Monitoring protocol for lighting and daylighting retrofits

T50.D3

A Technical Report of IEA SHC Task 50

April 2016

IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.*

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- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
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A Technical Report of Subtask D (Case Studies), T50.D3

IEA SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings

April 2016

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KEYWORDS

Measurements, monitoring, protocol, procedures, retrofit, electric lighting, daylighting, energy use, energy savings, light quality, user assessment, retrofit costs, field studies, light fixtures, lamps, controls, sensors, dimming.

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PREFACE

Lighting accounts for approximately 19 % (~3000 TWh) of the global electric energy consumption. Without essential changes in policies, markets and practical implementations, it is expected to continuously grow despite significant and rapid technical improvements like solid-state lighting, new façade and light management techniques.

With a small volume of new buildings, major lighting energy savings can only be realized by retrofitting the existing building stock. Many countries face the same situation: The majority of the lighting installations are considered to be out of date (older than 25 years). Compared to existing installations, new solutions allow a significant increase in efficiency – easily by a factor of three or more – very often going along with highly interesting payback times. However, lighting refurbishments are still lagging behind compared to what is economically and technically possible and feasible.

"IEA SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings" therefore pursues the goal to accelerate retrofitting of daylighting and electric lighting solutions in the non-residential sector using cost-effective, best practice approaches.

This includes the following activities:

- Develop a sound overview of the lighting retrofit market;
- Trigger discussion, initiate revision and enhancement of local and national regulations, certifications and loan programs;
- Increase robustness of daylight and electric lighting retrofit approaches technically, ecologically and economically;
- Increase understanding of lighting retrofit processes by providing adequate tools for different stakeholders;
- Demonstrate state-of-the-art lighting retrofits;
- Develop as a joint activity an electronic interactive source book ("Lighting Retrofit Adviser") including design inspirations, design advice, decision tools and design tools.

To achieve this goal, the work plan of IEA-Task 50 is organized according to the following four main subtasks, which are interconnected by a joint working group:

Subtask A: Market and Policies
Subtask B: Daylighting and Electric Lighting Solutions
Subtask C: Methods and Tools
Subtask D: Case Studies
Joint Working Group (JWG): Lighting Retrofit Adviser

ABSTRACT

This document presents a monitoring protocol to assess the overall performance of a lighting and/or daylighting retrofit of a building. This protocol covers four key aspects:

1. Energy use;
2. Retrofit costs;
3. Photometric assessment;
4. User assessment.

This document develops each aspect in detail, presenting the required measurements and necessary equipment as well as providing guidelines for data analysis.

The protocol is written as a general guideline document which could be used by non-expert assessors. A step-by-step general procedure is described, including five main phases, where each phase is described in detail, including the required documentation for two distinct monitoring levels: a ‘basic’ and a ‘comprehensive’ monitoring level.

EXECUTIVE SUMMARY

This document presents a monitoring protocol to assess the overall performance of a lighting and/or daylighting retrofit of a building. The protocol is developed in the context of IEA-SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings. IEA-SHC Task 50 focuses on the existing non-residential building stock.

This protocol is based on the assumption that the retrofitted buildings can be monitored before and after the retrofit actions take place. However, in cases where it is not possible to monitor the pre-retrofit situation due to practical limitations, an alternative method is proposed. This method consists of comparing the values obtained from the post-retrofit monitoring program to benchmark values for similar types of existing buildings.

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The protocol is written as a general guideline document which could be used by non-expert assessors. A step-by-step general procedure is described, including five main phases:

1. Initial visit survey (IVS);
2. Pre-monitoring decision making;
3. Monitoring preparation;
4. Monitoring process;
5. Analysis.

Each phase is described in detail, including the required documentation for two distinct monitoring levels: a ‘basic’ and a ‘comprehensive’ monitoring level. Standard templates to fill in each part are proposed in the Appendices.

TABLE OF CONTENTS

ABBREVIATIONS

AC	Alternative current
ADF	Average daylight factor
CCT	Correlated colour temperature
CFF	Critical flicker fusion
CIE	Commission internationale de l'éclairage
CMYK	Cyan, magenta, yellow and key (black)
CRI	Colour rendering index
DF	Daylight factor
DGP	Daylight glare probability
DSLR	Digital single-lens reflex camera
HDR	High dynamic range
HTML	Hypertext markup language
LCC	Life-cycle cost
LENI	Lighting energy numeric indicator
MF	Maintenance factor
NCS	Natural colour system
PV	Photovoltaics
RGB	Red, green, blue
RSMF	Room surface maintenance factor
SHC	Solar heating and cooling
SPB	Simple payback period
TCO	Total cost of ownership
UGR	Unified glare rating

SYMBOLS

A	Total useful floor area of the building (m^2)
$b_{glazing}$	Total of the width of the transparent glazing of all windows (m)
d	Longer dimension of the calculation area (m)
d_{room}	Depth of space (m)
$C_{daylighting}$	Total cost of daylighting systems (€/m^2)
$C_{electricity}$	Cost of electricity in the area where the building is located (€/kWh)
$C_{lighting}$	Total cost of retrofitted electric lighting system (€/m^2)
$C_{maintenance}$	Maintenance cost, (€/m^2)
$C_{operation}$	Operation costs (€/m^2)
C_{retro}	Total cost of the retrofit project (€/m^2)
$D_{operation}$	Annual operation time (hours/year)
E	Illuminance (lux)
E_{hg}	Exterior horizontal global illuminance (lux)
$E(max)$	Highest illuminance at the surface of a diffuse sphere (lux)
$E(-max)$	Illuminance measured at the opposite side of the diffuse sphere (lux)
$E_{surround\ task}$	Horizontal illuminance surrounding the task (lux)
E_s	Scalar illuminance (lux)
E_{task}	Horizontal illuminance on task (lux)
E_v	Vector illuminance (lux)
$E_{vertical\ eye}$	Vertical illuminance on the eye (lux)
E_{vgs}	Vertical sky illuminance on façade (lux)
E_{wp}	Horizontal illuminance at work plane height (lux)
foc	Luminance ratio between the exterior vertical sky illuminance and the exterior horizontal global illuminance
F_C	Constant illuminance factor
F_{cc}	Efficiency factor of the constant illuminance control
F_D	Daylight dependency factor

F_O	Occupancy dependency factor
L	Luminance of luminaire in the direction of the observer's eye (cd/m^2)
L_b	Background luminance (cd/m^2)
$L_{ceiling}$	Luminance of the ceiling (cd/m^2)
L_{task}	Luminance of task (cd/m^2)
L_{ergo}	Luminance surrounding the task in the ergorama (cd/m^2)
$L_{(p)}$	Luminance of point on perfectly diffusing white sphere (cd/m^2)
L_{pano}	Luminance surrounding the task in the panorama (cd/m^2)
L_s	Luminance of a glare source (cd/m^2)
L_{walls}	Luminance of the walls (cd/m^2)
p	Maximum grid cell size (m)
P	Guth's position index
P_{ci}	Standby power for the luminaire controls (W)
P_{em}	Total installed input charging power of the emergency lighting luminaires in the room or zone (W)
P_i	Maximum luminaire power (W)
P_{ei}	Luminaire emergency battery charging power (W)
P_n	Total installed lighting power in the room or zone (W)
P_{pc}	Total installed parasitic power of the controls in the room or zone (W)
Ra	Colour rendering index (also called CRI)
t_D	Daylight time (h)
t_e	Battery charge time only (h)
t_N	Daylight absence time (h)
t_s	Time step (hour/month/year)
W	Annual energy requirement for lighting (kWh)
W_t	Energy per time step (W/t_s)
$W_{L,t}$	Total energy for illumination (W/h)

$W_{P,t}$	Total energy for standby (W/h)
$\alpha_{view,space}$	Width of the view (m)
ρ	Reflectance
$\tau_{v,\ n\text{-}n}$	Normal/normal transmittance
$\tau_{v,\ n\text{-}dif}$	Diffuse part of light transmittance
ω or ω_s	Angular size of a glare source (sr)

DEFINITIONS

Some definitions are directly retrieved from standard SS-EN-12464-1 (2011).

Activity area
Area within which a specific activity is carried out.

Background area
Area adjacent to the immediate surrounding task area.

Colour rendering index (CRI)
Index designed to express synthetically a quantitative evaluation of the differences in colour between eight test colours lit directly by the standard illuminant D65 and by the same illuminance transmitted through the window, shading device or electric lighting system.

Extreme task position
Task position in a room representing an ‘extreme’ situation in terms of daylight or electric lighting.

Flicker index
Relative measure of the cyclic variation in output of various sources at a given power frequency. It takes into account the waveform of the light output as well as its amplitude.

Immediate surrounding area
Band surrounding the task area within the visual field.

Task area
Area within which the visual task (computer, paper based or other) is carried out.

Transmittance
Ratio of transmitted to the incident flux.

Typical task position
Task position in a room representing a ‘typical’ or ‘representative’ light situation.

FIGURES

TABLES

“I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be.” Lord Kelvin, 1883

1. Introduction to monitoring of light environments

This document presents a protocol to monitor the lighting environment in buildings, before and after they have been retrofitted to improve their daylighting and/or lighting energy efficiency and general light quality. The aim of this protocol is to provide guidance to the light expert to be able to assess – based on measurements – the success or failure of a lighting and/or daylighting retrofit operation.

1.1. Objectives

The main objective of this monitoring protocol is to establish a standard and repeatable method for the assessment of the overall performance of the lighting and/or daylighting retrofit of non-residential building types, taking into consideration four main aspects: 1) energy use, 2) retrofit costs, 3) photometric assessment and 4) users assessment, see Figure 1.

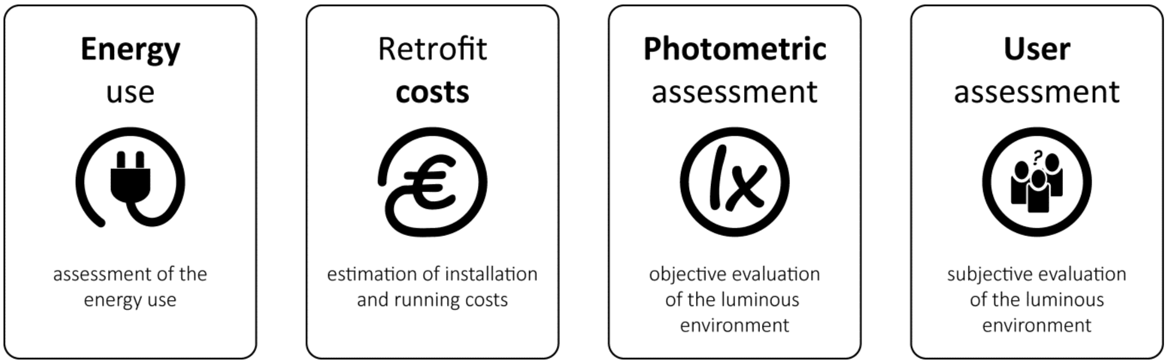


Figure 1 Four main aspects covered in this monitoring protocol.

1.2. Basic assumptions

As far as possible, monitoring the light environment before and after retrofit of the lighting and/or daylighting systems will establish the overall performance of the retrofit. When possible, the performance of the lighting and/or daylighting retrofit should be assessed under similar sky conditions by comparison with the conditions prior to retrofit. However, due to practical or time constraints, it is not always possible to monitor the building both before and after the retrofit. In this case, the building could be monitored only after the retrofit and the values obtained could be instead compared with benchmark values (for energy use) available for similar types of existing buildings. The monitoring procedure is schematically outlined in Figure 2 for the basic and comprehensive level of monitoring.

The monitoring protocol is thus applied to the pre-existing lighting situation and to the retrofitted one or only to the post-retrofit situation and compared to benchmark values. The procedure does not change when investigating the pre- or post-retrofit building. However, different approaches for the calculation methodology are proposed. These approaches are provided to overcome issues due to lack of information, impossibility in providing them or practical limitations in applying a complex monitoring protocol in real, occupied buildings.

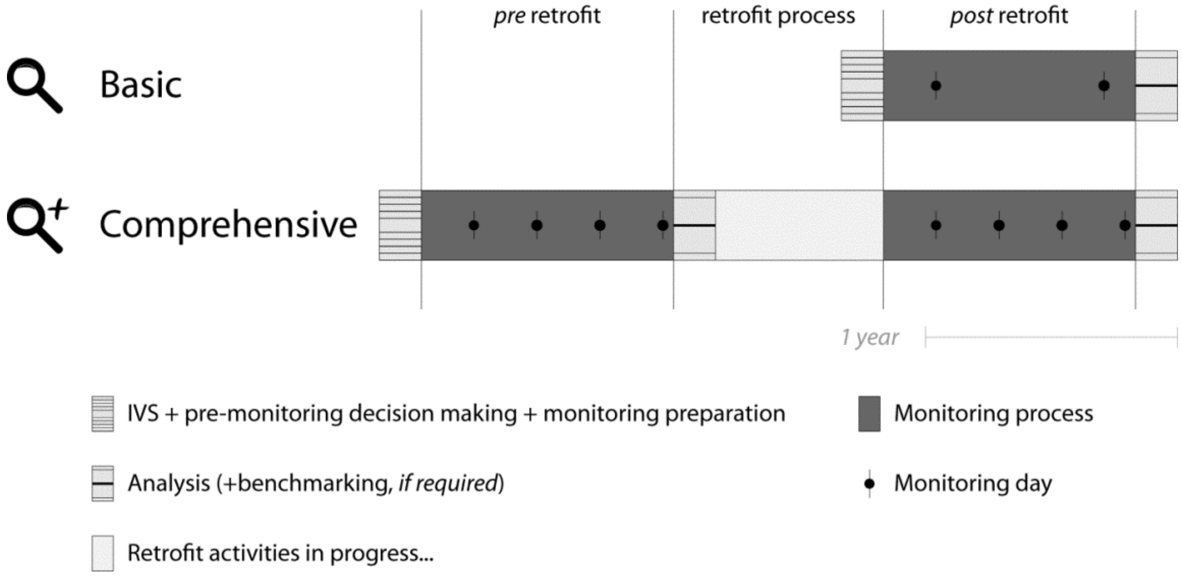


Figure 2 Schematic description of the general monitoring procedure.

1.3. Outline of this document

The complete workflow involved in preparing, performing and concluding a complex monitoring program in real buildings may consist of five phases totally, described in Figure 3. These phases determine the general workflow and structure of this document, as outlined below:

Phase 1 (Chapter 2)
Initial visit survey (IVS) of the building, in which the building to monitor is visited and geometrical and practical information about the building and retrofit are gathered in a document.

Phase 2 (Chapter 3)
Pre-monitoring decision making, in which decisions are made about the level of monitoring to perform. This decision depends on the ambition of the monitoring team, access to the building, time available for the monitoring and availability of measuring equipment.

Phase 3 (Chapter 4)
Monitoring preparation, in which information is provided on the monitoring equipment and conditions.

Phase 4 (Chapter 5)
Monitoring process, in which the rooms are monitored.

Phase 5 (Chapter 6)
Analysis, in which the performance of the lighting and/or daylighting retrofit is analyzed based on the collected data.

Note that apart from the forms/templates printed in the Appendices, the original Excel sheets with fully descriptive pull-down menus may be retrieved from the website http://task50.iea-shc.org/subtasks.

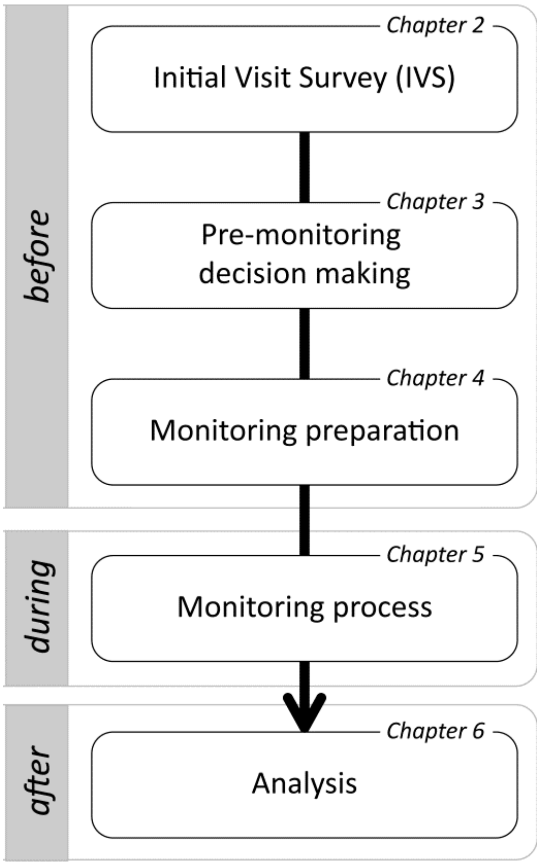


Figure 3 Description of the general workflow before, during and after the monitoring.

