) calculations and the metrics derived from luminance (i.e., DGP, luminance ratios). It should be noted that, according to Khanie et al. (2017)[23], a fixed-gaze analysis that assumes a single camera target is limited compared to a gaze-driven target, where the occupant focuses on different regions of the visual field depending on the task conducted and the luminance of surrounding surfaces. However, the same study showed that for visually demanding tasks, such as typing or reading on a computer screen, it is realistic to assume a fixed gaze direction toward the computer.

13.6 Space usage

When simulating a daylight scene, it is important to consider the actual usage of the investigated space. Different types of rooms can have varying target illuminances based on the tasks conducted. They can also have different occupancy schedules depending on room function. Different target illuminances or acceptable luminance ranges per room type were previously presented in Chapter 8. Occupancy schedules should be set in accordance with the actual room occupancy patterns, unless otherwise specified by a standard, regulation, or certification system. For office spaces, a common format used is a fixed period during the day, such as ‘from 9:00 to 17:00’. The reader is urged to be careful with the simulation software entries for defining these time extents. A simple entry of ‘9’ for start and ‘17’ for end might not always indicate that the timespan ends at 17:00. Depending on the software tool, it might mean that the hour between 17:00 and 18:00 is also included in the calculation. A good practice to avoid such misinterpretations is to locate the occupancy schedule file created by the software and to validate that the inputs are the desired ones. The author has observed errors arising from such ambiguous inputs in software interfaces in the past.

It should be noted here that some researchers in the daylighting field are sceptical about the current norm of using fixed periods of time (i.e., ‘from 9:00 to 17:00’) for a couple of reasons. Mardaljevic & Christoffersen (2017)[24] pointed out that a fixed period is not a robust criterion, due to deviations between local and solar time, software input misinterpretations, and the possibility that a space schedule might change during a building’s lifetime. An alternative time span for evaluation can be a fixed portion of the annual time series, i.e., ‘the average room illuminance should be at least 300 lux for at least 2 190 hours per year’. A growing number of certification systems (e.g., LEED, BREEAM, WELL) include illuminance criteria based on such time spans, in line with the European Daylight Standard SS-EN-17037[12].

13.7 Simulation engine

Once the geometrical scene, sky conditions, analysis areas and space usage have been defined, a simulation engine is used to merge them into a single algorithm that calculates the desired daylight quantities. The algorithm will use a specific calculation technique that dictates light propagation in space. Different software tools may deploy various calculation techniques or a combination of them. It is very important

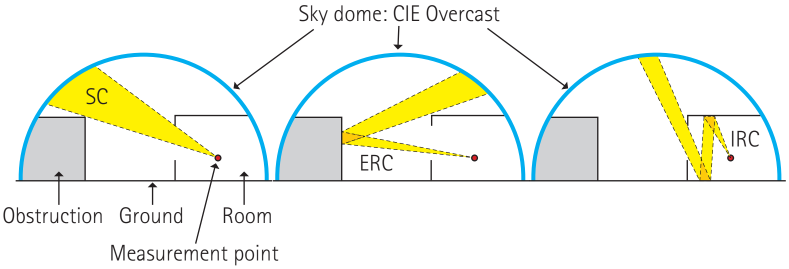


Figure 13.6
Illustration of the three daylight components of the BRE split-flux method for a given measurement point. Illustration: Iason Bournas.

that the user understands the desired outcome in order to select the simulation tool that employs the appropriate technique. Different techniques can address different complexities, and they require various learning approaches, some of which are more straightforward while others have a steeper learning curve. In this subsection, we will briefly mention four such techniques: The BRE split flux method and the numerical light transfer techniques (global illumination algorithms) of radiosity, raytracing, and photon mapping.

13.7.1 BRE split flux method

The BRE split flux method was introduced by the British Building Research Station (BRS), now called the British Building Research Establishment (BRE), as a technique to calculate the Daylight Factor using formulae developed by Dufton (1946)[25]. The method included hand calculations based on graphical and tabular data. The assumption made was that, in the absence of direct sunlight, daylight can reach to a point inside a room in three ways:

- Sky Component (SC): Directly from the sky through an opening.
- Externally Reflected Component (ERC): Daylight reflected off the ground and surroundings.
- Internally Reflected Component (IRC): The inter-reflection of (SC) and (ERC) off interior room surfaces.

Figure 13.6 shows the concept of the different light components. The distinction is justified by the fact that each component is affected by different geometrical elements of the scene. The resulting Daylight Factor (DF) is then calculated as: DF = SC + ERC + IRC. The BRE split flux method can generate accurate results for points in the scene that have a greater view of the sky dome. However, it cannot account for multiple internal reflections in all user-specified scenes and may thus underestimate illuminance for points located deeper in the space. The method is generally not used today, as advances in computer graphics and computational resources have led to more sophisticated techniques.

13.7.2 Rendering equation

The calculation techniques described in the following subsections (radiosity, raytracing, and photon mapping) are numerical approaches that have been refined over the years and are employed in current daylight simulation tools. Light transfer between room surfaces was initially developed in the field of computer graphics to mimic light propagation via reflection, transmission, and refraction, in creating a 'global illumination algorithm'. Although the developed calculation techniques employ different approaches to calculate light transport, they are all approximations of the rendering equation presented by Kajiya (1986)[26] as a unifying equation to calculate all light transfer involved in a scene. According to the rendering equation, the outgoing light in a particular direction w from a point x on a surface is defined as:

$$L_0\,(x,w) = L_e\,(x,w) + \int_{\Omega} f_r(x,w',w)\; L_i(x,w')(-w' \cdot n)\; dw' \tag{13.1}$$

Where:

$L_o(x,w)$ is the outgoing radiance in a particular direction w from a point x on a surface.

$L_e(x,w)$ is the radiance emitted from point x towards the direction w.

Ω is the unit hemisphere centered around point x and oriented according to surface normal n.

$\int_{\Omega} \ldots\, dw'$ is an integral over all directions w' in the hemisphere Ω above point x.

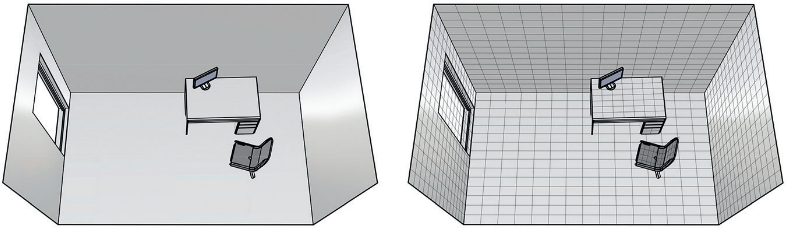


Figure 13.7
Subdivision of model surfaces in discrete patches prior to the calculation of form factors of a radiosity simulation. Illustration: Iason Bournas.

$f_r(x,w',w)$ is the proportion of radiance reflected from point x towards direction w, when received from direction w'. This term is known as the Bidirectional Reflectance Distribution Function (BRDF).

$L_i(x,w')$ is the incoming radiance at point x from the direction w'.

$(-w' \cdot n)$ is an attenuation factor of radiance incoming at point x, according to the cosine of the angle between the surface normal n and the incoming radiance direction w'.

Evaluating the radiance of point x towards a direction w involves evaluating the right side of the equation, which sums the emitted radiance from point x and all radiance reflected from x based on the radiance it receives (from radiation sources or other surfaces). The fact that the radiance of point x depends on the radiance received by other surfaces (from direction w') indicates a recursive process, as other surfaces emit light based on the radiance they received from point x. Light bounces between surfaces and attenuates until convergence is reached. A detailed description of the associated terms of the rendering equation can be found in Glassner (1995)[27].

The form factor between i,j indicates:

1. How much *surface i* is visible from *surface j*
2. How much radiance will be transferred

dA(i) = elemental area on surface *i*
A(i) = area of surface *i*
c(i) = contour of surface *i*
r = distance between *dA(i)* and *dA(j)*
dω = solid angle subtended by *dA(j)* as seen from *dA(i)*
¢(i) = angle between surface normal of *i*, *n(i)*, and the line *r*
¢(j) = angle between surface normal of *j*, *E(j)*, and the line *r*

dA(j) = elemental area on surface *j*
A(j) = area of surface *j*
C(j) = contour of surface *j*

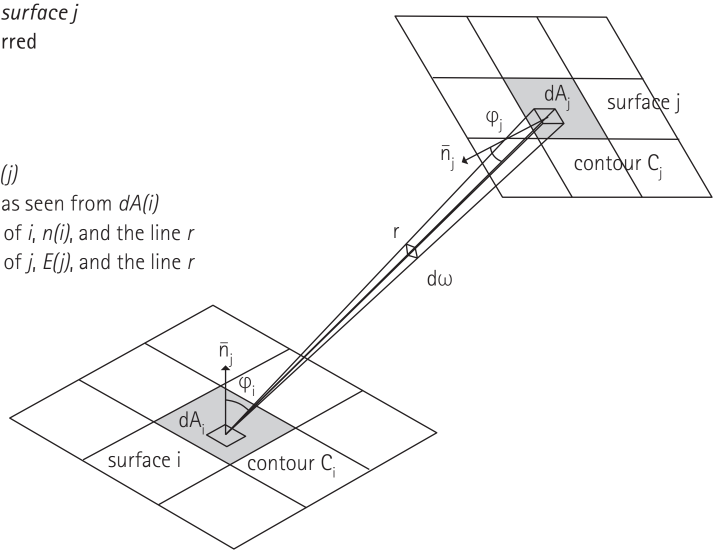


Figure 13.8 The geometry assumed for the derivation of a form factor between two patches of individual surfaces, according to Goral et al. (1984)[28]. Image redrawn without alterations according to the original[23], Original available from: https://dl.acm.org/citation.cfm?id=808601 page nr 217.

13.7.3 Radiosity

Radiosity was developed by Goral et al. (1984)[28] as a global illumination algorithm based on methods used in thermal engineering: the calculation computes the transport of radiative light energy between model surfaces. In an initial discretization step, all surfaces are subdivided into patches (Figure 13.7) and *form factors* are calculated for every pair of patches. A form factor between two patches is a coefficient that describes the fraction of energy that leaves the first patch and reaches the second patch (Figure 13.8). It accounts for the distance between the centres of the patches and their orientation in space relative to each other. Form factors are dimensionless quantities that range from zero, for patches that are mutually invisible (no light transfer between them), to one for maximum light transfer. The amount of light entering in a room (e.g., through a window) is considered a total luminous flux that the radiosity algorithm distributes to all room surfaces according to the assigned form factors. Light transfer between each pair of patches iterates over a number of light bounces until the algorithm converges to a solution. The same calculation is performed for all possible pairs. It is evident that the level of accuracy depends on the degree of surface subdivision into patches and the number of light transfers (bounces) between patches. For scene surfaces with higher luminance gradients, finite elements approaches can further subdivide surfaces. For more details on the calculation routines used in radiosity, the reader can consult resources by Sillion and Puech (1994)[29].

Radiosity calculations are view-independent, which increases computational requirements but provides results that are useful for all possible scene viewpoints, as all surfaces are calculated. This is particularly advantageous for creating interactive scene walkthroughs, making radiosity widely used in the computer games industry. Calculation time is generally lower for simple scenes with minimal surface detail, but it increases in proportion to the square of the number of patches, making simulation time a major drawback for daylighting analyses of complex scenes. The algorithm can also simulate the ‘colour bleeding’ effect, create soft shadows, and model diffuse interreflections. A major limitation is that radiosity is only applicable to scenes composed of ideally diffuse reflecting surfaces. It cannot render highlights observed on specular surfaces (e.g., specular blinds or redirecting systems), which are essential for glare analysis. Another limitation is that curved surfaces must be divided into patches,

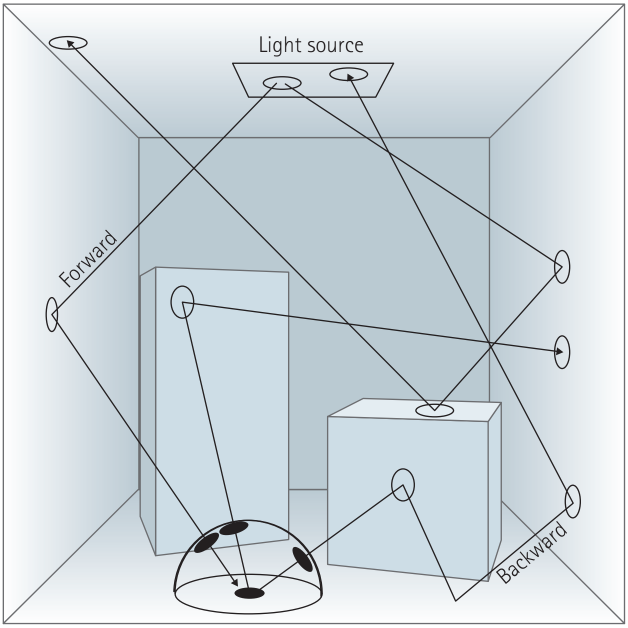


Figure 13.9
Illustration of the concepts of forward (from light source to measurement point) and backward (from measurement point to light source) raytracing.

resulting in possible discontinuities at the seams, which hinders the technique's ability to simulate arbitrary geometries accurately.