2. Initial visit survey (IVS)

2.1. Description of the IVS and data to be collected

The selection of a building to monitor is influenced by various considerations. When exploring monitoring possibilities, the first contact person often provides incomplete information about the building. Therefore, an initial visit may be needed in order to get a general impression of the building, and initiate contacts with the staff in charge of operating the building must be made. The IVS may also be used to collect basic information, which is necessary to further plan the monitoring, or to simply decide whether the building should or should not be selected as part of a specific monitoring program. Since the monitoring protocol focuses on individual spaces in the building, the selection of spaces to monitor is a priority and the IVS should in fact be a support for this space selection. If possible, spaces should be selected before performing the IVS based on architectural plans and sections when available. In this case, the IVS is simply used to confirm the preliminary space selections.

When selecting spaces to monitor, the following should be kept in mind:
- Select spaces where significant lighting and/or daylighting retrofit measures are applied.
- Select spaces that are representative of the most common usage of the building. For example, in an office building, select office rooms.

- Select spaces that represent a ‘typical’ situation where possible. For example, in a four-storey office building, select a typical office on a typical floor (e.g. office located in the middle of a façade on the second or third floor).
- If it is possible to monitor several spaces, select 3-4 spaces that correspond to the different usages of the building. For example, in a typical office building, you could select: one individual office, one landscape office, one regularly used conference room, one coffee or lunch room regularly used by the staff, etc.
- Select spaces that are regularly occupied by people so that users’ assessment may also be collected.
- Select spaces that are more easily accessible and where staff cooperation will be easier.
- Avoid selecting spaces that are unique and untypical of the building usage.
- Avoid selecting spaces with special features. Since the selected spaces should be representative, a space with unique features should generally be avoided.

Depending on the specific aim of the monitoring program, the focus area in the building may be different and the information of interest may also be different. Data collection forms have been developed as part of this monitoring programme and are available through IEA Task 50 website. Some of the fields may be filled before or after the actual IVS. For example, it is much less time consuming to take room dimensions from plans than to measure them in situ.

3. Pre-monitoring decision making

The starting point for any measurement is to decide what is the appropriate quantity to measure (Goodman, 2009). The second phase thus consists of determining which measurements or evaluations should be performed in order to approach - as far as possible - a comprehensive evaluation of the four main aspects covered in this protocol: 1) energy use, 2) retrofit costs, 2) photometric assessment 3) user assessment.

A basic assumption of this protocol is that the monitoring level may differ according to the ambition and budget of the monitoring team and also the possibility to access the building on a regular basis. Therefore, the protocol develops two levels of monitoring: the ‘basic’ and ‘comprehensive’ monitoring level. The basic monitoring level demands fewer days of measurements i.e. one overcast and one sunny day preferably around the equinox. In contrast, the comprehensive monitoring level requires more points of measurement as well as more frequent access to the monitored building and a longer monitoring period, including both solstices and one equinox for sunny day measurements in addition to the overcast day. The comprehensive monitoring may be difficult to carry out in practice due to time constraints, building access or even availability of measuring instruments. Therefore, the selection of the monitoring level should be considered carefully during the decision phase.

During the decision phase, the practical constraints need to be assessed in order to choose between the basic or comprehensive monitoring level. Both monitoring levels are thought to minimize the building site visits.

Decision regarding monitoring level

When planning a monitoring program and thereby deciding the desired level of monitoring, the following aspects should be carefully considered:

o Establish time, budget and responsibilities for the actual monitoring process, to make it possible to determine the monitoring level in relation to the available budget, time, access to building and measuring equipment.

- When planning a monitoring session, it is necessary to establish contact to the person in charge for the monitored building already in the decision phase, to plan where in the building it is possible to perform the monitoring regarding occupancy, company sensitive information, general access to the building, etc.

- Gather all relevant building documents for the pre-retrofit as well as the post-retrofit.

- The actual monitoring time and schedule should be based on the occupancy patterns since the time and usage is depending on building type and spaces.

- When the actual monitoring process is planned, make sure that the occupants are informed of the monitoring date, time and expected time duration for monitoring. This will in many cases reduce the occupants' dissatisfaction caused by interruptions of their daily activities by the monitoring team.

A table is provided to assist in the decision phase about the monitoring level, see Table 1.

Table 1 Comparison of basic and comprehensive monitoring levels.

		Basic	Comprehensive
Monitoring periods			
	1 overcast day		
	1 clear day close to the equinox (±1 month)		
	1 clear day around summer solstice (±1 month)		
	1 clear day around winter solstice (±1 month)		
Time of day			
	Morning or afternoon and night		
ENERGY USE			
	Estimated use of electricity for lighting		
	Measured use of electricity for lighting		
RETROFIT COSTS			
	Total cost of ownership		
PHOTOMETRIC ASSESSMENT			
Distribution	Reflectance of room surfaces		
	Glazing transmittance		
	Task position HDR photography		
	Spot luminance measurements		
Illuminance	Exterior (global and diffuse)		
	Interior in relevant spots		
	Daylight factor		
	Grid of interior horizontal illuminances		
	Horizontal illuminance on task		
	Horizontal illuminance surrounding task		
Glare	Observations (sun patches or very bright surfaces) areas, veiling reflections, …)		
	Task position HDR analysis (UGR, DGP)		
	Vertical illuminance at the eye		
Directionality	Observations		
	Detection of shadows		
	HDR of perfectly diffuse white sphere		

	Cylindrical illuminance		
Colour	Technical specifications, lamps, luminaires		
	Comparison with colour references		
	Correlated Colour Temperature (CCT)		
	Colour Rendering Index (CRI)		
Flicker	Observations		
	Technical specifications, lamps		
	Detection with mobile phone and/or rod-cloth or		
	Critical flicker fusion (CFF)		
View out	Photographs of main views		
	View description		
	Glazing-to-floor ratio		
	Glazing-to-inner-wall ratio		
	Shading device description		
	Photographs of view from relevant task(s)		
USERS' ASSESSMENT			
User	General questionnaire		
	Lighting quality assessment questionnaire		
Expert	Short assessment (text of 500 words)		

Issues to consider regarding space and occupancy

In any real-life situation, unforeseen events can occur which complicate the monitoring process. Changes to the design or layout of specific spaces can happen at any time and without notice to the monitoring team. A space might have been selected as representative during the IVS, but upon arrival for conducting photometric or user assessments, it might no longer be relevant because its function has changed or the architectural or spatial changes make a comparison with a previously monitored situation impossible. Monitoring procedures can also interfere with expectations of privacy and confidentiality for both building owners and users. Such concerns should be discussed when initiating a monitoring process and agreement about how to treat potentially sensitive data should be reached. Agreements in writing with building owners and users are best. Even if such agreement was reached, special circumstances might nevertheless interfere on the monitoring day. Users might be too busy with work and not able or willing to interrupt their activities to allow the monitoring team to take measurements or conduct a user survey. In such cases, it might be necessary to reschedule the monitoring or reduce the monitoring program.

3.1. Energy Use

Despite the fact that energy use for lighting is a concrete physical quantity, its exact computation is often complicated. Indeed, most buildings do not have a separate electricity meter for lighting and it is usually very difficult to add one without invasive interventions. Consequently, the electricity use for lighting is often estimated based on information collected about the electric lighting system, control systems, and typical operation of the space and its architecture.

The calculation needs to follow a commonly accepted procedure in order to yield reliable and comparable results. For this reason, it is suggested to base the monitoring procedure at the basic monitoring level on the European Standard prEN-15193-1 (CEN, 2014). However, note that one should aim at having everything measured that is measurable. Table 2 provides general guidelines about the basic and comprehensive monitoring level for energy use assessment.

Table 2 Required measurements for energy use assessment.

Space function	Basic	Comprehensive
Usage of the space (e.g. individual office, open space office, classroom, …)		
Space geometry		
Types of luminaire: product codes (manufacturer and model information), ballast, drivers and lamps		
Quantity of each type of luminaire		
Control system and device types		
Lamp specifications: type (fluorescent, LED, HID, etc), efficacy (lm/W), CCT (K) and CRI (R_a)		
Maximum luminaire power (W)		
Standby power (W)		
Measured electricity consumption for lighting during the monitoring day or during a longer period (kWh)		

The basic monitoring level proposes the application of the European Standard prEN-15193-1 (CEN, 2014) *calculated method* only when direct measurement is not possible. This method requires knowledge about the light fixtures (e.g. producer, model) in order to obtain the power consumption. The calculation methodology requires additional information for the energy consumption, such as geometry and room function. This information may be retrieved either through real data (comprehensive calculated method) or using the annexes of the ‘quick calculated method’.

The comprehensive monitoring level consists in the adoption of the prEN-15193-1 (CEN, 2014) *measured method*. It requires a separate electricity meter for lighting in the investigated building. The electricity meter should record the electricity consumption for lighting during each complete day of measurement. Finally, while the basic monitoring requires a minimum of one visit to the site, but does not require invasive intervention, the comprehensive monitoring demands the installation of a separate electricity meter for lighting (when not already installed), but provides actual data on the energy consumption. The selection of monitoring level is determined by practical possibilities and constraints rather than by the expert’s will or ambition.

Parasitic losses during standby and for control systems, as well as charging of the batteries for emergency lighting must be included in this process. As measurements can sometimes be difficult to conduct in practice, other appropriate means are suggested in the monitoring protocol, including e.g. readings on separate electricity meters for lighting (best available option), a wattmeter connected to a light fixture, etc. The method of data collection and its reliability should be stated in the monitoring report.

The measurements should be extrapolated to the whole year. When continuous logging is not possible, the measurement period may include three representative days during the year (close to an equinox and the summer and winter solstices). Measured values are then extrapolated for the relevant period (e.g. summer solstices values are used for the three months of summer). The occupancy schedule should always be considered, e.g. if the space or building is not occupied during the summer holidays. In such case, the electricity consumption for lighting should consist only of the parasitic losses and emergency lighting, where applicable. Similarly, the use of control systems should always be included. In general, some freedom is left in the determination of the measuring method, as long as the methodology is reported and the results reasonably represent the actual electricity use for lights. In case of more significant obstacles in collecting the electricity use data, the use of the Lighting Energy Numeric Indicator (LENI) expressed in kWh/m^{2}yr, is suggested in prEN-15193-1 (CEN, 2014). Please note that this method typically overestimates the electricity use.

3.2. Retrofit costs

The cost of the lighting or daylighting retrofit should be analysed and reported as part of this monitoring protocol by asking the building owner to provide this information. However, a detailed cost analysis entails collecting a large amount of information (retrofit cost, running costs including electricity use and maintenance, increment in running and electricity costs, etc.), which is beyond the scope of the present protocol. This information is also difficult to obtain in many cases or simply not available shortly after the retrofit (e.g. electricity and maintenance costs are not known yet). Therefore, at the basic monitoring level, it is suggested to estimate the retrofit costs by using the Relight Tool developed as part of IEA-SHC Task 50 -Subtask C. However, at the comprehensive monitoring level, the following information should be collected:

- Total cost of the retrofit project;
- Total cost of retrofitted electric lighting or daylighting systems;
- Cost of electricity in the area where the building is located;
- Maintenance cost;
- Annual operation time.

This information will allow calculating:

- Operation costs;
- The total cost of ownership (TCO);
- Life-cycle cost (LCC).

The total cost of ownership (TCO) is a financial estimate intended to help buyers and owners determine the direct and indirect costs of a product or system. A TCO analysis includes total cost of acquisition and operating costs.

The life-cycle cost (LCC) refers to the TCO over the life of an asset. Typical areas of expenditure which are included in calculating the whole-life cost include planning, design, construction and acquisition, operations, maintenance, renewal and rehabilitation, depreciation and cost of finance and replacement or disposal. Costs could also include the environmental and social costs which are more difficult to quantify and assign numerical values. In this protocol, only the acquisition, maintenance and operation costs are considered.

3.3. Photometric Assessment

The photometric assessment pursues the goal of providing information about light quality in the spaces. Lighting quality is much more than just providing an appropriate quantity of light (IEA, 2010). Other factors are potential contributors to lighting quality, e.g. illuminance uniformity, luminance distribution, light colour characteristics and glare (Veitch & Newsham, 1998). This monitoring protocol covers the measurements of detailed, objective photometric quantities, identified by previous research, as described in Table 3. In addition, the appropriate timing of measurements for the basic and comprehensive monitoring levels are suggested in Table 3 and discussed in the next chapter. These key parameters of lighting and daylighting quality are selected based on previous research in this field, see e.g. Ruck, et al. (2000), Liljefors & Ejhed (1990), IEA (2010) and SS-EN-12464-1 (2011).

Table 3 Required measurements for the photometric assessment of the light environment.

		Basic	Comprehensive
1	**Distribution**		
	▪ Reflectance of room surfaces		
	▪ Glazing transmittance		
	▪ Task related[1]: HDR (fisheye) photography of the task (including a grey, evenly illuminated reference surface placed in the scene)		
	▪ Task related spot luminance measurements of: o walls (L_{wall}) o ceiling ($L_{ceiling}$) o work task, e.g. task (L_{task}) o ergorama (L_{ergo}) o panorama (L_{pano})		
2	**Illuminance**		
	▪ Exterior horizontal global illuminance (E_{hg}) - overcast conditions only		
	▪ Exterior vertical sky illuminance on the façade (E_{vgs}) - overcast conditions only		
	▪ Interior horizontal illuminance at work plane height along a central line with respect to window (5-6 points) and four additional points in dark corners - overcast and sunny conditions		
	▪ Interior horizontal illuminance at work plane height according to a tight grid - overcast and sunny conditions		
	▪ Task related: horizontal illuminance on task (E_{task}) – overcast and sunny conditions		
	▪ Task related: horizontal illuminance surrounding task ($E_{task\ surround}$) – overcast and sunny conditions		
3	**Glare**		
	▪ Observations (detection of sun patches, areas of high luminances and reflexes)		
	▪ Detection of veiling reflections		
	▪ Task related: HDR (fisheye) photography of the task (including a grey, evenly illuminated reference surface placed in the scene)		
	▪ Task related: Vertical illuminance on the eye ($E_{vertical\ eye}$)		
4	**Directionality**		
	▪ From the middle of room: observations and		

[1] Task related means that the measurements are performed in relation to a specific task position. For example a typical and extreme task positions should be selected, see definitions at the beginning of this document. In the case where there is no specific task position, a typical sitting or standing position could be selected. In any other case, the centre of the room should be selected.

	detection of shadows		
	▪ From the middle of room: HDR photography of a perfectly diffuse white sphere (one picture from each side of the sphere)		
	▪ From the middle of room: cylindrical illuminance		
5	**Colour**		
	▪ Technical information about the installed lighting system		
	▪ Colour of main surfaces by comparison to a colour chart		
	▪ From middle of room: correlated colour temperature (CCT)		
	▪ From middle of room: colour rendering index (CRI)		
6	**Flicker**		
	▪ Observations		
	▪ Technical information about the installed lighting system		
	▪ Detection with mobile phone device and/or pen-cloth method		
	▪ Critical flicker fusion (CFF)		
7	**View**		
	▪ Photographs of main views		
	▪ Description of scene viewed		
	▪ Glazing-to-floor ratio		
	▪ Glazing-to-inner wall ratio		
	▪ Technical information about the shading device(s)		
	▪ Task related: photographs of views through window(s) from tasks		

3.4. Users' assessment

The photometric assessment has the advantage of providing objective and comparable information about the investigated space. Nevertheless, a light environment presents a complexity which is difficult to fully describe with the photometric assessment alone. The investigation of users' experience and opinions is a valuable complementary tool for a better understanding of this complexity. The opinion of the occupants also helps to discover local or transient unpleasant occurrences (e.g. glare from daylight, erratic response of the automatic control system, etc.), which are hard to pinpoint when visiting and monitoring the space during a few days in a year. Table 4 summarizes the information about users' assessment that should be collected during monitoring.

Table 4 Required measurements for the users' assessment.

		Basic	Comprehensive
Time - When to monitor?			
	Information collected while performing the photometric assessment		
Parameters - What to monitor?			
1	Users' assessment		

	▪ General questionnaire		
	▪ Interviews		
2	Expert assessment		
	▪ Collected in a written form (500 words)		
Subjects – How many subjects are needed?			
	General questionnaire	≥ 15	≥ 15
	Interviews		minimum 6 ideally ≥ 12
	Lighting expert	≥ 1	≥ 1

During the decision phase, it is necessary to collect some background information about the approximate number of users and time available for data collection. In fact, the application of the basic or comprehensive monitoring level is also determined by time and sample size issues.