13.7.4 Raytracing

The raytracing technique calculates light by tracing the path of individual light rays in a scene, following the approach originally proposed by Whitted & Foley (1980)[1]. The assumption is that light travels in the form of infinitely thin rays along which radiance remains constant. Rays may be cast from the light source toward the analysis area (forward raytracing) or in the opposite direction, where rays travel from the analysis area toward light sources (backward raytracing). Figure 13.9 illustrates these two concepts. Forward raytracing can be useful when evaluating a single object; for instance, we can cast rays onto a shading device to measure its bidirectional reflectance distribution function (BRDF). For complex scenes where specific points need to be evaluated, backward raytracing will converge to a result with far fewer ray paths, saving considerable time[2]. A recursive process is used to trace the light path. In backward raytracing, a ray is cast from a user-defined point A (analysis area) in a direction where it can intersect with another surface (e.g., a wall or furniture) or a light source (e.g., a sky dome or lamp). If the ray intersects with a light source, the known luminance of the source contributes to the illumination of point A. If the ray intersects a surface, then the luminance at the intersection point B (on the surface) must first be evaluated to determine how much illumination it will contribute to point A. Therefore, a secondary ray is cast from the intersection point B in the direction of reflectance, transmittance, or refraction, depending on the optical properties of the surface material. The secondary ray may intersect a light source and 'read' its luminance, which is required to calculate the illumination at point A, or it may intersect another surface. In the latter case, the recursive process continues until the ray intersects with a light source or until a user-defined number of light bounces occurs. Some tools allow the user to set a termination threshold based on ray weight, after which the simulation is concluded[8]. A benefit of raytracing is that it can model any mathematically defined surface due to its inherent geometrical assumption of point light transfer. It can also account for surface transmittance and specular reflection, which is crucial in studies evaluating glare sources and luminance highlights in the occupant's field of view. Compared to radiosity, raytracing is the preferred choice for scenes of higher complexity, as computation time increases sub-linearly with the number of model surfaces. Nevertheless, the primary drawback for raytracing tools is computation time, especially when multiple diffuse rays must be spawned and traced recursively. A solution provided by Ward et al. (1988)[30] is to sample a set number of rays to calculate specific points in the scene, and then interpolate the rest of the points from neighbouring cached values. The advantage of this approach is decreased computation time for accurate horizontal illuminance predictions. However, it may lead to reduced physical accuracy if the interpolation settings are not properly

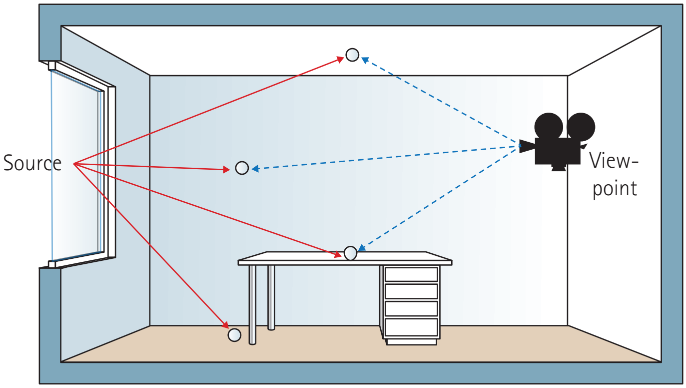


Figure 13.10
Illustration of the concept of the two-pass algorithm used in photon mapping. Photons (depicted as grey spheres) are shot from the light source during the forward pass (red arrows) and the scene is rendered in the backward pass (blue arrows) by tracking the photons from a user-defined viewpoint. Illustration: Iason Bournas.

configured by the user. It should be noted that most software tools are now adopting a 'simplified interface' approach, where numerical values for individual inputs have been replaced with general settings such as 'low/medium/high quality'. Users are advised to understand the underlying inputs, as these can fundamentally affect physical accuracy and simulation time. Another limitation of raytracing for image-based renderings is that calculations are view-dependent, meaning that for the same scene, a separate simulation is required for each view perspective to be evaluated.

13.7.5 Photon mapping

Photon mapping, developed by Jensen (1996)[31], could be regarded as a forward raytracing technique. However, it is distinctly different in that it decouples the data generated by raytracing from the scene geometry using an intuitive two-pass algorithm. In the first step (the forward pass), a photon map (data cache) is constructed from illumination information. In the second step (the backward pass), the scene is rendered using the illumination information in the photon map.

In the forward pass, photons are 'shot' from light sources into the scene using forward raytracing and are traced as they interact with scene surfaces (Figure 13.10, red arrows). Each photon that leaves the source is assigned a starting point location, an initial flux, and a direction. Upon intersecting a surface, the photon flux, the intersection point, and the incident direction of the photon are stored in the photon map. Like raytracing, the photon will subsequently bounce off the surface. Probabilistic functions define whether the bounce will occur as diffuse scattering, specular reflection, or whether there will even be a bounce (absorption). A recursive process simulates the photon's travel within the scene, where its flux is attenuated by each surface based on the surface's bidirectional reflectance distribution function (BRDF). Upon completion of the first pass, the photon map is constructed.

In the second step (backward pass), rays are cast from the camera point (Figure 13.10, blue arrows) towards the scene. When a ray intersects with a particular point on a surface, the radiance of that point is calculated from the flux of a user-defined number of neighbouring photons found in the photon map cache. The illumination of a point depends on the density, flux, and direction of the nearest photons. The idea is that illumination at point A will depend more on the photons located nearby. Accuracy can be increased by increasing the number of initial photons shot into the scene. Details on the algorithm calculations can be found in Jensen (2001)[32] and Schregle (2004)[33].

Photon mapping can handle diffuse and specular reflections, colour bleeding, and caustics, which are not accurately rendered by either radiosity or raytracing. A significant advantage of photon mapping is that there are no limitations on surface geometries due to the separation of the map from the geometry. The algorithm can be easily integrated into raytracing tools with minimal modifications.

13.8 Annual daylight simulations

All aspects of daylight simulations described previously are only capable of calculating daylight for a single point in time, assuming a fixed sky condition. A point-in-time simulation is useful for evaluating a 'worst-case' scenario or making coarse predictions. Given that daylight depends on dynamic climatic conditions (such as cloudiness and the solar path), assessing a space over an annual period would provide a comprehensive estimate of its daylight performance. The required type of simulation,

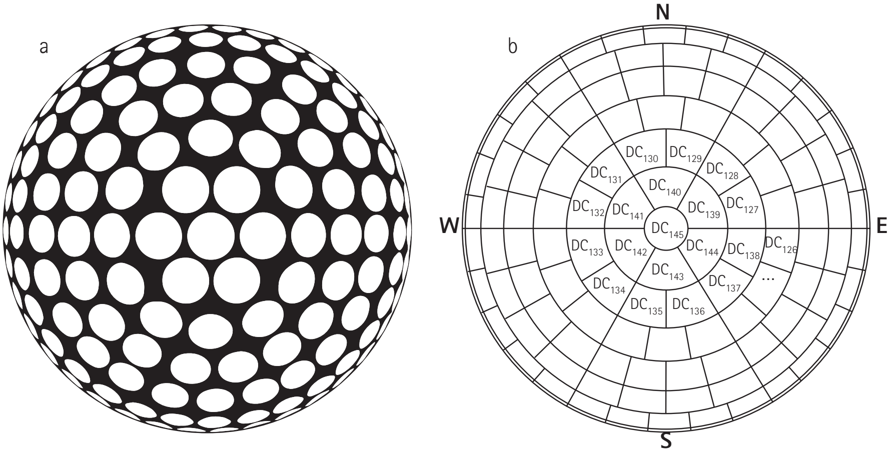


Figure 13.11
Sky division schemes according to a) Tregenza and b) continuous subdivision.
Source: Reinhart (2001)[36].

known as ‘dynamic’ or ‘climate-based’, is possible by using hourly or sub-hourly outdoor climatic data to generate illuminance time series for a space under a given climate. These generated time series are known as annual illuminance profiles and can be used in combination with annual electric lighting or energy simulations.

13.8.1 Daylight coefficients

An annual simulation with a one-hour time step would require the user to simulate the scene 8 760 times under the corresponding sky type of each hour of the year. While the implementation of such a routine is possible, it would result in immense computation time. A framework to avoid such costly simulations was established by Tregenza & Waters (1983)[34], who introduced the *daylight coefficients*. Daylight coefficients relate the illuminance of an interior point to the luminance of a specific sky region, accounting for scene obstructions and their optical properties.

For daylight coefficients to work, the sky dome must be subdivided into discrete patches, which represent discrete zones of altitude and azimuth. The subdivision of the sky has been proposed several times, beginning with Tregenza (1987)[35] and further developed by Mardaljevic (1999)[16] and Reinhart (2001)[36]. Figure 13.11 shows the sky dome subdivision in 145 circular patches (Tregenza subdivision) and 145 ellipsoid patches (continuous subdivision). The centres of the patches are in the same location for both schemes; however, the continuous subdivision of the sky dome (ellipsoid patches) has become the norm, as it accounts for the full sky dome area.

A daylight coefficient is a ratio between the illuminance of an interior point and the luminance of a particular sky patch considering

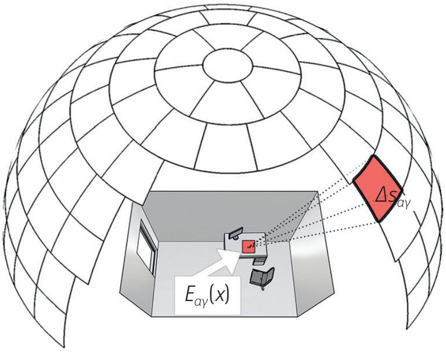


Figure 13.12
Geometrical definition of a daylight coefficient. Illustration: Iason Bournas.

any obstructions. The coefficient for a point x due to the sky patch at altitude γ and azimuth α is calculated as follows:

$$\mathrm{DC}_{\alpha\gamma}(x) = E_{\alpha\gamma}(x) \,/\, (L_{\alpha\gamma} \cdot \Delta s_{\alpha\gamma}) \tag{13.2}$$

where:

$E_{\alpha\gamma}(x)$ is the illuminance on point x received from the sky patch.
$L_{\alpha\gamma}$ is the luminance of the sky patch.
$\Delta s_{\alpha\gamma}$ is the angular size of the sky patch.

Figure 13.12 illustrates the scheme of the daylight coefficient for a single sky patch. The illuminance at point x attributed to the sky patch is the product of the sky patch's luminance, its angular size, and the daylight coefficient for point x. Summing the illuminances from all sky patches provides the total illuminance at point x.

In practice, daylight coefficients are used in conjunction with time series of climatic data (weather files) and a dynamic sky luminous distribution model, such as the Perez All-Weather sky model, to expedite the annual simulation process. The calculation of the spatial relationship between an interior point and a sky patch requires a raytracing step that consumes most of the simulation time. Once the relationship (daylight coefficient) is established, iterating the sky luminous distribution for each hour of the year becomes lightning fast, delivering an annual illuminance profile for the interior point. Similarly, if the daylight coefficients for a point inside a room have been calculated, simulating its illuminance for different climates (different locations) is

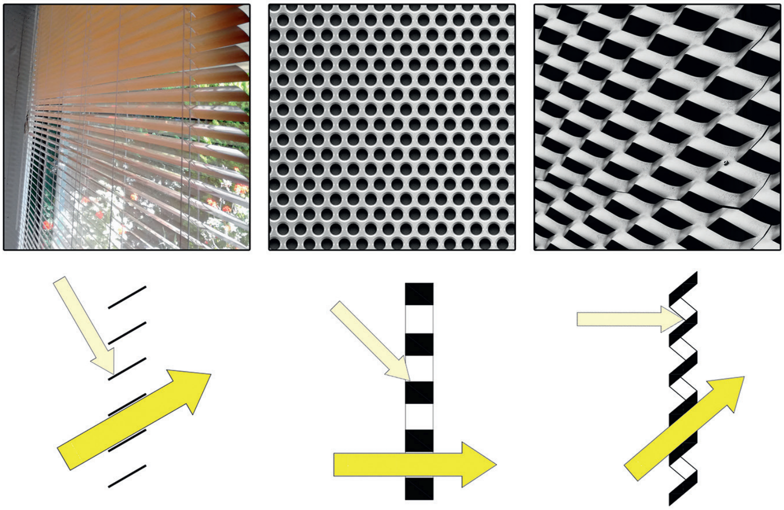


Figure 13.13
Schematic illustration of how light transmittance differs with different solar positions. Starting from left: Venetian blind, perforated metal mesh, and expanded metal mesh.

a straightforward task, simply by switching the sky dome luminous distribution according to the weather file. Setting up an annual simulation is almost the same as setting up a point-in-time simulation, the former only requiring the use of a weather file. Simulation time has been found to be five to eight times longer compared to a point-in-time evaluation when a raytracing engine is used[37].

Daylight coefficients for annual illuminance simulations were first implemented in Daysim[38], a Radiance-based program created by Reinhart (2001)[36]. Since then, there have been advancements in simulation algorithms regarding the spatial accuracy of the sky model for annual simulations, particularly the accuracy of the sun's position in each time step. Currently, there are Radiance-based executables that handle direct solar contributions with much higher accuracy than Daysim and at a lower computational time cost.

It is also possible to use coefficients to conduct annual glare analyses[39], but there are limitations regarding the accuracy of the results and preconditions for the results to be considered reliable. Currently, there are

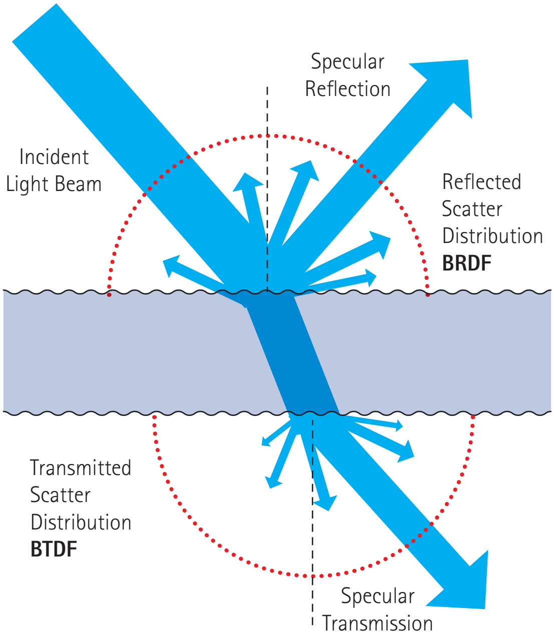


Figure 13.14 Directional distribution of light in a BSDF, incorporating two light components. The transmitted component that is calculated with a BTDF (Bidirectional Transmittance Distribution Function) and the reflected component that is calculated with a BRDF. (Bidirectional Reflectance Distribution Function). Image: CC BY Jurohi SA 3.0.

different approaches for assessing annual glare occurrence with so-called 'imageless' analysis based on daylight coefficients (e.g., the Imageless DGP method proposed by Jones (2019)[40], using the dcglare Radiance executable). The most accurate method thus far is the raytraverse method proposed by Wasilewski et al. (2022)[41]. Users of such methods should be aware that they are still under development and have limitations. The overall goal of efficiently deriving glare metrics from annual simulations will always be less accurate compared to a point-in-time assessment.