General Questionnaire

The general questionnaire is an instrument developed within this IEA SHC Task 50 with the purpose of obtaining a general understanding of the light environment as perceived by the users. It combines closed and open questions. The questions involve both daylight (e.g. glare, sun patches, etc.) and electric lighting (e.g. uniformity, use of control systems, etc.). This questionnaire can be filled in less than five minutes and does not require major efforts from the interviewer or the interviewee. To obtain meaningful results, at least 15 subjects are required to answer the questionnaire. The general questionnaire output is the average score for each question. Since no complex statistics are applied, the reader should qualitatively – rather than quantitatively – consider the results.

Interviews

In general, open and semi-structured interviews are powerful instruments, but before choosing this form of evaluation tool, the expert should consider the following constraints during the decision phase:

- Privacy concerns: not all interviewees may agree on audio recording.
- Time constraints: a single semi-structured interview takes about ten minutes, but the length could vary widely, since the interviewee should be left free to express him/herself.
- Number of subjects: being a time-consuming activity, there may be a tendency in reducing the number of interviewees. Previous studies suggest that six interviews may show basic elements of the theme, but the saturation of information is generally reached with over 12 interviews (Guest, Bunce, & Johnson, 2006).
- Need for a voice recording transcription software: using voice recording transcription software for the audio recording is a time-saving strategy, but this type of software entails license costs.
- Time constraints in the post-elaboration: the amount of generated data is usually large, which means several hours of work for the coding, categorization and analysis.

Expert appraisal

Assuming that the expert conducting the monitoring process is an expert in the lighting field, his/her opinion is a valuable instrument for evaluating the quality of the lighting retrofit. The field appraisal is probably the best way to identify or predict the success of a lighting installation. The expert appraisal consists of free text of maximum 500 words.

4. Monitoring Preparation

This section describes the preparation planning of building visit and arrangements with building owners and users.

4.1. Listing and preparation of monitoring equipment needed

This section provides recommendations related to the monitoring equipment and number of instruments needed. For more detailed information about exterior measurements and instrumentation requirements, guidelines and recommendations on data quality control, archiving and dissemination, consult the CIE published Guide to recommended practice of daylight measurements (CIE, 1994).

Table 5 presents a suggestion for measuring equipment needed for the basic and comprehensive monitoring. Note that the number of instruments required depends entirely on the type and size of room(s) to monitor. It is a good idea to make a complete list of the monitoring equipment used and to make several copies of this list, which can be carried around as a checklist in order to avoid losing or forgetting instruments on site. Also, all instruments should fit into a large solid bag with handles, which can be carried around. It is also a good idea have other items in this bag such as office stationary, paper, coloured pens, scotch tape, masking tape for marking the floor, erasers, paper clips, spare sets of batteries for the sensors, etc., since measuring in situ always requires some form of adjustments.

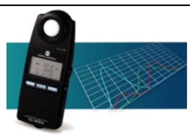
For energy use, we suggest to monitor occupancy patterns by using a temperature sensor on the lamps if possible even at the 'basic' monitoring level. The temperature of the lamp rises immediately after being turned on and can thus provide a profile for occupancy over time. A temperature logging sensor which can be placed just above the lamp housing or on the LED driver works really well and does not need wiring.

In the part about the photometric assessment, we suggest using good quality, 'ordinary' digital single lens reflex (DSLR) cameras but note that there exist companies providing cameras that are pre-calibrated and compatible with HDR analysis software for luminance analysis, see for example Photolux, TechnoTeam, etc.

Table 5 Required measuring equipment at the basic and comprehensive monitoring level.

		Basic	Comprehensive
	General equipment		
	Notepad		
	Pen(s) in different colours		
	Hand calculator		
	Double sided tape		
	Masking tape		
	Scotch tape		
	Paper clips		
	Laptop with internet connection		
	1 mobile phone with imbedded camera		
	Bag to carry equipment 		

	Architectural plans and sections of building and monitored room(s) (sufficiently large for annotations)			
	1 measuring tape			
	1 long measuring tape (50 m)			
	1 level to adjust camera position			
	Clamps to fix equipment			
1	Energy use			
	Temperature sensor for logging the operation of light sources via an on/off-temperature profile			
	Separated energy meter for electricity for lighting			
	Wattmeter with plug			
	Voltmeter			
2	Retrofit costs			
	Relight software			
3	Photometric assessment			
	1 reference reflector			
	Reference grey surface			
	1 reference colour chart			

	1 hand-held lux meter (interior)			
	1 hand-held lux meter (exterior)			
	1 good quality digital camera (preferably Nikon or Canon) for HDR photography (with 1 wide angle and 1 fisheye lens)	 		
	1 remote shutter control			
	1 tripod, preferably with integrated levels			
	1 small laser pointer mounted on camera to adjust position			
	1 hand-held luminance meter			
	1 perfectly diffusing white sphere 120 mm			
	1 hand-heldcolourimeter			
	1 CFF meter			
4	Users' satisfaction			
	General questionnaire (1 copy/participant per day)			
	Software for statistical elaboration			

The monitoring equipment may differ from the list provided in Table 5 so a specific description of the monitoring equipment should be provided including information on:

- Position of interior measurement points

- Monitoring equipment (date of calibration, calibration error, V(□) match error, cosi response error, fatigue error)
- Data acquisition system when used (manufacturer, type, data acquisition software)

The estimated overall accuracy of the measurements should be given, which is mostly based on the information provided by the manufacturers of the monitoring and data acquisition equipment

Exterior illuminance measurements

When conducting exterior measurements, the following should be kept in mind:

- Sensors should be Vλ corrected and cosine-corrected by rotation symmetry and only be dependent on the angle of incidence and independent of the azimuth angle.
- Sensors should have a linear response with increasing illuminance.
- Sensors should be accurate in the illuminance range 0 – 100,000 lux up to 150,000 lux, depending on the daylight availability at the location where the monitoring takes place.

It is also preferable that the exterior illuminance sensors are waterproof and able to maintain a stable temperature to prevent condensation and ice coating, see also (CIE, 1994). However, this is hardly a problem when using hand-held instruments since the instruments are used for a very short period of time and normally not under rainy or snowy conditions.

4.2. Description of the monitoring process to be applied

Once the main decisions have been taken about the building and rooms to monitor, the monitoring level (basic or comprehensive), necessary task positions and measuring points, it is time to start preparing the monitoring sessions more concretely. The first step consists of gathering the necessary equipment, sending instruments for calibration if needed, and preparing a schedule for the monitoring procedure. This chapter provides support to ease this process by giving recommendations and more detailed information related to the monitoring equipment and procedure.

Once the monitoring equipment is ready, it is a good idea to prepare a description of the monitoring procedure explaining the timing and duration of each measured parameter as a function of level of the selected monitoring level (basic or comprehensive). Table 6 presents a general outline of a typical monitoring day. As there are a large number of parameters to be measured, it is perhaps a good idea to carry this list as a checklist to make sure that nothing is forgotten once on site. A minimum of one day is necessary for each monitored space but of course, if anything goes wrong during the monitoring day (e.g. meter out of function, drastic change in weather conditions, etc) then it is necessary to plan staying on site one or two more days in order to complete the measurements.

Table 6 Example of monitoring sequence and procedure.

Suggested time		**Additional information**
BEFORE monitoring:		
	Acquire measuring instruments	
	Have all instruments calibrated	
	Check batteries	
	Checklist all instruments in the bag	
DURING		

monitoring:		
8:30	Arrival on site	
8:30	Take note on changes in room conditions	[movable systems, movable curtains, external obstructions, ground conditions (snow), etc.]
	Take note on weather conditions	[clear, hazy, overcast, partly overcast, with sun, etc.]
	Estimate sky cover	Expressed as x eights of the total sky dome: [x/8]
	Complete/correct IVS template	
9:00	Distribute user assessment questionnaires	
	Collect space information and information on usage	
9:30	Mark grid and measuring points on floor	
10:30	Determine exterior meter position	
NOON measurements:		
	Estimate dimming level (if present)	
11:00	Measure distribution	
	Measure glare	
12:00	Measure illuminance	(electric light + daylight)
	Measure illuminance	(daylight only – if possible)
13:00	Measure directionality	
	Measure colour	
	Measure flicker	
	Measure view	
14:00	Collect technical information about lighting system(s)	
AFTERNOON measurement:		
	Estimate dimming level (if present)	
15:00	Measure distribution	
	Measure glare	
15:30	Measure illuminance	(electric light + daylight)
	Measure illuminance	(daylight only – if possible)
16:00	Measure directionality	
	Measure colour	
	Measure flicker	
	Measure view	
16:30	Collect user assessment questionnaires	
	Collect window information	
17:00	Take note on changes in room conditions	[movable systems, movable curtains, external obstructions, ground conditions (snow), etc.]
	Take note on weather conditions	[clear, hazy, overcast, partly overcast, with sun, etc.]
	Estimate sky cover	[x/8]

	Collect expert opinion	
18:00	Measure illuminance	(electric light only)
18:30	Checklist all instruments in the bag	
AFTER monitoring:		
	Backup and organisation of measured data	

5. Monitoring Process

This chapter provides detailed information about the monitoring process. The actual monitoring is much easier to carry out when the session is carefully planned. This helps streamline the data collection and avoids using too much time on site or forgetting information.

This monitoring protocol provides a description of important parameters in terms of timing and method (i.e. when each item should be monitored and how). The descriptions provided here follow the 'comprehensive' level. The monitoring process may be simplified following a more 'basic' level of monitoring to adjust to time and budget constraints.

5.1. Points of attention in the monitoring process

The monitoring program consists of the collection of data through measurements and observations. Some aspects that are important in this program are mentioned in the following paragraphs.

Duration of monitoring

In general, measurements should be taken as fast as possible.

Registration of the weather conditions

In order to be able to extrapolate the results to other times of the year, it is necessary to record at least manually the weather conditions during the test period. Generally, it will be sufficient to describe the weather conditions such as clear, hazy, overcast, partly overcast with sun, etc. In this way, the retrofit performance can be related to the environmental conditions under which the monitoring was performed.
The registration of weather conditions should be done at the start of the monitoring process, and repeated during the day as the weather conditions change.

At the 'comprehensive' monitoring level, measurements under a clear sky with direct sun should ideally be conducted several times during an entire day atthe following times of the year:

- winter solstice (+/- 4 weeks, 1 day);
- equinox, either spring or autumn (+/- 4 weeks, 1 day). In locations where there is a significant difference between the spring and autumn equinox, it is recommended to measure during both equinoxes;
- summer solstice (+/- 4 weeks, 1 day).

Thus, the 'comprehensive' monitoring program will cover at least a six months period (i.e. the winter and summer solstice, spring or autumn equinox) with clear sky conditions for each room condition (pre- and post-retrofit), i.e. at least one year totally.

In the case where the 'basic' monitoring is selected, the clear day measurements should preferably concentrate around the spring or autumn equinox (+/- 4 weeks, 1 day).

5.2. Detailed information about the data collection

5.2.1. Energy use

5.2.1.1. Lighting system data

Features regarding the lighting system need to be collected. In particular, the following characteristics need to be reported according to prEN-15193-1 (CEN, 2014):

- Types of luminaires, identified by product reference codes when in their original packages, or the types of luminaires, ballast, LED drivers and lamps when changes occurred to the original luminaire package;
- Quantities of each specific luminaire;
- Control technique and device types.

The energy use data for each of the luminaires must be collected:

- Maximum luminaire power (P_i) [W];
- Standby power for the luminaire controls (P_{ci}) [W];
- Luminaire emergency battery charging power (P_{ei}) [W].

Whenever the luminaire has an accessible plug, the information may be directly measured on site using a voltmeter and/or an electricity meter. Nevertheless, in most practical cases, this possibility does not exist and the features can be retrieved from the luminaire manufacturer data sheets. For this purpose, it is strongly recommended to bring a laptop with an internet connection during the monitoring or retrieve this information from the Internet after the first monitoring day. The declared values are given for standard reference test conditions in the document prEN-15193-1 (CEN, 2014).

5.2.1.2. System design data

System design data refers to the impact of occupancy, daylight and maintenance factors on the energy consumption. These factors are considered in the calculation procedure through the following variables:

- F_O : occupancy dependency factor
- F_D : daylight dependency factor
- F_C : constant illuminance factor

The calculation procedure including these factors is explained in the standard prEN-15193-1 (CEN, 2014).

During the monitoring preparation, it is important to know that the final calculation requires knowledge of the following features:

- For the determination of the occupancy dependency factor (FO)
  - Building type (e.g. educational, etc.);
  - Space function (e.g. classroom, lecture hall, etc.);
  - Lighting control system typology, in particular whether the lighting is turned on centrally (e.g., single automatic system, time schedule, timers, etc.) or not;
  - Specification about the lighting control system (e.g. presence sensors, absence sensors, daylight harvesting, etc.).

- For the determination of the daylight dependency factor (F_D)
  - Inner length of walls;

- Clear ceiling height;
- Net surface area;
- Detailed features of windows;
  - Window sill height;
  - Window head height;
  - Window dimensions including frames;
  - Glazing dimension (excluding frames);
  - Obstructions;
  - Type of shading devices;
  - Etc.

- If present, detailed featured of the roof lighting:
  - Raw area of the rooflight;
  - Area lit by daylight from the rooflight;
  - Transmittance of the diffusive rooflight glazing without shading;
  - Transmittance of the diffusive rooflight glazing with shading;
  - Reduction factor for frames and subdivisions;
  - Reduction factor for pollution;
  - Reduction factor for non-vertical light (0,85 if not available);
  - Roof slope angle.

Much of this information is collected either in the IVS form or in the monitoring program forms.

- For the determination of the constant illuminance factor (F_C)
  - Efficiency factor of the constant illuminance control (F_{cc}) if known
  - Maintenance factor (MF).

5.2.1.3. Operating conditions

The operating conditions are defined by the typology and space usage. It is very important at this stage to determine the occupancy pattern of the space. The standard occupancy patterns are given in CSN EN 15251 (2007), but it is suggested to assess it through interviews, logging of presence sensors (when available), thermal sensors on the lamps or, if possible, by using an appropriate survey system (presence sensor, CO_2 concentration sensors, etc.).

5.2.1.4. Electricity use for lighting

When a separate metering of the electricity use for lighting is available or can be installed, the actual consumption over each monitoring day can be recorded. The consumption in kWh is the output data, which may be extrapolated to one year with knowledge about the typical occupancy patterns.

5.2.2. Photometric assessment

In a real building, both daylight and electric light may be simultaneously used during the day. The electric lighting system may even be dimmed to a certain level, depending on the daylight contribution when a photoelectric dimming system is installed. In general, the photometric and users' assessment should be carried out under 'typical' conditions i.e. conditions typical of a normal utilization of the lighting-daylighting systems. The monitoring of the electric lighting and daylighting contributions should also be carried out separately as far as possible, which means performing at least two or even three series of measurements per day i.e.

a. During daytime - with electric lights fully off (only daylight – especially relevant for measurement of the daylight factor);
b. During daytime – with electric lights fully or partially on representing the ‘typical’ conditions of utilization (with electric light and daylight);
c. During night time - with electric lights fully on and no daylight.

These measurements may be recorded the same day at different times. For example, condition c) may be recorded after the sun set when there is no daylight. This makes it possible to determine the contribution of electric lighting separately. However, care should be taken to make sure that the electric lighting system has reached stability in output in this case. For fluorescent lighting, this entails having the lights on for a while i.e. about 30 minutes before proceeding to measure.

In addition to the question of when and what to monitor, it is essential to determine the exact measuring points and task positions in the rooms. The task position could differ greatly in each room and each building. For example, in a large landscape office, the task position should either be a typical position of a person or a position that might obviously create glare or illumination problems. Such positions are usually close to the façade and/or facing façade orientations, where low sun positions often occur (east or west facing facades). In a classroom, it may be important to consider a task position representative of typical pupil positions, but this may be difficult to determine due to highly varying seat arrangements in modern classrooms. The IVS should allow for determining one or even two critical task positions to assess in each room prior to commencing the monitoring process.

5.2.2.1. Distribution

Reflectance of surfaces

The reflectance of all main surfaces in each room (walls, floor, and ceiling) should be measured. This can be done by using one of two methods described in Velds & Christoffersen (2001).

Glazing transmittance

Glazing transmittance should also be determined using one of the two methods described in Velds & Christoffersen (2001).

Luminance of walls and ceilings (L_{wall} and $L_{ceiling}$)

At the comprehensive monitoring level, a luminance meter can be used to spot measure the luminance on the ceiling and lateral walls using a spot luminance meter in order to estimate the luminance ratios within the room. Luminance values on the side walls should be taken at eye-level, both seated and in a standing position (1.2 and 1.6 m from the floor) for a typical and one or two extreme task positions. These values could also be compared to values extracted from the HDR photos, provided that tests have been made to ensure their reliability.

Luminance of task (L_{task}), ergorama (L_{ergo}) and panorama (L_{pano})

Spot luminance should be taken of the task (computer screen or other) compared to luminance in the immediate and remote surroundings. When it is difficult or impossible to precisely determine what consists the immediate and remote surroundings, the luminance within the ergorama and panorama should be measured instead. 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 (Meyer, Francioli, & Kerhoven, 1996), see Figure 4. According to Meyer, Francioli, & Kerhoven (1996), maximum luminance ratios of 1:3 in the ergorama and 1:10 in the panorama should be respected. Note that the real panorama is usually not perfectly circular due to the presence of our nose which cuts off a part of the lower visual field. In addition, the shape of the external limit of the visual field is usually not a perfect circle since the field is normally slightly larger than high due to the fact that we have two eyes.

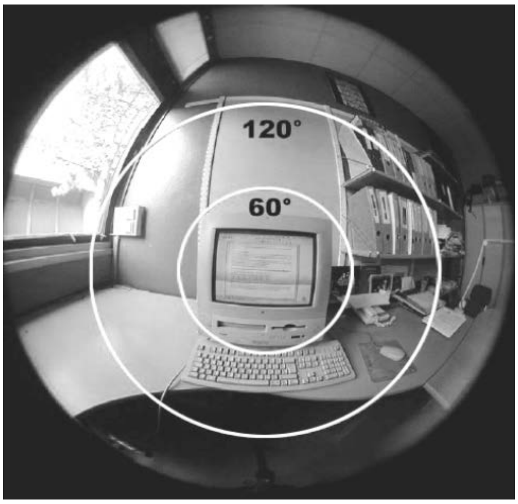


Figure 4 Picture showing the ergorama (60°) and panorama (120°), according to Sutter, Dumortier, & Fontoynont (2006).

Information on luminance values and luminance distributions can be recorded on HDR fisheye or non-fisheye photographs from the task position(s), see for example Figure 5.

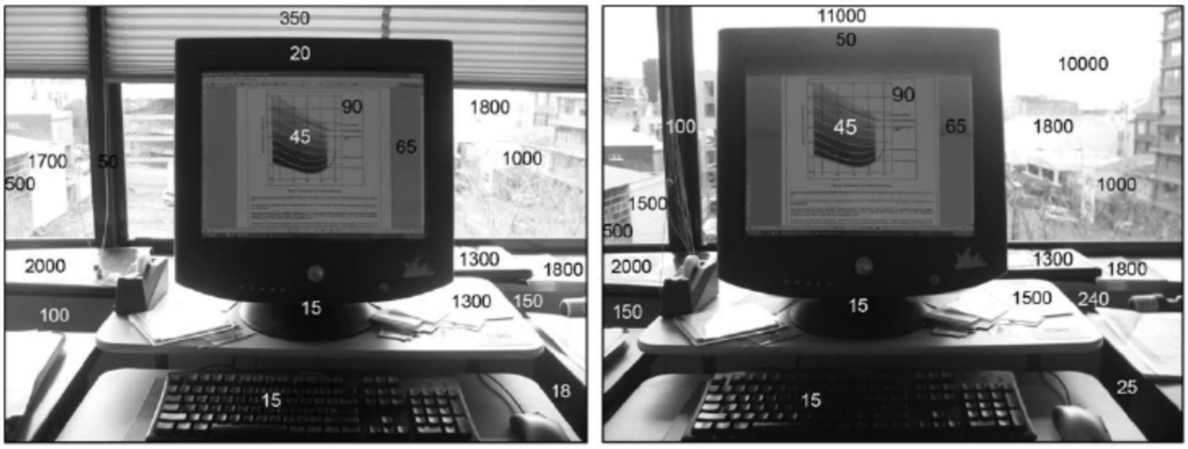


Figure 5 Example of photographs of a task with superposed luminance spot measurements, by Madsen & Osterhaus (2014).

HDR fisheye photography

HDR photography, preferably with a fisheye lens, or with a wide angle lens should be taken at the typical and one or two extreme task positions, in order to record the luminance distribution around the task area. In order to check the validity of luminance values in this picture, it is recommended to measure the luminance of an evenly illuminated reference grey surface located in the scene. Figure 5 shows an example where the grey reference surface is fixed at the top of the computer screen, which is the recommended method. The measurement and comparison of spot luminance measured values with the software-generated integrated image from eight or more individual images at different exposures provides some confidence in the luminance mapping procedure.

5.2.2.2. Illuminance

Under overcast sky conditions, horizontal illuminance should be measured indoors and at task height, at the same time as the exterior global illuminance is measured. The relation between these two values allows determining the daylight factor (%), which is a standard metric used in many standards and certification systems.

When using a hand-heldlux meter for the exterior as well as interior measurements, care should be taken in order to ensure that:

- The lux meter is held at a horizontal position (use a level);
- The lux meter is not shaded by the person in charge of the measurements;
- The lux meter has been calibrated prior to monitoring;
- The lux meter integrates a cosine-corrected V(λ) illuminance sensor;
- The appropriate scale for the readings is available (up to 150 000 lux for exterior measurements) and noted (most lux meters allow adjusting the scale for outdoor measurements).

Exterior global illuminance on a horizontal plane, E_{hg}

Exterior sky measurements can be carried out using a hand-held lux meter or an exterior sensor, mounted on a horizontal plane with an unobstructed horizon (e.g. roof or parking space remote from surrounding building obstructions) in orderto measure horizontal global illuminance. If there are significant external obstructions, the measurements should be corrected according to the recommendations proposed in Velds & Christoffersen (2001). This correction is only applicable to CIE overcast sky conditions.

Interior measurements

Horizontal illuminance on the work plane (E_{wp})

The quantity and distribution of the horizontal illuminance can be monitored by a number of illuminance sensors or alternatively, by hand-held lux meters. The actual number depends on several aspects, such as the availability of sensors or lux meters, the system to be tested, the number of light zones to cover, the size of the window opening, the level of monitoring performed, etc.

In the case of ‘basic’ monitoring, a line of measurement points should be drawn from the window center towards the back of the room. Normally, the first measurement is taken at 0.5 m from the window and then every meter towards the back of the room. It is necessary to have more measurement points close to the window where daylight varies significantly while fewer points are needed in the back of the room. Then even when the ‘basic’ monitoring is performed, it is recommended to take at least four points in the areas that are darker (for example close to the four corners of the room).

For the ‘comprehensive’ monitoring level, a formula proposed in the European Standard SS-EN-12464-1 (2011) to determine a grid system to measure illuminance may be used.

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).

Horizontal illuminance task (E_{task}) and around the task ($E_{task\ surround}$)

At the 'comprehensive' monitoring level, the illuminance at and around the task for a typical and one or two extreme task positions should also be recorded at work plane height.

Uniformity of illuminance

Uniformity of lighting in space can be desirable or less desirable depending on the function and type of activities performed in the space. Complete uniform lighting is usually undesirable whereas uneven illumination may cause discomfort. Lighting standards and codes usually provide recommended illuminance ratios between the task area and its surroundings, see e.g. SS-EN-12464-1 (2011), CIBSE (1994, 2002), IESNA (2011).

5.2.2.3. Glare

Observations

At the 'basic' and 'comprehensive' monitoring levels, monitoring through observation can take place in unoccupied as well as occupied rooms. It is advisable that the responsible expert may be present in rooms during a significant part of the testing period, because of the very dynamic behavior of daylight (if present), especially under clear sky conditions. This will additionally save time in the analysis of the recorded data, when decisions have to be made about whether data are valid, and which data have to be excluded. It is also preferable to take photographs during the observations, so that the evaluated lighting conditions are registered.

The responsible expert in the monitored room should note observations throughout the day, as described in the following paragraphs.

Detection of sun patches

A detection of time periods when undesirable sun patches are present in the room should be made. The information should be reported through notes, photographs or a time lapse video when available.

Detection of areas with high luminance

The recording of high luminance areas in selected rooms and testing positions should be made. Ideally, luminance measurements and luminance ratios need to be recorded for both overcast and clear sky conditions. The evaluations should be made throughout the day if possible when performing the 'comprehensive' monitoring and at least once during the day with the 'basic' monitoring level.

Detection of veiling reflections

Veiling reflections are specular reflections that appear on the object viewed and which reduce the visual task contrast. The determining factors are the specularity of the surface and the geometry between the surface, observer and sources of high luminance (e.g. luminaires, windows, bright walls). Glossy papers, glass surfaces and task screens are subject to cause veiling reflections. Veiling reflections in the space, especially on the task area, task screen or paper, should be noted.

HDR fisheye photography and vertical illuminance at the eye ($E_{vertical\ eye}$)

High Dynamic Range (HDR) images provide a complete luminance map of a scene and are thus very useful for assessing luminance distribution and glare. However, the use of these images demands knowledge of technical aspects under three steps:

1. Camera and software preparation;
2. Photographing;
3. Image processing.

For calibration of the processed image, spot luminances on a reference surface in the scene of the photographed image is needed.

Camera and software preparation

A task and a luminance meter are needed at this stage as well as a good quality digital camera with options for manual mode. The quality of the results depends largely on the quality of the technical equipment and skills used. Here are several criteria that are of importance: possibility to control settings manually - preferably without touching the camera, satisfactory resolution of the final images, possibility to use ultra wide angle (or even fish eye) lens if needed. High quality cameras like Canon or Nikon digital cameras are recommended since they normally have high quality image sensors. As the set of multiple low dynamic range images are taken during the photographing stage, it is obvious that blurred images should be prevented. Therefore a tripod is needed along with a remote shutter suitable for the camera or a software allowing control of the camera settings.

The luminance meter is needed in order to perform spot luminance measurements of a grey, evenly illuminated reference surface located in the picture. The luminance meter could also be mounted on the tripod if needed, especially when photographing is repeated several times and spot measurements are always taken from the same position. It is important to choose a correct target for point measurements with the luminance meter. A grey, evenly illuminated reference surface is ideal while very dark or highly saturated surfaces result in large errors that may affect further calibration and luminance readings from the image.

Photographing

Photographing is a process demanding skills that directly affect the quality of the final results. The photographing session should be very well planned and prepared. First, it is necessary to determine where the camera and additional equipment (if needed) should be placed, which angle of view is the best in each particular case, and whether a wide-angle or fish eye lens is needed. Photographing is usually performed using strictly defined camera settings as defined in Table 7.

Table 7 Digital camera settings for a set of HDR image photography.

Parameter	Recommended selection
White balance	Daylight or other appropriate to the case
Sensitivity	100 ISO
Aperture size, fixed	f/8, f/9, f/10
Difference in exposure values between photos taken	1 EV[2]

It is quite common for photography equipment manufacturers to express steps between exposure values for 100 ISO sensitivity, which explains why this setting is advisable. Taking a photo at each EV step helps to capture the full dynamic range of light. In addition, aperture size strongly affects the vignetting fall-offs, and increases dramatically with wider apertures. Settings different from the above should be considered carefully. Luminance spot measurements used in the HDR image calibration process could be done both before and after the photographing session or only once depending on the lighting conditions during the process. Lighting conditions should be as stable as possible but it is not always possible to maintain very stable lighting conditions with daylight.

Field studies of discomfort glare indicated that the vertical illuminance at eye level is a good indicator of glare from daylight, at least for workplaces where daylight is dominant. There is currently no standardized formula for calculating discomfort glare from daylight, but the application of the daylight glare probability (DGP) is a reasonable approach for office environments or the like.

The DGP can be measured directly using a HDR camera (mounted on a tripod) using a fish eye lens (full 180° or more) or with a HDR camera with a non-fish eye lens and an additional vertical illuminance value at eye level. Note that commercially calibrated HDR cameras might calculate the DGP directly. The DGP can also be calculated by free available software (e.g. Evalglare) through the use of the .hdr file format. In case the lens does not cover a full 180° view, an additional illuminance meter is needed to measure the vertical eye illuminance. The height and position of the vertical illuminance at the eye should be chosen to imitate the typical user's eye. This value has to be provided to the evaluating software in addition to the .hdr image.

5.2.2.4. Directionality

At the ‘basic’ monitoring level, directionality can be assessed with simple observations of light incident on objects or faces in the room.

Apart from observations, the suggested method to assess directionality in this protocol at the ‘comprehensive’ monitoring level consists of measuring luminance on a perfectly diffuse white sphere located at the center of the room or at any other point of significant interest. For example, in a classroom, the position of the teacher’s head may be of significant importance for light directionality in the 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, where the vector and scalar values can be obtained from a HDR image. This is explained further down in the section about data analysis.

[2] It is however preferable that the whole dynamic range is taken and thus we recommend that from the middle of exposure values, the full range be photographed so totally white and totally black pictures are taken at each end of the range in addition to intermediate steps.

Detection of shadows

At the ‘basic’ and ‘comprehensive’ monitoring levels, shadows in the space may be negative or positive depending on the application. A good balance between direct and diffuse light is necessary in order to see the way light falls on objects. It is worthwhile studying the shadows of objects in the monitored room: the light side of an object, the shadow side, the cast shadow and the presence of reflected light. Any abnormality or quality should be noted, since it provides indication of lighting qualities. Further information on shadows may be found in IEA (2010).

5.2.2.5. Colour

The ‘basic’ monitoring level requires a simple determination of the colours of main surfaces in the room in addition to collecting technical information about the lighting and glazing systems.

Colour of surfaces

At the ‘basic’ and ‘comprehensive’ monitoring levels, the colour of all main surfaces in the room should be determined by comparing each surface to a reference colour chart from a chosen colour system, e.g. NCS (Natural Colour System). This process consists of placing colour samples directly on the surface to assess and determine the colour by simple visual inspection. The colour code of the sample matching the colour of the examined surface should then be noted.

Note that registration of a surface colour may also be done by using an instrument, e.g. NCS colour scan 2.0 which registers the NCS colour symbol. The instrument has a built-in standard light source D56 10^0 that illuminates the surface while the instrument is placed on it. By using a colour scan instrument, some additional information may be collected, including the lightness (reflectance) of the surface, CIE lab coordinates (L, a, b), RGB, HTML and CMYK-values. This information may be especially useful if the colours of room surfaces need to be documented to prepare for a future refurbishment.

At the ‘comprehensive’ monitoring level, the colour characteristics of light in space can further be determined by directly measuring (using a hand-heldmeter) two properties: the correlated colour temperature (CCT) and the general colour rendering index (CRI) (IEA, 2010). The colour appearance of a light source is evaluated by its correlated colour temperature (CCT).

hand-held. The colour of light should be measured at a central point in the room unless some special colour variations are noticed (e.g. close to a coloured glass façade or under a special light source). In this case, colour should be measured in each zone presenting a special and unique colour rendering. Technical information about the installed lighting system should also be collected in order to obtain colour related information.

5.2.2.6. Flicker

At the ‘basic’ monitoring level, flicker can be noted by observations. At the ‘comprehensive’ monitoring level, flicker can be observed by looking at light sources through a mobile phone or other digital pocket camera that indicate whether flicker is present, proposed by Osterhaus, Stoffer & Erhardtsen (2014) and Kitsinelis et al. (2013). It appears that the more the camera image ‘moves’, the more flicker is present. Sources which exhibit little or no flicker will result in a ‘still’ image on the camera screen. When actually taking a photograph of a flickering source, stripes will be visible in the image. However, this technique cannot be used to determine flicker index or percentage.

Another method is proposed by Bullough et al. (2012) and Poplawski & Miller (2013). This method consists of waving a white plastic rod or light coloured pencil rapidly back and forth underneath the luminaire, preferably with a black cloth as background. Consistent movement speed is required and might need some practice. Flicker or stroboscopic effects are present when multiple or striated images of the pencil or rod are perceived.

Recording technical information about each light source is also suggested in order to trace back flicker information about each installation. Alternatively the critical flicker fusion (CFF) may be measured using a special instrument.

5.2.2.7. View

At the 'basic' monitoring level, the view can be evaluated with reference to the whole space. At the 'comprehensive' monitoring level, the view can be additionally evaluated for specific workplaces.

Basic monitoring level

The width of the view and the approximate view distance (depth) should be registered. The width of view is the summarized horizontal view angle of all transparent glazing portions of all windows in one facade seen from a reference point in the space. At the basic monitoring level, the width of the view may be estimated for the selected space by using the following simplified equation:

$$\alpha_{view,space} = 2 \cdot \arctan\left(\frac{b_{glazing}}{d_{room}}\right) \qquad (1)$$

where $b_{glazing}$ is the total of the width (m) of the transparent glazing of all windows, and d_{room} is the depth (m) of the space.

The outside view distance is the distance to the most distant landscape element (tree, building, etc.) and the facade seen through the window. Additionally, the view layers should be recorded i.e. 1) sky, 2) landscape and 3) ground. The reference position for checking the number of view layers and identifying the most distant landscape element is the center of the selected space at a height of 1,2 m above floor level. The height of 1,2 m assumes a sitting person. Photographs documenting the view should be taken from this position as well.