13.8.2 Bidirectional Transmittance Distribution Function

During the last 15 years, significant progress has been made in calculating annual illuminance profiles for geometrical models that involve complex fenestration systems (CFS). CFS are devices that exhibit variable optical properties (reflectance/transmittance) depending on the sun's position and/or user operation. CFS include, among others, Venetian blinds, louvers, roller screens, metallic and micro-perforated meshes, prismatic films, patterned or fritted glass, and woven shades.

Due to the complex geometries of CFS, their properties are angular-dependent. In these cases, transmittance and reflectance cannot be represented by a single value when evaluating performance over an annual period, due to the variation in light intensity and incident direction according to the sun's position (Figure 13.13). Instead, these dynamic properties can be expressed as a function that incorporates the incident and outgoing light direction, termed the Bidirectional Scattering Distribution Function (BSDF). The directional distribution of light in a BSDF incorporates two light components: the transmitted and the reflected components (Figure 13.14), which are calculated separately using the BRDF (Bidirectional Reflectance Distribution Function) and the BTDF (Bidirectional Transmittance Distribution Function). McNeil (2014)[53] puts it simple: A BSDF is to a fenestration system what an IES file is to a luminaire, with the addition that it considers many light incident directions.

For daylight simulations, BSDF data to characterize CFS can be obtained through: a) laboratory measurements using a scanning goniophotometer[42], b) numerical models that are CFS-specific, such as those for Venetian blinds[43], or c) simulations[44]. Laboratory measurements can be considered the most accurate source, as they derive properties from the actual manufactured materials. However, obtaining such measurements requires sophisticated and expensive equipment, and the measuring process takes substantial time based on the angular resolution. Andersen & de Boer (2006)[45] provide an overview of available experimental instruments. Numerical models have also been developed for specific CFS types and validated through experiments[46]. The drawback of numerical models is that they cannot be applied to arbitrary geometries. A simulation technique to calculate BSDF data via raytracing for arbitrary geometries has been developed within the Radiance suite of programs. This technique is deployable by use of the *genBSDF* executable[47], which has been experimentally validated by McNeil et al. (2013)[48] and Molina et al. (2015)[49]. It should be noted that in the case of simulations, prior to generating a BSDF for a CFS, the different material properties (reflectance/transmittance) should be obtained, preferably using a spectrophotometer. Other software that can generate BSDF files characterizing a CFS include WINDOW[50] and TracePro[51].

13.8.3 Matrix multiplication techniques

Approaches for conducting annual simulations using BSDF data for complex fenestration systems have been implemented in various tools, utilizing both radiosity and raytracing methods. Here, we will briefly describe the approach used by the developers of Radiance, which employs raytracing and matrix algebraic operations. This approach is based on the work of Klems (1993)[52], who developed a model for calculating solar heat gains through CFS using BSDF data for each layer. The model computes incoming and outgoing radiance by assuming

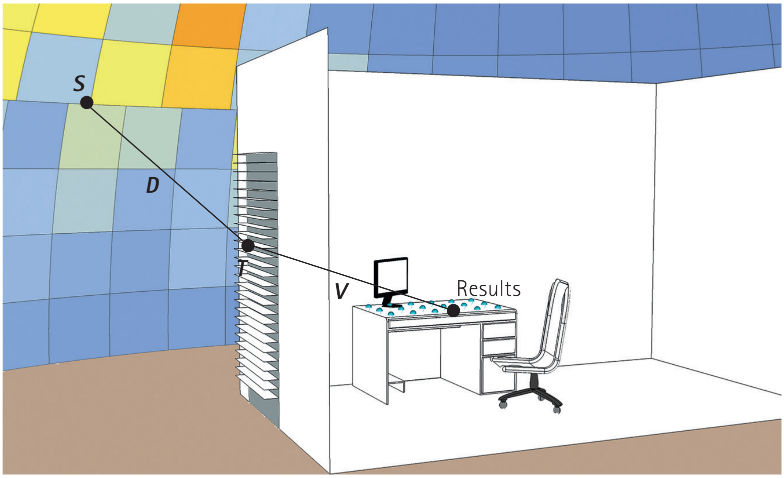


Figure 13.15 Schematic overview of the Three-Phase method and the involved matrices to evaluate daylight for points on a workstation of a room with external louvers. Image: Iason Bournas.

incoming and outgoing hemispheres (*Klems hemispheres*), each centred around the normal of the fenestration system.

In the Radiance Three-Phase Method[53], which utilizes the Klems hemispherical basis for incoming and outgoing radiance, light flux from the sky to the room's interior is divided into distinct phases for independent simulations. The method comprises the following phases that represent stages of light transport:

1. From sky dome to exterior side of fenestration.
2. Transmission/reflection from fenestration (second matrix, which is the BSDF of the fenestration).
3. From the interior side of fenestration to the analysis area.

The method calculates coefficient matrices that relate light flux input and output for each phase. The initial luminance input from the sky dome is multiplied by these coefficient matrices to compute the result. Both the initial sky dome luminance and the results are represented as vectors. This process, illustrated in Figure 13.15, is described by the following equation:

$$I = V \cdot T \cdot D \cdot S \tag{13.3}$$

where:

I Matrix containing time series of illuminance or luminance results, depending on the type of study.
S Sky matrix, a collection of N vectors, where N is the number of sky patches.
D Daylight matrix, relating sky patches to vectors incident on the window.
T Transmission matrix, relating incident vectors on the window to exiting vectors (BSDF).
V View matrix, relating outgoing vectors from the window to results in the interior.

Radiance generates the V and D matrices. The T matrix represents the BSDF of the fenestration, created as previously explained. The S matrix is also generated by Radiance by discretizing the sky dome using user-defined division schemes (e.g., Tregenza-145 patches, Reinhart MF:2-577 patches, Reinhart MF-4-2305 patches).

Users should be mindful of modelling implications arising from this approach. For instance, windows should be grouped according to their relationship with surrounding obstructions to generate accurate *daylight matrices* (D), which are influenced by obstructions and the window's visual connection to the sky dome. This means that windows with different orientations should be arranged in separate groups. Another consideration is the accuracy of the evaluated metric. For example, in a glare analysis where precise sun positioning is crucial, dividing the sky dome into large-area patches can distort the direct light contribution, as it cannot accurately model the sun's solid angle.

Accuracy limitations in the direct solar component have been addressed by using additional phases[54], where the direct contribution is calculated separately, using a grid of points (sun positions) across the sky hemisphere. This approach ensures that solar flux is not distributed over neighbouring sky patches. Readers are encouraged to follow relevant research advancements when planning to use such simulation schemes, as this is an area of ongoing research.

13.9 Simulation quality control

The extent to which a daylight simulation output represents real-world conditions depends on the simplifying assumptions made by the software. For instance, cloud patterns may be represented by a smooth luminance gradient over the sky dome, and different building surfaces may be treated as having uniform reflectance across their area. Although these may seem like crude simplifications, they are valid in certain scenarios. The key is to select the appropriate model for the specific conditions and objectives. Initial massing studies, for example, can be assessed using quick estimates to compare design alternatives. As design stages progress, more complexity can be introduced to produce robust results. In the final stages, a 'realistic' simulation should be conducted to provide reliable insights about performance.