Since the access to environmental information may not always correlate with the layers of view, the access to the following information should be noted:

- location (orientation regarding water, food, heat, sunlight, escape routes, destination);
- time (environmental conditions which relate to our innate biological clocks);
- weather (need for clothing, need for shelter, heating/cooling, opportunities for sunbath);
- nature (the presence of trees, bushes, plants, insects, birds and other animals);
- people (the presence of people and their activities).

Table 8 Classification of the ability of the shading device to provide a view.

Classification	Description of the view when looking through the device
no view	A view is not possible.
not satisfactory	A view is almost not possible, only outlines can be guessed.
satisfactory	The view is significantly restricted, but contours can be seen.
good	Although the view is restricted, details can be recognized.
excellent	The view is virtually not restricted.

In addition, the glazing-to-floor and glazing-to-inner wall ratios should be determined by measurements. Finally, the quality of the view through the shading device should be described. The description should include whether a view through the shading device is possible, and to which degree the information on time, weather, nature and people can still be achieved, see Table 8.

If technical information about the shading device(s) is available, the following metrics could be registered additionally:

- the normal/normal transmittance ($\tau_{v,\ n\text{-}n}$)
- the diffuse part of light transmittance ($\tau_{v,\ n\text{-}dif}$).

If the selected space has multiple facades, at the 'basic' monitoring level the quality of the view is determined for main facade offering the best view. Rooflights are not considered in any case.

Comprehensive monitoring level

At the 'comprehensive' monitoring level, the width of the view should be measured without using the simplified equation given for the basic monitoring level. Movable daylighting systems are withdrawn when the width of the view is determined. They are only taken into account if they or other parts of the facade are obstructing the view

If the selected space has multiple facades, the quality of the view is determined for each facade separately. The comprehensive monitoring level includes the evaluation of the view for selected workplaces. Typically, one workplace close to the facade and one workplace distant from the facade should be selected, but this may differ for the specific case. As for the selected space, the width of the view, the distance of the view, the number of layers and the access to environmental information should be recorded for each selected workplace. For the height of the reference position, the typical position of the person working is used.

5.2.3. Users' assessment

5.2.3.1. General questionnaire

The general questionnaire should preferably be distributed to participants during the monitoring day. It is essential to give time and privacy to the interviewee. A good idea is to provide the questionnaires at the monitoring start, in the morning, and to collect them just before the monitoring ends. The general questionnaire is provided on paper, but an online version might be used. When using the online version, the interviewee might reply on a different day. Be sure that the day still corresponds to the monitoring period (i.e. do not use an answer given in September for the summer solstice evaluation).

5.2.3.2. Interviews

The interviewer should consider that the interview might be time consuming. A defined time plan for the day is a good idea to organize the interview sessions. Authorization for recording the interview should be requested in advance. The interviewee should be left free to express himself/herself freely. The questions should be very open (e.g., “What do you think about the daylight in this room?” and not “Do you think that this room is too dark?”) and the interviewer should avoid suggesting answers.

The answers should cover the following topics: daylight conditions, glare, room appraisal, electric lighting and lighting control system, windows and shading devices, view out. Approaching the end of the interview, if the answers do not cover some of the topics, a more direct question for the missing element can be formulated. Any additional information coming with the interviewee flow of opinions should be encouraged and recorded.

5.2.4.3. Expert appraisal

The surveyor has generally more than one occasion for visiting the site, from the IVS to the monitoring days. During these occasions, which generally occur in different seasons, it is strongly suggested to take notes of anything which draws the surveyor’s attention. This expert appraisal is then compiled with the help of the notes collected throughout the whole monitoring period.

6. Analysis and presentation of data

6.1. Energy use

The energy consumption for lighting is always measured as proposed in the European standard prEN-15193-1 Metered method 3 (CEN, 2014). When exceptional conditions prevail, e.g. electric lighting circuit is not isolable, the ‘basic’ monitoring method may use the ‘calculated comprehensive method 2’ of document prEN-15193-1 (CEN, 2014). However, when the ‘comprehensive’ monitoring method is adopted, the energy assessment should always refer to the ‘measured method’ in the standard.

In both cases, the output data is the LENI (Lighting Energy Numeric Indicator), defined as:

$$LENI = W/A \qquad (kWh/m^2 year) \qquad (2)$$

where W is the annual energy use (kWh) for electric lighting and A is the total useful floor area (m^2) of the considered space.

6.1.1. Calculated method

The annual energy use for electric lighting W is given by the contribution of a) energy for illumination $W_{L,t}$ and b) energy for standby or parasitic losses $W_{P,t}$. The calculation can be divided in hourly, daily or monthly time steps (t_s). A time step energy use for electric lighting W_t is obtained, which is the sum of illumination and parasitic power for the given time step ($W_{L,t}$ and $W_{P,t}$).

According to the ‘Calculated Comprehensive Method 2’ of prEN15193-1, the latter are calculated based upon knowledge of luminaires, lighting system and geometric data of the space. In particular:
- Installed power for illumination (P_n);
- Required power for charging the batteries of emergency luminaires (P_{em});

- Required power for standby (P_{pc});
- Occupancy, daylight supply and constant illuminance dependency factors (F_O, F_D and F_C);
- Daylight time and daylight absence time (t_D and t_N);
- Battery charging time (t_e).

The energy for illumination for a determined time step t_s is then defined as:

$$W_{L,t} = \frac{\sum \{ (P_n \cdot F_O) \cdot F_O [(t_D \cdot F_D) + t_N] \}}{1000} \qquad \text{(kWh/t}_s\text{)} \qquad (3)$$

Similarly, for the energy use for standby and batteries charging:

$$W_{P,t} = \frac{\sum \{ \{ P_{PO} \cdot [t_s - (t_D + t_N)] \} + (P_{em} \cdot t_e) \}}{1000} \qquad \text{(kWh/t}_s\text{)} \qquad (4)$$

As mentioned, the total energy consumption required for lighting - for a given time step in a room or zone of the building - is given by:

$$W_t = W_{L,t} + W_{P,t} \qquad \text{(kWh/t}_s\text{)} \qquad (5)$$

While the total annual energy consumption is calculated as:

$$W = \frac{8760}{t_s} \sum W_t \qquad \text{(kWh/year)} \qquad (6)$$

where all the rooms and zones are summed. The LENI is consequently derived (eq. 2).

6.1.2. Measured method

The total energy consumption for lighting measured during one day (Wh) is simply extrapolated for a year with some assumptions and knowledge about the occupancy patterns and ratio between overcast and clear days and then divided by the surface of the considered space.

6.2. Retrofit costs

For cost calculations, the Relight tool should be used at the 'basic' monitoring level and results should be summarized according to the standard output of the Relight tool.

At the 'comprehensive' monitoring level, the following items should be collected:

- Total cost of the retrofit project, C_{retro} (€/m^2);
- Total cost of retrofitted electric lighting or daylighting systems, $C_{lighting}$ or $C_{daylighting}$ (€/m^2);
- Cost of electricity in the area where the building is located, $C_{electricity}$ (€/kWh);
- Maintenance cost, $C_{maintenance}$ (€/m^2);
- Annual operation time, $D_{operation}$ (hours/year);
- Operation costs (€/m^2) ($C_{operation} = D_{operation} * P_n * C_{electricity}$);
- The total cost of ownership (€/m^2) (TCO = $C_{lighting}$ and/or $C_{daylighting}$ + $C_{maintenance}$ + $C_{operation}$);
- The life-cycle cost (€/m^2) (LCC = TCO * total life time).

All values should be reported as cost density i.e. € or US$/m^2 with relation to annual time (one year) or total life time assuming a normal operation of the lighting or daylighting system.

6.3. Photometric assessment

The next sections elaborate the analysis of the large amount of data collected for each parameter during the photometric assessment. The focus of this section is on the 'comprehensive' monitoring level since the 'basic' monitoring level is included in the 'comprehensive' level.

The data measured during the monitoring phase must be evaluated according to lighting standards and guidelines and represented in a way which summarizes the outcomes and makes it easy to read. In this protocol, examples are presented showing how the final data could be arranged in a table. Values presented in the tables are fictive; they are provided here simply to help the reader imagine how the final data presentation could be arranged. We suggest using a colour code to indicate whether reflectance and luminance ratios pass or fail the acceptability criteria (suggestion: green = pass; red = fail; yellow = borderline). A comment box at the end should mention the standard or criterion used for the analysis and whether the measurements generally reveal 'pass', 'fail' or 'borderline' values.

6.3.1. Distribution

The importance of considering luminance ratios in the visual environment comes from the fact that the human eye, in spite of its capacity to sustain great variations in luminance, cannot adapt to large luminance variations simultaneously (Marty et al., 2003). Athienitis & Tzempelikos (2002) outlined that too high contrast between two adjacent surfaces can create discomfort and visual fatigue. According to a recent Swedish source (Svensson, 2010), it is the average luminance of different surfaces which determine the adaptation of the eye and the speed at which the eye adapts to different luminance ratios depends on the difference between the light and dark patterns.

Most lighting guidelines and standards (SS-EN-12464-1, 2011; CIBSE, 1994, 2002; IESNA, 2011) contain recommendations for luminance distribution and ratios, especially in relation to work environments.

How to interpret the data on luminance ratios and room reflectances

Spot luminance values measured at each task position should preferably be pasted on the HDR images of the task, which should be provided as a part of the photometric assessment. An average of at least three spot luminance measurements should be used to determine the average luminance in the different parts of the visual field (task: ergorama: panorama).

Room surface reflectances are also an important part of a lighting system and affect both the uniformity and energy usage of lighting (IEA, 2010). Acceptable reflectances are also provided in many lighting standards. For example, the European standard SS-EN-12464-1 (2011) proposes the following reflectance factors for the main room surfaces:

- Ceiling: 60-90%;
- Walls: 30-80%;
- Floor: 10-50%;
- Work surface: 20-60%.

In the case when many different materials and colours are used in the room, the values should be reported separately in the section on reflectance.

The data measured for the parameter ‘distribution’ should be summarized in the final analysis and report sheet as shown in Table 9. The values presented in the table are fictive; they are only shown here to help the reader imagine how the final data presentation should look like.

Table 9 Summary of information collected for the parameter ‘Distribution’.

Parameter	Example			
Reflectance, ceiling-walls-floor	90-85-40%			
Glazing type and visual transmittance	Double clear glass 72%			
Materials, ceiling-walls-floor	acoustic tiles - white painted gypsum - linoleum			
Specularity, ceiling-walls-floor	mat - mat - glossy			
Time of monitoring:	**Overcast**	**Clear Winter solstice**	**Clear Equinox**	**Clear Summer solstice**
Typical task position, noon				
Luminance ratios, task:ergorama:panorama	1:3:10	1:10:50	1:1:3	1:3:10
HDR images of task integrating measured spot luminance values				
Extreme task position, noon				
Luminance ratios, task:ergorama:panorama	1:3:10	1:10:50	1:1:3	1:3:10
HDR images of task integrating measured spot luminance values				
Typical task position, afternoon				
Luminance ratios, task:ergorama:panorama	1:3:10	1:10:50	1:1:3	1:3:10
HDR images of task integrating measured spot luminance values				
Extreme task position, afternoon				
Luminance ratios, task:ergorama:panorama	1:3:10	1:10:50	1:1:3	1:3:10

HDR images of task integrating measured spot luminance values	
Conclusions regarding light distribution:	Reflectances fall within the acceptable range according to SS-EN-12464-1 (2011). Luminance ratios are not acceptable according to SS-EN-12464-1 (2011), only under overcast sky conditions, post-retrofit.

6.3.2. Illuminance

Illuminance on the working plane is the key factor determining the acceptability of the lighting for visual task performance in most environments (Goodman, 2009). A pilot study by Berrutto, Fontoynont, & Avouac-Bastie (1997) indicated that the horizontal illuminance appeared to be a major lighting quality parameter. Newsham et al. (2008) also found that illuminance measured on the desktop was a better predictor of participant dimmer choice than any luminance-based measure, which is also an indication of the importance of desktop illuminance for office environments.

How to interpret data on absolute illuminance, daylight factors and illuminance ratios

The absolute illuminance on a working plane should be plotted on a map showing values and measurement points in the room. The absolute illuminance evaluated through the daylight factor, illuminance uniformity and illuminance ratios on the surroundings of the work area should also be reported.

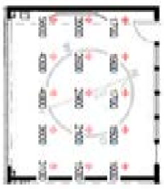
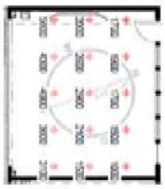
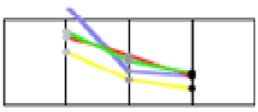
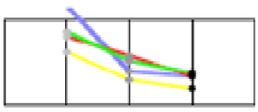
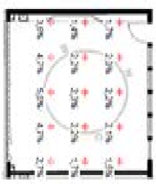
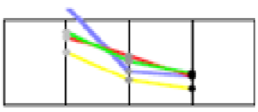
The daylight factor is the most common and simple daylight metric and is a ratio of interior to exterior horizontal illuminance under fully overcast sky conditions, and should likewise be plotted on a map showing calculated values and points. According to most standards, an average daylight factor at least 2 % at working places should ensure minimum daylight levels.

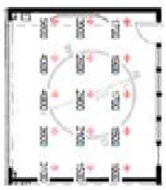
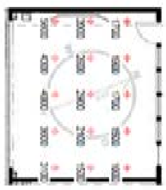
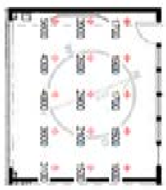
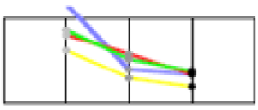
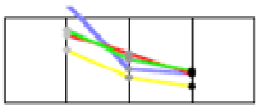
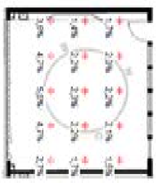
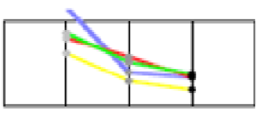
Illuminance uniformity on the working plane and across rooms is often highly desirable (Veitch & Newsham, 1995), why lighting standards often contain recommendations regarding the uniformity of illuminance on the work plane, see e.g. SS-EN-12464-1 (2011). The uniformity consists of the ratio between minimum and average or maximum illuminance on the work plane.

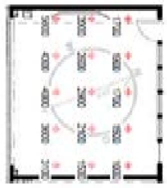
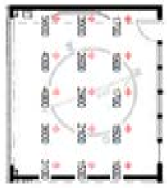
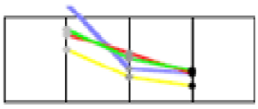
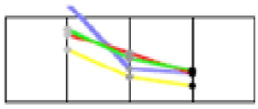
The ratio between task and surrounding surface illuminance is also often used as an expression for the uniformity criterion instead of luminance ratios. According the European standard SS-EN-12464-1 (2011), the illumination of the task area and its immediate surroundings should provide a well-balanced luminance distribution in the field of view.

The data measured for the parameter ‘illuminance’ should be summarized in the final analysis and report sheet as shown in Table 10. This table presents minimum, average, median and maximum values regarding interior and exterior illuminance values, daylight factors and illuminance uniformity. The table also presents small maps and profiles of illuminance and daylight factor values.

Table 10 Summary of information collected for the parameter 'Illuminance'.

NOON measurements	Overcast		Clear Winter solstice		Clear Equinox		Clear Summer solstice	
Exterior diffuse illuminance (lx) | Exterior global illuminance (lx)								
Average	2000	20000	2000	20000	2000	20000	2000	20000
Median	2000	20000	2000	20000	2000	20000	2000	20000
Minimum	2000	20000	2000	20000	2000	20000	2000	20000
Maximum	2000	20000	2000	20000	2000	20000	2000	20000
Vertical illum. (lx) | Vertical-to-horizontal diffuse illum. ratio	5000	1:3	6000	1:3	7000	1:3	4000	1:3
Interior illuminance (lx), electric light + daylight | daylight only								
Average	250	150	250	150	250	150	250	150
Median	250	150	250	150	250	150	250	150
Minimum	250	150	250	150	250	150	250	150
Maximum	250	150	250	150	250	150	250	150
Illuminance uniformity	1:7	1:4	1:7	1:4	1:7	1:4	1:7	1:4
Task illuminance (lx), electric light + daylight | daylight only								
Average task	250	150	250	150	250	150	250	150
Average task surround	250	150	250	150	250	150	250	150
Extreme task	250	150	250	150	250	150	250	150
Extreme task surround	250	150	250	150	250	150	250	150
Illuminance maps, electric light + daylight								
Illuminance profiles, electric light + daylight								
Daylight factor daylight only								
Average	3							
Median	2.5							
Minimum	0.5							
Maximum	8							
Daylight factor maps, daylight only								
Daylight factor profiles, daylight only								
AFTERNOON	**Overcast pre-**		**Overcast post-**		**Clear pre-**		**Clear post-**	

measurements	retrofit		retrofit		retrofit		retrofit	
Exterior diffuse illuminance (lx) | Exterior global illuminance (lx)								
Average	2000	20000	2000	20000	2000	20000	2000	20000
Median	2000	20000	2000	20000	2000	20000	2000	20000
Minimum	2000	20000	2000	20000	2000	20000	2000	20000
Maximum	2000	20000	2000	20000	2000	20000	2000	20000
Vertical illum. (lx) | Vertical-to-horizontal diffuse illum. ratio	5000	1:3	6000	1:3	7000	1:3	4000	1:3
Interior illuminance (lx), electric light + daylight | daylight only								
Average	250	150	250	150	250	150	250	150
Median	250	150	250	150	250	150	250	150
Minimum	250	150	250	150	250	150	250	150
Maximum	250	150	250	150	250	150	250	150
Illuminance uniformity	1:7	1:4	1:7	1:4	1:7	1:4	1:7	1:4
Task illuminance (lx), electric light + daylight | daylight only								
Average task	250	150	250	150	250	150	250	150
Average task surround	250	150	250	150	250	150	250	150
Extreme task	250	150	250	150	250	150	250	150
Extreme task surround	250	150	250	150	250	150	250	150
Illuminance maps, electric light + daylight								
Illuminance profiles, electric light + daylight								
Daylight factor daylight only								
Average	3							
Median	2.5							
Minimum	0.5							
Maximum	8							
Daylight factor maps, daylight only								
Daylight factor profiles, daylight only								
EVENING measurements	**Overcast pre-retrofit**		**Overcast post-retrofit**		**Clear pre-retrofit**		**Clear post-retrofit**	
Interior illuminance (lx), electric light + daylight | daylight only								
Average	250	150	250	150	250	150	250	150
Median	250	150	250	150	250	150	250	150

Minimum	250	150	250	150	250	150	250	150
Maximum	250	150	250	150	250	150	250	150
Illuminance uniformity	1:7	1:4	1:7	1:4	1:7	1:4	1:7	1:4
Task illuminance (lx), electric light + daylight | daylight only								
Average task	250	150	250	150	250	150	250	150
Average task surround	250	150	250	150	250	150	250	150
Extreme task	250	150	250	150	250	150	250	150
Extreme task surround	250	150	250	150	250	150	250	150
Illuminance maps, electric light + daylight								
Illuminance profiles, electric light + daylight								
Conclusions regarding illuminance and uniformity:	Illuminances and daylight factors fall within the acceptable range according to (SS-EN-12464-1, 2011). Illuminance uniformity ratios are not acceptable according to (SS-EN-12464-1, 2011), only under overcast sky conditions, post-retrofit.							

6.3.3. Glare

'Glare is a subjective human sensation that describes light within the field of vision that is brighter than the brightness to which the eyes are adapted' (HarperCollins dictionary 2002 via Reinhart & Wienold, 2011). Glare is typically characterized as disability glare, which is the inability of a person to see certain objects in a scene due to glare, or discomfort glare, which is the premature tiring of the eyes due to glare (Reinhart & Wienold, 2011). Generally, if discomfort glare limits are met, disability glare is usually not a major concern (SS-EN-12464-1, 2011).

For calculating discomfort glare from daylight and electric light in buildings, different glare indices have been developed. The two most common glare indices are:

- UGR (CIE Unified Glare Ratings);
- DGP (Daylight Glare Probability).

The UGR is used to calculate glare from electric light sources while the DGP is normallyused for calculating glare from daylight, applicable to work environments similar to offices.

How to interpret data on glare

Since the calculation of the UGR and DGP is fairly complex, we suggest to use instead the HDR photographs taken during the monitoring, and then convert them to .hdr images. These images can then be analysed using the program Evalglare embedded into the RADIANCE Lighting Simulation and Rendering System. This procedure is described in the paragraphs below and consist of image processing and then obtaining the UGR and DGP from the HDR images.

Image processing

Special software is needed for further image processing of the photographs taken of the tasks. The purpose of this software is to convert a series of low dynamic range images of the same scene into a single HDR image. It is reasonable to use programs scientifically verified and tested by others before, e.g. PhotoLux, Photosphere, WebHDR and Aftab, where the three last are free of charge.

Obtaining UGR and DGP from HDR images

Glare can be analysed using .hdr images and the validated RADIANCE Lighting Simulation and Rendering System, which may be downloaded from the following site: http://radsite.lbl.gov/radiance/framed.html

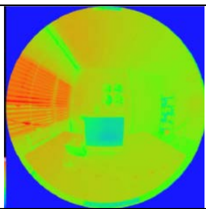
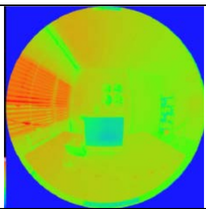
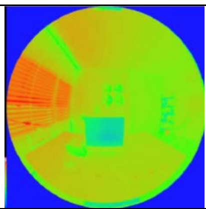
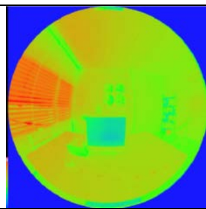
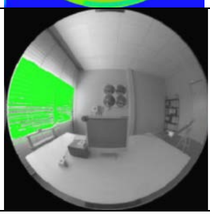
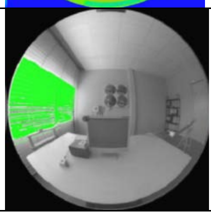
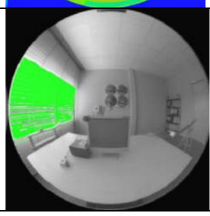
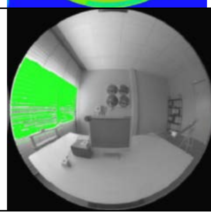
There are two programs for glare analysis in Radiance:

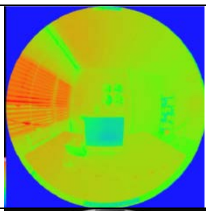
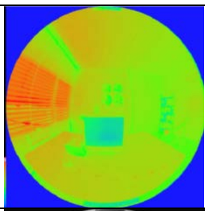
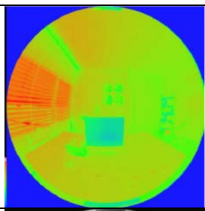
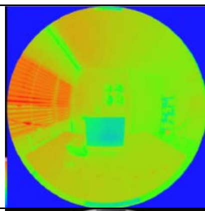
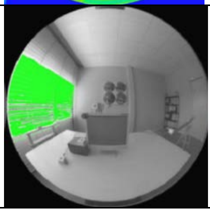
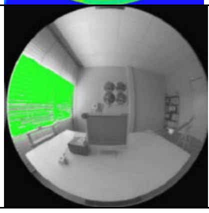
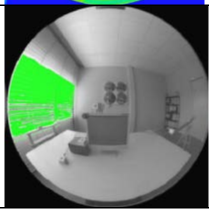
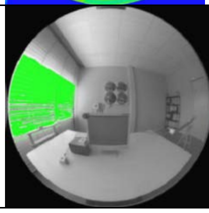
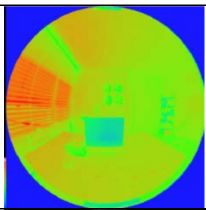
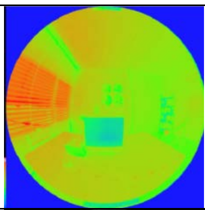
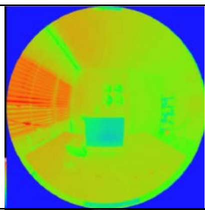
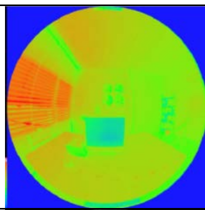
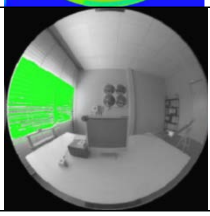
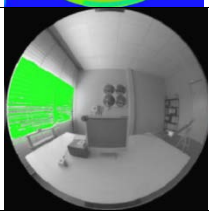
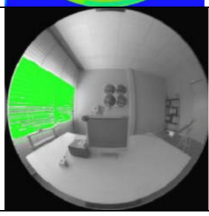
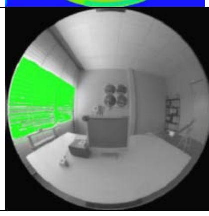
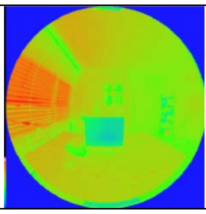
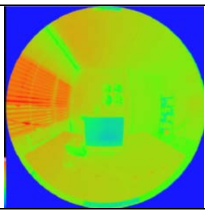
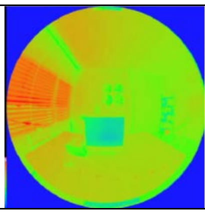
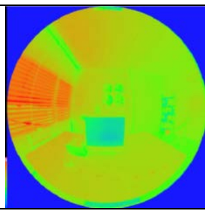
- Findglare and Glarendx (see findglare.exe, glarendx.exe at http://dev.man-online.org/man1/glarendx/);
- Evalglare (evalglare.exe, version 1.11).

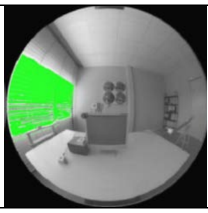
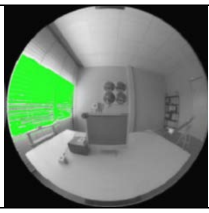
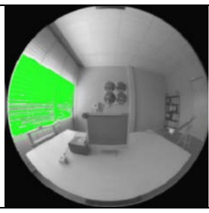
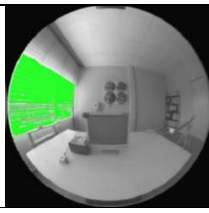
In each glare analysis program, both fish eye and rectangular images may be used as input. Findglare calculates the UGR while Evalglare can be used for UGR, DGP as well as other glare indices. Note however, that glare from daylight and electric light must be evaluated separately and respectively with DGP or UGR otherwise it will result in inappropriate ratings.

The data measured for the parameter 'glare' should be summarized in the final analysis and report sheet as shown in Table 11. This table presents UGR and DGP values, HDR false-colour images and images showing the glare source from the tasks at different times.

Table 11 Summary of information collected for the parameter 'Glare'.

	Overcast	**Clear Winter solstice**	**Clear Equinox**	**Clear Summer solstice**
Typical task position, noon				
Vertical eye illuminance (lx)	550	550	550	550
UGR	28	25	22	19
DGP (%)	23	52	33	21
Original HDR photo of task (luminance values in false colour)				
Output of evalglare showing glare				
Observations	High glare source at window	High glare source at window	High glare source at window	High glare source at window

Veiling reflections	Yes	No	No	No
Typical task position, afternoon				
Eye illuminance (lx)	550	550	550	550
UGR	28	25	22	19
DGP (%)	23	52	33	21
Original HDR photo of task (luminance values in false colour)				
Output of evalglare showing glare				
Observations	High glare source at window	High glare source at window	High glare source at window	High glare source at window
Veiling reflections	Yes	No	No	No
Extreme task position, noon				
Eye illuminance (lx)	550	550	550	550
UGR	28	25	22	19
DGP (%)	23	52	33	21
Original HDR photo of task (luminance values in false colour)				
Output of evalglare showing glare				
Observations	High glare source at window	High glare source at window	High glare source at window	High glare source at window
Veiling reflections	Yes	No	No	No
Extreme task position, afternoon				
Eye illuminance (lx)	550	550	550	550
UGR	28	25	22	19
DGP (%)	23	52	33	21
Original HDR photo of task (luminance values in false colour)				

Output of evalglare showing glare				
Observations	High glare source at window	High glare source at window	High glare source at window	High glare source at window
Veiling reflections	Yes	No	No	No
Conclusions regarding glare:	Glare index values within the acceptable range according to (SS-EN-12464-1, 2011). Glare index values are not acceptable according to (SS-EN-12464-1, 2011), only under overcast sky conditions, post-retrofit.			

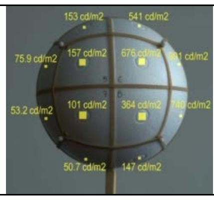
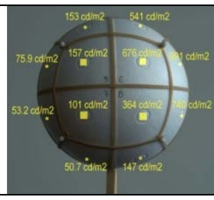
6.3.4. Directionality

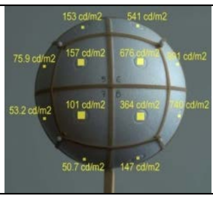
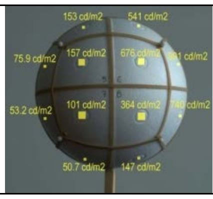
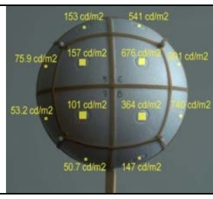
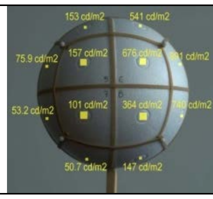
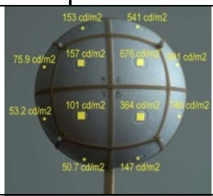
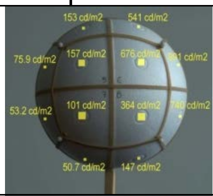
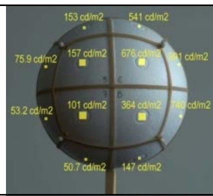
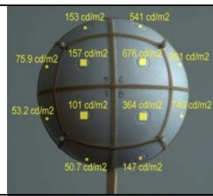
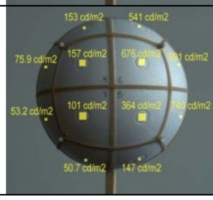
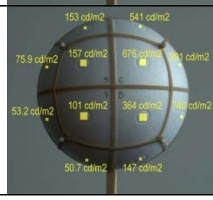
According to SS-EN-12464-1 (2011), the general appearance of an interior is enhanced when its structural features; the people and objects within it are lit so that form and texture are revealed clearly and pleasingly. This occurs when the light comes predominantly from one direction; shadows so essential to good modeling are then formed without confusion. On the other hand, the lighting should not be too directional or it will produce harsh shadows, neither should it be too diffuse or the modeling effect will be lost entirely, resulting in a very dull light environment (SS-EN-12464-1, 2011). According to Svensson (2010), it is more natural to understand the environment when light falls diagonally from above (as in the case of outdoor landscape lit by sunlight).

How to interpret the data on directionality

The data measured for the parameter 'directionality' should be summarized in the final analysis and report sheet as shown in Table 12. This table presents vector-to-scalar ratio and its interpretation as well as images of the diffuse spheres from both sides. Observations should also be collected in the boxes underneath the images.

Table 12 Summary of information collected for the parameter 'Directionality'.

	Overcast	**Clear Winter solstice**	**Clear Equinox**	**Clear Summer solstice**
Noon, middle of room				
Vector-to-scalar illuminance ratio	2	4	5	7
Interpretation	Sharp shadows	Sharp shadows	Soft shadows	Weak shadows
HDR photo of sphere, side 1				

HDR photo of sphere, side 2				
Observations	Diffuse light	Diffuse light	Diffuse light	Diffuse light
Detection of shadows	No shadow	No shadow	No shadow	No shadow
Afternoon, middle of room				
Vector-to-scalar illuminance ratio	2	4	5	7
Interpretation	Sharp shadows	Sharp shadows	Soft shadows	Weak shadows
HDR photo of sphere, side 1				
HDR photo of sphere, side 2				
Observations	Diffuse light	Diffuse light	Diffuse light	Diffuse light
Detection of shadows	No shadow	No shadow	No shadow	No shadow
Conclusions regarding directionality:	The light is diffuse; directionality is not defined, etc.			

6.3.5. Colour

The colour rendering of a light source should be adequate for the task being performed. The electric lighting should be designed so that warning signs, emergency buttons and the like are easily identified. Exposure to UV radiation from the electric lighting system should be as low as possible so that risks for health are eliminated to a minimum (Arbetsmiljöverket, 2009). Lamps of different temperatures should not normally be used in the same room, unless a specific effect is required (Energy saving trust, 2006).

According to standard SS-EN-12464-1 (2011), it is important for visual performance and the feeling of comfort and well-being, that colour in the environment, of objects and of human skin are rendered naturally, correctly and in a way that makes people look attractive and healthy.

How to interpret the data on colour

Most lighting standards express requirements related to colour of light sources and colour of room surfaces. For example, the European standard SS-EN-12464-1 (2011) has requirements regarding:

1. The colour appearance of light sources (CCT);
2. The capacity of the light source to render colour, i.e. the way it affects the colour of objects, surfaces, and people in the room, which is normally described by the CRI.

These two attributes should be considered separately.

As stated in this standard, the choice of colour appearance is a matter of psychology, aesthetics and of what is considered to be natural. The choice will depend on illuminance level, colours of the room and furniture, surrounding climate and the application. In warm climates, a cooler light colour appearance is generally preferred, whereas in cold climates a warmer light colour appearance is preferred (SS-EN-12464-1, 2011; Svensson, 2010).