Daylight simulations require three elements to produce reliable results: a) precise input data (e.g., sky conditions, material properties, geometries etc.), b) advanced simulation software, and c) a simulation expert who understands the software.

Databases for surface properties exist, as discussed in section 13.3.3. However, in some cases, information on input data may not be available. As a result, users might need to make educated guesses, which can reduce accuracy. Surface properties, such as precise BSDF data, are still lacking for a wide range of objects. In cases of uncertainty, users should rely on recommended values to help limit errors.

Simulation algorithms are not always straightforward. Stochastic techniques used by various tools can lead to variance in results for the same scene. In such cases, multiple runs may be necessary, with the final result determined as the average of all runs. Furthermore, validated software tools can provide reliable results, provided the evaluated scene is of comparable complexity to those in the software's validation process. Different settings may need to be adjusted for various scene types, depending on the assessed metric. Users should be aware of the implications associated with complex geometries, such as angle-dependent shading devices, to ensure the chosen software can accurately evaluate such scenarios. Another consideration is time efficiency, as daylight attenuates gradually with multiple interactions across scene objects. Due to time constraints, simulations must be terminated at a certain point, leading to a trade-off between simulation time and accuracy. A good approach is to follow a stepwise process, iterating settings to improve accuracy until convergence is achieved. However, it is important to note that relying on absolute illuminance or luminance values predicted by a simulation tool is less reliable than making relative comparisons between different designs. In other words, it is more challenging to estimate absolute illuminance levels in a room than to assess the relative increase in illuminance when, for example, increasing the window size.

With respect to the simulationist, it is important to note that a certain level of expertise is required to ensure simulation quality. The reality is that the learning curve for daylight simulations is shallow (long progression), due to the intrinsic complexity of light transport, which makes modelling details and rendering settings crucial. Calculation errors can occur even when considering only diffuse skylight.

In an evaluation study of the accuracy achieved by third-year Bachelor of Architecture students, Ibarra & Reinhart (2013)[9] compared the DF results generated by the students to those obtained from a reference best-practice simulation of the same room. The study concluded that most students over- or under-predicted the average room DF compared to the reference simulation result. Reasons for the discrepancies included omitting scene geometries (e.g., wall thickness), inaccurate optical properties of surfaces, and errors arising from imported CAD geometry prior to simulation (e.g., unimported glazing).

The same study included a short checklist for use by both beginners and experts, which can be consulted at all stages of a daylight simulation (early considerations, scene modelling, simulation setup, and results processing). An adaptation of this checklist can be found in Table 13.2.

A simple way to validate simulation results is to compare them to outcomes obtained using rules of thumb. The inherent simplicity of such rules means that only specific daylight conditions can be validated in this manner. In case of DF analyses for side-lit spaces, simulation results can be validated relatively quickly using the Lynes equation[55], which was derived from empirical data. A detailed description of the Lynes equation can be found in Chapter 7.

Table 13.2 Daylight simulation checklist.

Before you start	• Did you decide which performance indicators (metrics) to simulate? • Do you know what values you are pursuing? e.g., an average Daylight factor below 1% is considered unacceptably low and above 5% it is associated with overheating issues. • Did you verify that the simulation program that you intend to use is validated for calculating the metrics you desire? e.g., annual daylight metrics require programs with climate-based analysis capability. • Do you have credible climate data? E.g. a valid weather file for the building location is necessary for climate-based analysis.
Preparing the scene	• Did you model all significant obstructions such as adjacent buildings and trees? • Did you model the ground plane? • Did you model all significant elements of the building that can affect your sensor points? Try to model space dimensions with a 5 cm tolerance and window mullions with a tolerance of 2 cm. • Did you check the directionality of your model surfaces? Opaque surfaces should be pointing towards the direction of the reflection, e.g. interior walls point inside, exterior walls point outwards, ceilings point downwards, etc. • Did you consider wall thickness and window frames? • Did you check that your glazing geometry consists of a single surface? Several CAD tools model double/triple glazing as two/three closely spaced parallel surfaces, whereas daylight simulation programs tend to assign the optical properties of multiple glazing to a single surface. • Did you assign meaningful optical properties for all scene elements? Use measured or recommended values. • Did you model shading devices? These can have a significant impact on daylight.

Setting up the simulation	• Check that your material names or project names do not contain any blanks (" ") or uncommon characters ("ö") in case this affects the software. • Verify that your sensors have the correct orientation. E.g. work plane sensors should be facing upwards. • Make sure your sensors are spaced closely enough to capture daylight variation. Daylight varies significantly closer to windows or skylights. • Make sure your sensors are placed in the correct locations. E.g. working planes are set around 0.85 m above the floor. Eye level is 1.2 m above floor level for sitting and 1.7 m above floor level for standing. • Did you set your simulation parameters correctly? This depends on your "scene size" and "scene complexity". • Did you select the correct sky type for your metric? E.g. Daylight factor requires a CIE Overcast sky.
Process the output data	• Do you know what performance benchmarks you are aiming for? Depending on latitude, space type (office, residential, etc.) or existence of skylights, these benchmarks might vary. • Do you know how your resulting values translate to daylight availability and comfort? E.g. specific luminance ratios are associated with visual comfort. • Are you sure your values are reasonable? E.g. an average Daylight factor over 40 % might be the result of light leaking from a crack in the model or the result of omitting an element such as the ceiling. • Perform rules of thumb calculations of simple daylight metrics to validate your values. You can use the Lynes formula[55] to validate an average Daylight factor value.

Source: Reinhart.[4]

Reinhart and LoVerso (2010)[56] computed average DF values for 2304 side-lit spaces using Radiance simulations and found a strong correlation with the corresponding DF values derived from the Lynes equation ($R^2 = 0.896$ and $DF_{\text{LYNES}} = 0.813 \cdot DF_{\text{RADIANCE}}$). The simulations were conducted using a 0.305 m x 0.305 m point grid located 0.85 m above floor level. The high correlation between the Lynes-derived and Radiance results demonstrates that this formula serves an adequate quality control test for simulation output. However, it should be noted though that this numerical validation is applicable only for DF assessments of side-lit spaces consisting of Lambertian surfaces. Glare evaluations or climate-based simulation outputs cannot be validated with such simple formulas.

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CHAPTER 14

Observer-based lighting assessment

THORBJÖRN LAIKE AND PIMKAMOL MATTSSON

> ‘To be is to be perceived (esse est percipi).’
>
> GEORGE BERKELEY

THIS CHAPTER INTRODUCES THE FOLLOWING KEY TERMS AND CONCEPTS:

Construct validity, content validity, human perception, internal consistency reliability, interval, Likert scale, nominal, observer-based environmental assessment (OBEA), ordinal, perceived comfort quality (PCQ), perceived strength quality (PSQ), ratio, reliability, semantic differential, technical environmental assessment (TEA), validity.

Measurement is an important task when evaluating an environment or an object. However, some measures are easier to obtain than others. To get useful and meaningful information about the quality of light, one needs to look at different aspects. This chapter concerns methods for gaining information about human perception of lighting conditions and their relation to other measures used for describing lighting conditions. However, first, we need to explore a little bit more about human perception.

14.1 Human perception

As explained in Chapter 3, the human perception process involves previous experience, memory, expectation, attention, and learning, all of which need to be considered. This understanding has developed over the last century through the growth of experimental psychology, with numerous examples demonstrating that perception is an active process of selecting, organizing, and interpreting what is sensed. Early interesting experiments, such as Rubin's vase and the Cornsweet illusion (see Figure 14.1), illustrate this.

We need to be aware that there are at least three basic levels of impact affecting perception. First, there is the biological basis, rooted in our sensory system. This system is quite similar among most individuals, but there are differences across various groups of people. For example, the vision of elderly individuals differs from that of younger people. However, perception involves more than just sensory input. On a second level, human perception is influenced by learning; the way we are raised and educated impacts our environmental perception. For example, if

Figure 14.1
The Rubin's vase (top). The silhouette in Rubin's vase could be seen either as a vase or as two faces. The Cornsweet illusion (below). The same colour at the left and right parts is perceived differently because our brain uses information of dark and light gradients that meet in the middle.

you have a certain interest in lighting, you will learn more and become more aware and sensitive to lighting conditions.

Thirdly, there are individual differences. Perception is influenced by an individual's life experiences, memories, and thoughts. Does this mean we only have individual perceptions with no possibility for generalization? No, we also know that there are significant similarities among people with similar backgrounds. One could use a group of 15–20 individuals drawn from a population and then take another group from the same population. The likelihood that they will provide similar responses as a group is high. Therefore, it is possible to use information at the group level when investigating the perceived quality of a lighting environment.

14.2 Measurement

When we talk about measurement, we need to consider what it actually is. In everyday life, we think of measurement as something we do using an instrument, such as using a ruler to measure the length of an object. Other measuring instruments include thermometers, barometers, and so on. How are light and its quality measured? Other chapters in this book describe instruments used in lighting, such as luminance and illuminance meters. All these measurements are performed with instruments and involve specific units. We may refer to these as Technical Environmental Assessments (TEA), which are all quantitative in nature. The quality of environmental features, such as lighting, can also be assessed quantitatively using psychological 'instruments.' These instruments employ individuals as tools and can be termed observer-based environmental assessments (OBEA).

It is often said that TEAs are 'place-centered' and 'objective' because they do not involve humans. However, this is not entirely accurate. A human being decides how to perform the measurements and where to conduct and analyze the results. Therefore, subjectivity is always involved to some degree. On the other hand, OBEAs are sometimes described as 'person-centered' and 'subjective' since a human is the tool. Although individuals perceive the environment differently, groups of individuals can create an average perception of the environment that can be useful. TEAs and OBEAs should be viewed as two complementary quantitative methods for describing lighting conditions.

Here, we can clearly define the difference between qualitative and quantitative approaches. The qualitative approach is not based on figures and originates from exegetics, as information is gained by interpreting statements. In this chapter, the focus is on the quantitative approach, which aims to achieve a certain level of objectivity. To attain this level, we need to understand the quality of quantitative data collection and analysis.

Quantitative data can be described at certain levels depending on their quality, which is defined at the scaling level. The most basic level is called nominal scaling, where observations are divided into categories, such as apples and pears. We may assign numbers to these categories, for example, assigning 1 to apples and 2 to pears. It is then possible to perform calculations with these numbers; however, an arithmetic mean will not provide much meaningful information about your observations. Instead, you could present the frequencies, as seen in ordinary polls on various topics. For example, 'Do you use product A or B?' If we survey a sample group, we will obtain two figures showing how many use one product or the other.

The next level is called ordinal scaling, which indicates whether one category has a higher rank than another. A classic example is military rank: a sergeant has a lower rank than a captain, who has a lower rank than a general. However, it is not possible to combine one sergeant and one captain to obtain a general. The ordinal scale can only rank the order of categories. These types of scales are often used in psychological measurements.

Two other scales often used when conducting measurements with TEAs are interval and ratio scales. Both interval and ratio scales have equal distances between increments, but the ratio scale includes an absolute zero point (for example, zero Kelvin is absolute zero because temperature measured on the Kelvin scale cannot have a value below zero). In contrast to TEAs, nominal and ordinal scaling levels are primarily applied to OBEAs. This implies that we need to consider information in specific ways. Still, OBEAs are quantitative methods that can be used to assess the perception of lighting conditions.

Why should we use OBEAs? One reason is that we need detailed information about perception, as it significantly impacts our comfort in the environment. Another reason is that OBEAs can compare social categories, such as the perceptions of architects and designers versus laypersons or building end-users. Additionally, it is important to consider multiple perspectives when assessing environmental qualities, considering the place-specific contexts of individual perceptions. OBEAs facilitate this. Integrating individual perceptions of the physical environment is crucial for environmental design. Such an understanding, when combined, is more holistic, which is necessary in applied situations.

14.3 Quality of measurements

To gauge the quality of a particular OBEA measurement, we rely on two important concepts: reliability and validity. Reliability pertains to the consistency of the measurement, while validity concerns how accurately the measurement corresponds to what it is intended to measure. There are different types of reliability and validity.

For reliability, the first type is test-retest reliability, which indicates the extent to which repeated measurements yield the same results. The second type is inter-rater reliability, which measures how well two individuals agree on the same measurement. Finally, internal consistency reliability assesses how well the different scales in a set correspond to one another. Reliability can be calculated using statistical tools and is often expressed as a value between 0 and 1, with values closer to one indicating good reliability.

Among several types of validity, we will mention only content validity and construct validity for now. Content validity assesses how accurately the measurement reflects the attribute intended to be measured, which can only be achieved through systematic examination. In contrast, construct validity can be estimated through statistical analyses. It pertains to how well the measurement correlates with other measurements that assess similar attributes.

For example, if we want to measure the perceived brightness of the light environment, we can use a scale and ask people to rate their perception of brightness. This measure can then be correlated with the TEA measurement of illuminance. A strong correlation indicates a high construct validity of the instrument.

14.4 Development of an instrument for measuring light quality

Observer-Based Environmental Assessments (OBEAs) that utilize a variety of semantic differentials and/or Likert scales have been employed to capture individual perceptions of light in various environments, reflecting people's experiences with both electrical lighting and daylight conditions in laboratory settings and real-life situations. However, none of these instruments have been widely adopted.

We have a situation where different OBEA instruments are used instead of a single one. To develop an instrument that could be more widely adopted, certain features are important. For example, the instrument should be easy to understand and administer, and it should have a certain degree of validity and reliability. In 1977, Flynn[1] made the first attempt to suggest that lighting conditions could be described by a number of qualities captured by bipolar semantic scales. In the early seventies, Swedish researcher Rikard Küller also developed a semantic instrument as a useful tool to measure human perception of the total environment, known as the SED (Semantic Environmental Description) (Küller, 1991)[2].

Building upon Flynn's work, Küller and Wetterberg (1993)[3] used bipolar adjectives such as unpleasant–pleasant, bright–dark, unnatural–natural, cool–warm, and strong–weak to assess the perception of lighting quality. Through factor analysis, these adjective pairs could be categorized as hedonic tone and brightness, which discriminated between different lighting conditions. The instrument was used in both field and laboratory studies to compare perceived lighting quality between below-ground and above-ground work environments (Küller & Wetterberg, 1996)[4], between fluorescent and LED lighting in classrooms (Gentile et al., 2018)[5], and to examine the role of seasonal daylight on perceived lighting quality in offices (Maleetipwan-Mattsson, 2012)[6].