Lamps with a colour rendering index lower than 80 should not be used in interiors where people work or stay for longer periods (SS-EN-12464-1, 2011; Svensson, 2010). It is recommended that the light sources in offices have a colour-rendering index (CRI) of 80 or above but in industries where colour is very important (graphic design, health institutions, etc.) the recommended CRI is 90 and above (Svensson, 2010). According to ISO 3864 (ISO, 2001), security colours should always be identifiable.

The minimum acceptable value for CRI is given for each type of space in the European standard SS-EN-12464-1 (2011).

The data measured for the parameter 'colour' should be summarized in the final analysis and report sheet as shown in Table 13. This table presents descriptive colour information and colour codes for the main surfaces in the room, colour related information about the lighting systems, as well as measured CCT and CRI values at different points in the room. Observations should also be collected on each monitoring day and summarised at the end in the final comment box.

Table 13 Summary of information collected for the parameter 'Colour'.

Surfaces	Description			
Floor descriptive colour, code	Dark beige, NV67530VV			
Ceiling descriptive colour, code	White, MIT4509876			
Walls descriptive colour, code	White, NV67530VV			
Wall (south) descriptive, code	Blue, NV67530VV			
Light sources	CCT (K)			
Light source 1	5000			
Light source 2	4500			
Noon	Overcast	Clear Winter solstice	Clear Equinox	Clear Summer solstice
Middle of room				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations				
Key position 1				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations				
Key position 2				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations	Bluish light	Bluish light	Bluish light	Bluish light
Afternoon	Overcast	Clear Winter solstice	Clear Equinox	Clear Summer solstice

Middle of room				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations				
Key position 1				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations				
Key position 2				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations	Bluish light	Bluish light	Bluish light	Bluish light
Evening	Overcast	Clear Winter solstice	Clear Equinox	Clear Summer solstice
Middle of room				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations				
Key position 1				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations				
Key position 2				
CCT (K)	3600	3600	3600	3600
CRI (-)	90	80	90	80
Observations	Bluish light	Bluish light	Bluish light	Bluish light
Conclusions regarding colour:	Analysis of colour shows that light sources provide bluish light.			

6.3.6. Flicker

At the ‘comprehensive’ monitoring level, the data measured for the parameter ‘flicker’ should be summarized in the final analysis and report sheet as shown in Table 14. This table presents technical information about the light sources, as well as mobile phone or pen-cloth detection results and observations. Observations should also be collected on each monitoring day and summarised at the end in final comment box.

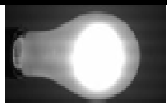
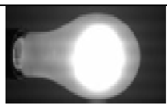
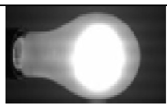
How to interpret the data on flicker

One source of stress in the environment is flicker from fluorescent tubes, especially in rooms lacking daylight. The light from conventional light bulbs and other incandescent lamps is produced through heating a metal wire or other element by means of an electric current. This illumination is fairly stable even with alternating current. The light emitted from fluorescent lamps, on the other hand, is based on electric discharges and is therefore modulated by the power supply. An alternating current of 50 Hz will cause flicker of mostly 100 periods per second, which will not be seen by the naked eye but still may reach the brain (Küller, 2004).

Flicker causes distraction and may give rise to physiological effects such as headaches (SS-EN-12464-1, 2011). Young persons are most vulnerable to flicker from fluorescent tubes. Amongst the effects reported are eyestrain, headaches, disturbed performance and increased secretion of cortisol (Küller, 2004). The sensitivity to flicker is also higher in the peripheral than in the central field of view (Svensson, 2010).

Electric lighting should be planned so that disturbing flicker is completely avoided, according to most lighting or workplace standards, e.g. Arbetsmiljöverket (2009) in Sweden, this can usually be achieved for example by the use of DC electrical supply for incandescent lamps or by operating incandescent or discharge lamps at high frequencies (around 30 kHz). At the ‘basic’ monitoring level, the simple detection of flicker is sufficient to establish a ‘pass’ or ‘fail’ judgment about a lighting installation. Flicker should simply not be detected at all.

Table 14 Summary of information collected for the parameter ‘Flicker’.

Light sources	Frequency (Hz)	Mobile phone detection	Pen-cloth detection	Observations
Light source 1	50	 yes	No	
Light source 2	100	 yes	No	
Light source 3	100	 yes	No	
Conclusions regarding flicker:	Observations show that flicker is present in Light source 1 and 2.			

6.3.7. View

The data measured for the parameter ‘view’ should be summarized in the final analysis and report sheet as shown in Table 16. The table is filled in for each selected space and for each selected workplace in the selected space.

Table 15 Summary of information collected for the parameter ‘View’.

Selected space	Basic	Comprehensive		Pre-retrofit	Post-retrofit
Glazing-to-inner-wall area	✓	✓	[%]		
Glazing-to-floor area	✓	✓	[%]		
Shading system normal/normal transmittance	✗	✓	[%]		
Shading system diffuse light transmittance	✗	✓	[%]		
Effect of shading device on view	✓	✓	[-]		
Selected space	Basic	Comprehensive		Pre-retrofit	Post-retrofit
View quality	✓	✓	[-]		
Width of view	✓	✓	[°]		
Outside distance of the view	✓	✓	[m]		
Number of layers	✓	✓	[-]		
Environmental information	✓	✓	[-]		
Observations	✓	✓	[-]		

Selected space	Basic	Comprehensive		Pre-retrofit	Post-retrofit
View quality	×	✓	[-]		
Width of view	×	✓	[°]		
Outside distance of the view	×	✓	[m]		
Number of layers	×	✓	[-]		
Environmental information	×	✓	[-]		
Observations	×	✓	[-]		

Additional to the summarization of data, a text describing the main aspects with respect to the evaluation of the view should be provided.

6.4. Users' assessment

The analysis phase for the users' assessment consists of three main parts:
a) digitalization of the questionnaires and interviews;
b) data analysis and elaboration;
c) reporting of the results and conclusions.

Depending on the number of participants as well as level of monitoring, the time needed may vary widely, especially for the digitalization part. In the present section, the instructions and some tips for the analysis of the collect data are reported.

6.4.1. General questionnaire

The general questionnaire is reported in the Appendix A. The general questionnaire analysis consists in a simple average score for the different items. The final average score is the main result from the general questionnaire.

The calculation may be performed by using the provided electronic sheet. The average rating is calculated by the sheet and reported in both numerical and graphic form. The average should be copied in the main report. The charts may be used for further graphical illustration.

6.4.2. Interviews

Depending on the type of interview, the elaboration and its required time can vary. The interviews should preferably be reported on paper and labeled by topic (e.g. 'control system', 'daylight', etc.). This operation will make it easier to later have a complete picture for each specific topic. The answers will provide a solid background for drawing conclusions on the users' perception of the light environment. The findings of the interviews should be reported in a qualitative form in addition to the expert assessment .

6.4.3. Expert assessment

As for the interviews, the expert assessment should be collected. This information is simply expressed in a qualitative text. The document is written for architects, engineers, or building owners without specific lighting background, thus clarity and concision are highly recommended.

7. Background and theory: additional information

7.1. Definition of weather conditions

7.1.1. Overcast sky conditions

The overcast sky conditions, by definition, will most likely provide conditions easy to reproduce, due to the distribution of daylight entering the room almost independent of the solar azimuth angle. The main problem is the variation in the sky luminance distribution under which the measurements are performed. To compensate for these variations, the following criterion for accepting the measurements is defined. The luminance ratio (foc) between the screened vertical sky illuminance and the global, unobstructed horizontal illuminance should be in the interval 0.36 < foc < 0.44. The 'true value' for the CIE overcast sky is foc = 0.396. The overcast sky measurements could be taken at any time of the year. For an overcast sky with an ideal CIE sky luminance distribution only one measurement is needed. However this ideal distribution is seldom reached in some climatic zones.
The daylight measurements for overcast sky conditions should be conducted in a period when the exterior illuminance level is high as far as possible. This will improve the accuracy of signals from the sensors.

7.1.2. Clear sky conditions

A clear sky can be defined by the rule of observation. At least 7/8 of the sky must be uncovered for the sky to be considered clear, and the covered patch of the sky must not cover the sun or be seen from the interior.

7.2. Luminance distribution

According to Madsen & Osterhaus (2014), Osterhaus (2009) and Dubois (2001), 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) claimed that the maximum luminance ratios of 1:3 in the ergorama and 1:10 in the panorama 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, with complaints being more likely when screen to surround luminance exceeds levels of 5:1 (Berrutto, Fontoynont, & Avouac-Bastie, 1997; Veitch & Newsham, 1999 via Moore, Carter & Slater, 2002). According to Veitch & Newsham, (2000), studies of preferred luminance conditions in offices, however, found that most workers actually preferred lower ratios. Note also that the Danish standard for artificial lighting in working environments (Dansk Standard, 1997) solely recommends that the luminance of the surround of a given task should be of the same order of magnitude as or darker than the task luminance. A recent publication (Svensson, 2010) 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.

The recommended luminance ratios are also 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’ according to Osterhaus (2002). Sutter, Dumortier & Fontoynont (2006) achieved an experiment to validate the 1:3:10 luminance ratios for work on task. Figure 4 shows the 60 and 120° cones used in this experiment. During a period of four days, the researchers measured the luminance in the visual field of eight employees who spent about 70% of their time working with 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, they observed that ratios 1:6:20 were accepted. A tolerance for a ratio of 1:50 has even been observed when the luminance from the window occupied a small portion of the visual field (about 5%).

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. Also, in a window-less laboratory experiment involving 47 participants and six workstations in open-plan arrangement, Newsham & Veitch (2001) found that the preferred maximum-to-minimum luminance ratio in the field of view was around 20:1 and that luminance ratios experienced during the day had an effect on end-of-day luminance ratio choice.

7.3. Illuminance

7.3.1. Exterior diffuse illuminance (E_{hd})

Under sunny sky conditions, one of the exterior lux meter should also be shaded just in the area of the cell, in order to determine the contribution from the diffuse sky. Different instruments and methodologies may be used to measure diffuse illuminance. The most precise method consists of shading the illuminance meter with a small disc, coin or ball synchronized with the sun's apparent motion. However, in this case, it is necessary to mount the disc, coin or ball at the end of a solid yet flexible metal wire in order to make sure that the construction and position of the disc, coin or ball remains fairly steady while measuring.

A more practical and widely used approach consists of using a shadow ring, especially when the measurements must be carried out continuously under a whole day or several days. In this case, a ring or band is placed parallel to the sun path thereby blocking the direct illuminance by simply preventing it from reaching the sensor. The shadow ring should only be adjusted every few days to account for changes in solar declination. Some studies have shown that measurements with shadow rings are comparable to measurements obtained by more sophisticated tracking devices under totally cloudy skies while under clear sky conditions, some differences appear (Ineichen, Gremaud, Guisan & Mermoud, 1984). The shadow ring blocks the sun but also a substantial portion of the sky and therefore, a correction factor should be applied in order to accurately estimate the diffuse illuminance reaching the sensor. This correction factor has been estimated to lie between 8.9% and 37.7% according to Kudish & Ianetz (1993) and depends on the latitude, weather conditions and type of shadow ring used (Steven, 1984). Further details about shadow ring correction factors may be found in Sanchez et al. (2012).

7.3.2. Exterior illuminance on a vertical plane (E_{vgs})

In an ideal situation, the exterior vertical illuminance (E_{vgs}) should be measured either with a hand-held lux meter (placed on the façade) or with the help of a sensor screened from ground-reflected light by a matt black screen, see Figure 6. An additional sensor might be needed in situations where the ground reflection may change significantly (for example, due to snow on the ground) and a distinction between the contribution of the ground and the prevailing sky condition needs to be made. If the sensor is unscreened, the ground reflected component can be found by subtracting the unscreened vertical sky and ground component from the screened sensor measuring the vertical sky illuminance. The ground component can also be measured directly with a screened sensor, seeFigure 6.

In the case where a hand-held lux meter is used, readings of the vertical illuminance are performed by simply holding the lux meter vertically in the direction of the monitored room's main windows. The exact direction can be determined by using a compass or by putting the lux meter against the façade when possible. If the room has more than one window in different directions, readings should be taken in each main window direction. When performing these measurements, the same rules as for global horizontal illuminance should be applied i.e. no shading by the person performing the measurements, perfect vertical position and state-of-the-art calibrated cosine corrected V(λ) lux meter.

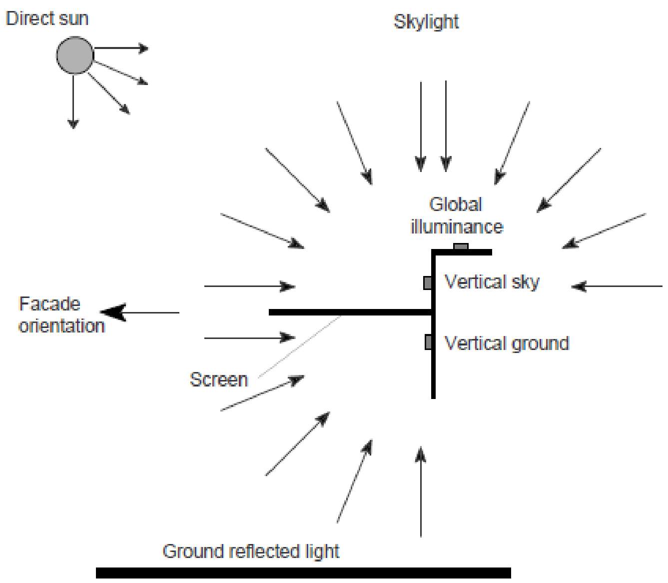


Figure 6 Vertical global sky illuminance on facade E_{vgs}, with permission from Velds & Christoffersen (2001).

7.3.3. Grid cells for interior illuminance measurements

A formula to determine a grid system to measure illuminance is proposed in the European Standard SS-EN-12464-1 (2011). 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:

$$p = 0{,}2 \times 5^{\log_{10}(d)} \quad (7)$$

where

p < 10m

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.

However, in most cases it will be impossible due to practical limitations to measure such a tight grid in a real inhabited building. Therefore, depending on in situ constraints and availability of sensors or time for taking illuminance with hand-held lux meters, it is suggested to double the grid spacing prescribed by equation 5. In areas of sharp light transitions (like e.g. close to window), intermediate points could be added to obtain a smoother, more precise description of light variation in space.

Normally, one grid line is set perpendicular to the window's center line starting at 0,5 m from the window and extending towards the back of the room. These lines are quite easy to determine. However, it is not always possible to monitor the full amount of grid points between the central window lines due to limitation of sensors, furniture, etc. In this case, it is recommended to select one line of measurement located between the window center lines, which normally corresponds to the darkest areas of the room, see for an example Figure 7, which shows an example of a classroom where the largest dimension is 10,85 m, which returns a grid size of roughly 1 m by applying equation 7. In this case, two central lines are determined with respect to window centers and points are taken at approximately each meter, except deep in the room where daylight does not vary so much. Then, one line between the window-center lines is measured and one at equal distance (H1-H3) on the other side, but only 3 points are needed to represent the darkest corners of the room. This example shows that it is not always easy to apply a strict rule and that judgment must be used in order to select the most logical measurement points, especially in irregularly shaped rooms. Note that the calculation of the average illuminance should however take consideration of equal amount of points in the light and dark zones of the room.

The sensor height should be according to the standard work plane height of each specific country. If no standard exists, the measuring height can be 0.8 m.

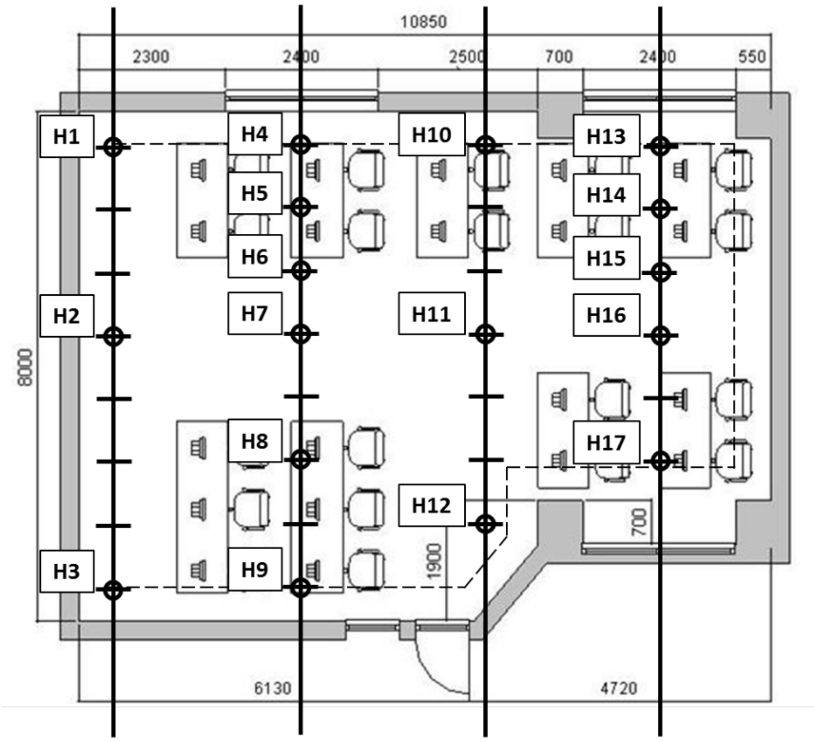


Figure 7 Possible position of sensors in an irregularly shaped room.