The present version of this instrument contains 17 bipolar adjectives with seven-point rating scales (Gentile et al., 2018; Küller & Laike, 1998; Maleetipwan-Mattsson, 2012)[5] [6] [7]. Factor analysis has divided the bipolar adjectives into two main categories: Perceived Comfort Quality (PCQ), which refers to the general quality of the lighting condition, and Perceived Strength Quality (PSQ), which pertains to brightness perception. Additionally, there are three more categories that assess how varied, coloured, and flickering the lighting condition is perceived.

An outdoor version of this instrument has been developed and evaluated for its reliability and validity (Johansson et al., 2014)[8]. The outdoor version has been shown to have an acceptable degree of validity and differs from the indoor version in some respects.

14.5 Description of the instrument

The instrument contains 17 bipolar semantic scales presented in random order (see Table 14.1) and one overarching question: 'How do you perceive the lighting condition in this room?' It can be administered either as a paper-and-pencil test or in a computer-based format. Table 14.1 also illustrates the relationship between the semantic scales and their categories. Each scale has steps from one to seven, where one indicates a high degree of the property of the first adjective, and seven indicates a high degree of the property of the opposite adjective. Eight bipolar scales correspond to Perceived Comfort Quality (PCQ), while four scales relate to Perceived Strength Quality (PSQ). Variation is measured using three scales, while color and flicker each use one scale.

14.6 How to use the instrument

As an OBEA instrument, the Perceived Indoor Lighting Quality (PILQ) instrument is always used in situ. It is recommended to use the instrument only in real environments due to the difficulty of simulating lighting conditions. In the environment being assessed, the subject is asked to look around and then fill out the form. It is important to note that the first impression is the most significant, and there are no right or wrong answers. Additionally, it is crucial that the instrument is used in the assessor's native language, as the effectiveness of the assessment relies on the semantic understanding of the words.

Table 14.1 The Perceived Indoor Lighting Quality instrument (PILQ).

Scale	Factor
dark – light*	PSQ
pleasant – unpleasant	PCQ
uncoloured – coloured	Colour
strong – weak*	PSQ
scattered – concentrated	Variation
warm – cool*	PCQ
unevenly distributed – evenly distributed	Variation
hard – soft*	PCQ
unfocused – focused*	Variation (PSQ)*
natural – unnatural*	PCQ
flicker – no flicker	Flicker
clear – drab*	PSQ
varied – monotonous	PCQ
mild – sharp*	PCQ
glaring – shaded*	PCQ
subdued – brilliant*	PSQ
very bad – very good	PCQ

* The scales that also are a part of the Perceived Outdoor Lighting Quality tool (POLQ). Note that unfocused–focused is part of another factor since POLQ only consists of two factors.

After completing the form, the figures are placed in the boxes under their respective categories in the summing form (see Figure 14.2). Some boxes have an (8-) in front of them because the figure needs to be 'reversed' to align with the direction of the other scales in the same category. Once this is done, the mean is calculated for each category. The raw data can be entered into a spreadsheet, making it easier to perform calculations on a computer.

14.7 How to interpret the data

To obtain generalizable results from the OBEA, a sample of between 15 and 20 individuals is needed. Furthermore, it is important to determine whether the sample is heterogeneous or homogeneous, i.e., the degree to which the subjects share similar backgrounds, ages, and genders. For instance, if assessing a light environment in a workplace, the investigator must be aware of the distribution among different age groups and genders, as well as other relevant aspects, to prevent potentially misleading results.

For the most useful results, all 17 scales must be rated. However, the

LIGHTING EXPERIENCE

	Hedonic tone	Brightness	Variation	Colour	Flicker
LIGHT		☐			
UNPLEASANT	8- ☐				
COLOURED				☐	
WEAK		8- ☐			
CONCENTRATED			8- ☐		
COOL	8- ☐				
EVEN DISTRIB.			☐		
SOFT	☐				
FOCUSED			8- ☐		
UNNATURAL	8- ☐				
NO FLICKER					8- ☐
DRAB		8- ☐			
MONOTONOUS	8- ☐				
SHARP	8- ☐				
SHADED	☐				
BRILLIANT		☐			
GOOD	☐				
SUM	:8	:4	:3	:1	:1
MEAN					

Figure 14.2
The summing form of PILQ.

OBEA should not be used in isolation. As mentioned earlier, TEA must also be employed when investigating a light environment. Comparing the results between different TEAs and OBEAs can be highly beneficial for verifying findings. Additionally, it is important to note that we are not always consciously aware of sensory stimuli, especially in the case of flicker. Light sources may emit subliminal flicker that affects humans even if they do not consciously perceive it (Wilkins et al., 1989; Küller & Laike, 1998)[7] [9]. Therefore, TEAs must be conducted to avoid such issues and capture a comprehensive description of the light environment.

The most reliable categories of the PILQ instrument are Perceived Comfort Quality (PCQ) and Perceived Strength Quality (PSQ) of the lighting condition. When interpreting the results, the focus should be on these categories. When used correctly and with caution, the instrument can serve as a valuable complement to the TEA, providing useful information for improving lighting conditions.

14.8 Other methods

Other methods to assess the perception of lighting conditions include checklists, questionnaires, and semi-structured interviews. A checklist contains several words describing the lighting condition, and the subjects are asked to choose the most suitable words that correspond to their perception. Using questionnaires or interviews provides a more open-ended approach to assessing lighting, such as asking, 'Is the light bright enough?' or 'Do you like the lighting in the room?'. However, comparing answers in these cases may be challenging due to variations in vocabulary among different subjects.

A recently developed methodological approach involves using a method from sensory science based on principles of experimental design and statistical analysis (Boork et al., 2015)[10]. In this approach, a panel of trained individuals conducts an analytical evaluation of specific features of the product or environment to obtain objective facts about it. This method has been applied to light sources in recent years, but development is still ongoing.

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Daylighting and lighting

UNDER A NORDIC SKY

After nearly a century in which electric lighting has dominated interior building design, there is now a shift back to using daylight as the primary ambient light source. This return is driven by considerations of energy efficiency, environmental impact, and human health. Effective daylighting in building interiors not only supports low energy consumption, but also has the potential to reconnect people to the natural day-night cycle, which is known to enhance health and well-being.

Daylight is particularly significant for people in the Nordic countries, where light is scarce in the winter and overabundant near the summer solstice. The unique character of Nordic daylight—characterized by weak intensity in winter and low sun angles in summer—demands careful study and consideration, as it holds special value in this region.

However, the trend of urban densification makes it increasingly challenging to ensure adequate daylight in buildings under Nordic sky conditions, particularly in winter. Advanced building simulation tools are often necessary to accurately predict daylight levels and guide design adjustments. Building regulations and certification standards, which play a critical role in promoting sustainable daylighting practices, must be thoroughly understood by practitioners. Additionally, integrating state-of-the-art electric lighting technologies, such as LEDs and advanced control systems, with daylighting design is essential for optimal results.

Addressing these challenges, this book offers essential knowledge and background for students and practicing professionals seeking to illuminate buildings under a Nordic sky. It focuses on utilizing daylight as the primary ambient light source, with support from energy-efficient electric lighting systems.

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