7.3.4. Dimming level

The dimming level is a measure of the fractional light output, assumed to run between 0 and 1. In a preparatory measurement ('comprehensive' monitoring only), the relation between the measured voltage (a measure for the dimming level of the electric light) and the power consumption can be determined, using a voltmeter and a power meter (Figure 8). With the established relationship, the dimming level can also be used to monitor the energy consumption. If it is not possible to measure the precise dimming level with a voltmeter at the time of monitoring, then the dimmer datasheet should be used for extracting the information. If this second option cannot be applied, an estimate of the dimming level should be made by using a lux meter located under a light source far away from windows or skylights and relating the measured value to the maximum and minimum light output.

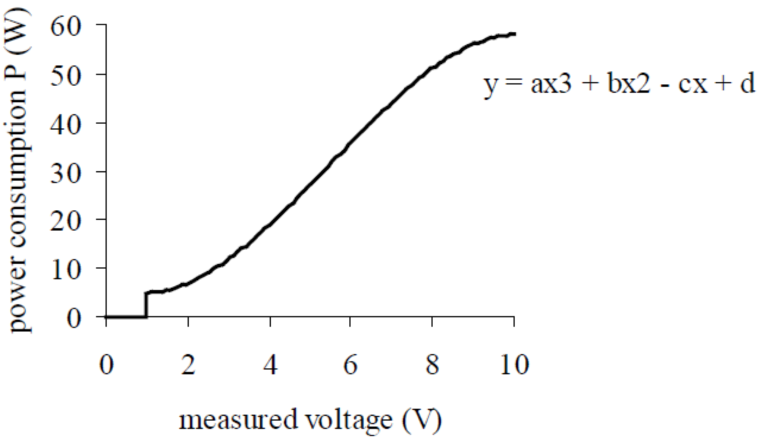


Figure 8 Example of relation between measured voltage and the power consumption of electric lighting, from Velds & Christoffersen (2001).

7.3.5. Absolute illuminance values

Generally, a positive association has been found between illuminance levels and task performance, see e.g. short review by Boubekri (1995). Boyce (1973) via Boubekri (1995) reported that as light levels increase, both satisfaction and performance increase. Other studies have shown that satisfaction and performance increase with the increase of light levels for low range of illuminance levels; but as illuminance reaches very high levels, satisfaction no longer increases but rather diminishes while performance remained unchanged (Boubekri, 1995). As Goodman (2009) puts it: 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 actually further reduce visual performance.

While it is generally agreed that the visual quality of a space cannot be fully described in terms of horizontal illuminance, this is the most commonly used metric for evaluating the adequacy of illumination levels in a space. 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 assessed or inferred (Mardaljevic, Heschong & Lee, 2009).

In normal lighting conditions, approximately 20 lx is required to discern features of the human face and is the lowest value taken for the scale of illuminances (SS-EN-12464-1, 2011). A value of 300–500 lx is commonly recommended for detailed office and clerical work, and many electric lighting systems are designed to deliver this level of illumination (Küller, 2004). The current lighting recommendations provide ranges of illuminance values for different types of rooms and activities (SS-EN-12464-1, 2011; CIBSE, 1994, 2002; IESNA, 2011) and should be consulted in order to determine what is an appropriate illuminance level in a room according to its function.

7.3.6. Daylight factor

According to Nabil & Mardaljevic (2005), the daylight factor (DF) remains the most widely used performance indicator for daylighting and for the majority of practitioners, the consideration of any quantitative measure of daylight begins and ends with daylight factor. In the LEED, BREEAM (and many other) building certification systems, one or several credits can be obtained when a minimum DF is reached (usually about 2%) in 75%-80% of regularly occupied spaces.

Love & Navvab (1994) mentioned some advantages of the DF:

- 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).

However, Love & Navvab (1994) and Nabil & Mardaljevic (2005), also outlined some shortcomings of the DF:

- 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;
- DF values are very variable even under overcast sky conditions due to variable sky 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.

Mardaljevic (2006) claimed that the DF persists as the dominant evaluation metric because of its simplicity rather than its capacity to describe reality.

Tregenza & Wilson (2011) proposed the following criteria for assessing light quality using DF values, as described in Table 17.

Table 16 Average daylight factor in offices compared with visual character of the room: temperate climates, side windows, from Tregenza & Wilson (2011).

Average daylight factor from side windows	Rooms without electric lighting	Rooms with daytime electric lighting
1%	Gloomy appearance, harsh contrast with view out	Electric lighting may mask daylight variations
2%	Areas distant from window may seem underlit	Appearance of daylit room even if electric lighting is the main task illumination
5%	The rooms looks brightly daylit. Visual and thermal discomfort may occur with large window areas	Electric lighting rarely needed
10%	The character of a semi-outdoor space, such as a conservatory. Visual and thermal conditions may be unsuitable for office-type tasks	

Note that Roche et al. (2001) reported on the findings of a British survey 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 people were more likely to be dissatisfied with daylight when the ADF was over 5%. High daylight levels, with ADFs above 5%, generated complaints of sun and glare. ADFs between 2% and 5% resulted in the highest levels of satisfaction.

7.3.7. Illuminance uniformity

Illuminance uniformity has been described as highly desirable, both across the working surface and across rooms (Veitch & Newsham, 1995). Excessive variation in horizontal illuminance may contribute to transient adaptation problems and should be avoided, according to a British lighting guide (CIBSE, 1994). Therefore, lighting standards often contain recommendations regarding the uniformity of illuminance on the work plane, see e.g. SS-EN-12464-1 (2011). These recommendations are expressed as the quotient of the minimum to the average or to the maximum illuminance on the work plane. Note, however, that Bean & Bell (1992) found that illuminance uniformity was far less important than illuminance level when they tried to correlate judgments of lighting quality by office workers and lighting performance index. Fontoynont (2002) outlined that the optimization of an environment only according to the tasks very often yields spaces that are judged monotonous. Although uniformity is desirable on and around the task area, complete uniformity at larger scale should not be a goal of lighting installations.

Many lighting standards require a uniformity ratio of 0.8 (minimum/average) or 0.7 minimum/maximum), but some research indicate that a ratio of 0.5 (minimum/maximum) may even be acceptable, see a review by Dubois (2001). Some authors (Slater & Boyce, 1990; Slater, Perry, & Carter, 1993) argued that these criteria may not be appropriate for interiors lit by side windows, where the tolerance to illuminance non-uniformity may be greater than in the case of electric lighting.

The European standard SS-EN-12464-1 (2011) requires that the task area shall be illuminated as uniformly as possible. The uniformity of the task area and the immediate surrounding areas shall be not less than 0.7 for the desk area and not less than 0.5 for immediate surrounding areas (ratio between the minimum and average illuminance).

Table 17 Uniformities and relationship of illuminances of immediate surrounding areas to task area according to standard SS-EN-12464-1 (2011).

Task illuminance (lux)	Illuminance of immediate surrounding areas (lux)
≥ 750	500
500	300
300	200
≤ 200	E_{task}
Uniformity: ≥ 0,7	Uniformity: ≥ 0,5

Task and surrounding task illuminance

The uniformity criterion is also often expressed in terms of illuminance of surrounding surfaces instead of luminance ratios. In the European standard SS-EN-12464-1 (2011), the illuminance of immediate surrounding areas shall be related to the illuminance of the task area and should provide a well-balanced luminance distribution in the field of view. Large spatial variations in illuminances around the task area may lead to visual stress and discomfort. The illuminance of the immediate surrounding areas may be lower than the task illuminance but shall not be less than the values given in Table 18. In this table, the task illuminance refers to an area where the actual task is performed and which measures 42 x 30 cm. The immediate surrounding area is a band of 0.5 m directly surrounding the task area and the remote surrounding area is the area outside the immediate surrounding area and which does not comprise a band of 0.5 m from the walls surrounding the task area.

In Svensson (2010), it is also written that for a workspace with light coloured walls, the ratio between illuminance within the task area and average illuminance on the room's walls shall not be larger than 3:1 within the visual field. The ratio between the illuminance within the task area and the lowest illuminance in the room shall not either be larger than 5:1. As an example, if the required illuminance within the task area is 500 lx, the lowest illuminance in the room shall not be below 100 lx.

7.4. Glare

Glare levels in buildings can be determined using 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 (Reinhart & Wienold, 2011). Two such glare indices are widely used: the CIE Unified Glare Rating (UGR) for electric lighting sources and the Daylight Glare Probability (DGP) for glare from daylight origin. The following paragraphs provide some information about these two glare indices.

7.4.1. UGR

CIE Unified Glare rating (UGR) may be used to assess discomfort glare from the luminaires of an indoor lighting installation using the following formula (SS-EN-12464-1, 2011):

$$UGR = 8\log_{10}\left(\frac{0,25}{L_b}\sum\frac{L^2\omega}{p^2}\right) \quad (8)$$

Where

- L_b Background luminance in cd/m2 calculated as $E_{vertical\ eye/\pi}$ in which $E_{vertical\ eye}$ is the vertical indirect
  illuminance at the observer's eye;
- L Luminance of the luminous parts of each luminaire in the direction of the observer's eye in cd/m^2;
- ω Solid angle (sr) of the luminous parts of each luminaire at the observer's eye;
- P Guth's position index for each individual luminaire which relates to its displacement from the line of sight.

Experience suggests that this index is reliable for electric lighting, but cannot be applied when daylight plays a significant role in interior lighting (Osterhaus, 2005). Many lighting standards provide threshold values for the UGR, see e.g. SS-EN-12464-1 (2011).

7.4.2. DGP

For situations with glare from daylight origin, the Daylight Glare Probability (DGP) developed by Wienold & Christoffersen (2006) is a more 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 based on previous research (Velds, 2002), which indicated that electric lighting has a negligible impact on glare level in a daylit space with lateral window. 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). The DGP formula is written below:

$$DGP = 5,87\cdot 10^{-5}\cdot E_v + 9,18\cdot 10^{-2}\cdot\log\left[1+\sum_i\left(\frac{L_{s,i}^2\cdot\omega_{s,i}}{E_v^{1,87}\cdot P_i^2}\right)\right]+0,16 \quad (9)$$

where :

E_v for $E_{vertical\ eye}$	Vertical illuminance at the eye (lux);
$L_{s,\ i}$	Luminance of the i^{th} glare source (cd/m^2);
$\omega_{s,\ i}$	Angular size of the i^{th} glare source (perceived at the eye position, sr);
P_i	Guth's position index for the i^{th} glare source.

The minimal DGP which may be obtained with this formula is 0,16 (16% probability of glare) but DGP values below 20% should be interpreted as situations where glare is not important.

7.4.3. Image processing and programs for glare analysis

Filter corrections to apply to fisheye images

A photometric calibration is necessary when using HDR techniques, especially when a fisheye lens is used. The fisheye lens is advantageous because it allows acquiring luminances over a hemisphere. However, the fisheye lens typically produces a brightness reduction from the center of the picture to its periphery, commonly called the vignetting effect. It is necessary to correct for the vignetting effect in order to obtain reliable data. Previous studies have shown that it is not negligible since it can reach, with some fisheye lenses and some settings, a 55 percent loss of luminance at the periphery of the picture (Inanici, 2010). In addition, Goldman & Chen (2005) have shown that the intensity of the vignetting effect depends on some lens settings: the focal length, the aperture and the lens focus. Cauwerts, Bodart, & Deneyer (2012) presented a detailed calibration procedure to determine the vignetting filter and this procedure could be applied when the expert has time and installations to perform such procedure. However, since this will be difficult in practice most of the time, it is possible to ignore vignetting effects if very large apertures are avoided. In fact, Cauwerts, Bodart, & Deneyer (2012) showed that luminance loss was enhanced for larger apertures (up to 73% luminance loss for an aperture of f/2.8), decreases with smaller apertures, is strongly reduced from f/6.3 to f/22 and is minimal for f/8, f/9 and f/10. For apertures smaller than f/8, the peripheral loss was less than 2% and thus can be neglected in architectural studies.

Cauwerts, Bodart, & Deneyer (2012) also showed that:

- The vignetting effect is not significant at the center of the lens and is maximal at the periphery.
- The vignetting curve for their specific camera-lens combination can be applied to any other similar combination of camera-lens.
- Radial symmetry was demonstrated and can be assumed.

We thus simply recommend using f/8, f/9 or f/10 for the the HDR photography proposed in this monitoring protocol and from these apertures simply vary the shutter speed. Most digital cameras will anyway automatically select one of these apertures in manual mode of operation.

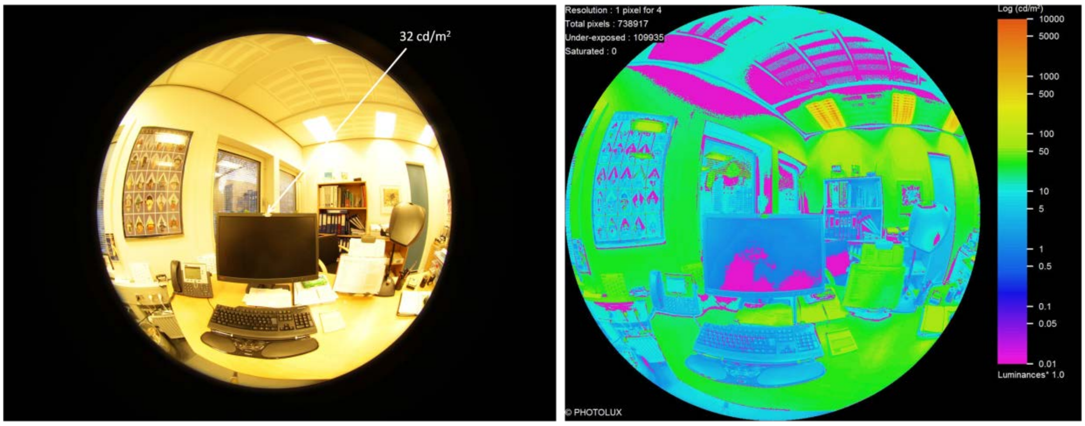


Figure 9 HDR photograph of a task at Horsens Town Hall and false colour luminance map of the scene (right).

Photosphere

Photosphere is the program that prevails over a number of other programs. This software is free of charge, but it works only on Tiger and later versions of Mac OS X. It can be downloaded from this site: http://www.anyhere.com.

The process of combining HDR images into the luminance map (HDRI) is very simple. After choosing appropriate images that were taken during the monitoring session, and the 'Make HDR' command in the Photosphere program (with additional settings), the HDR photo will appear. The next step is the calibration of the generated image according to luminance measurements performed in the real scene. It could be easily done by selecting the area of interest in the HDR image (for example the reference grey surface) and then the 'Calibration' button in the 'Apply Menu'. If the same camera is used subsequently for similar purposes, its specific response will be saved in the program. To save the image in the .hdr format, use Radiance 32-bit RGBE format, which will provide the .hdr file extension. After finishing these steps, the luminance or glare analysis of the .hdr image newly created may be started.

Other freewares for HDR image processing and running on Windows OS are also available and listed here:

- WebHDR
- Aftab

See http://www.jaloxa.eu/webhdr/software.shtml for more information on available sofware.

WebHDR

WebHDR is a free software available through the Internet. It allows downloading up to eight photographs with a combined upload size of 12 MB. The program is accessed via the link www.jaloxa.eu. Once on this website, select 'Roll-Your-Own' photos and proceed by clicking 'Yes, I understand everything that is explained above'. In the next window, the actual *jpg photographs can be simply downloaded by browsing and then clicking on 'upload' at the bottom of the window and finally 'upload the results'. At this point, the combined HDR image is shown and should be saved by right-clicking Medium or Large size 'Radiance RGBE' and select 'save target as' and then give a file name with an extension *.hdr. This will save the file as a Radiance readable HDR file, which can then be opened using the Radiance image viewer. In the Radiance Image viewer, it is then possible to type 't' (for 'trace') and click on any area of the scene to obtain a luminance value, see an example in Figure 10. This will allow further analysis of the image in terms of luminance distribution, directionality, etc. This image may also be used for the glare analysis.

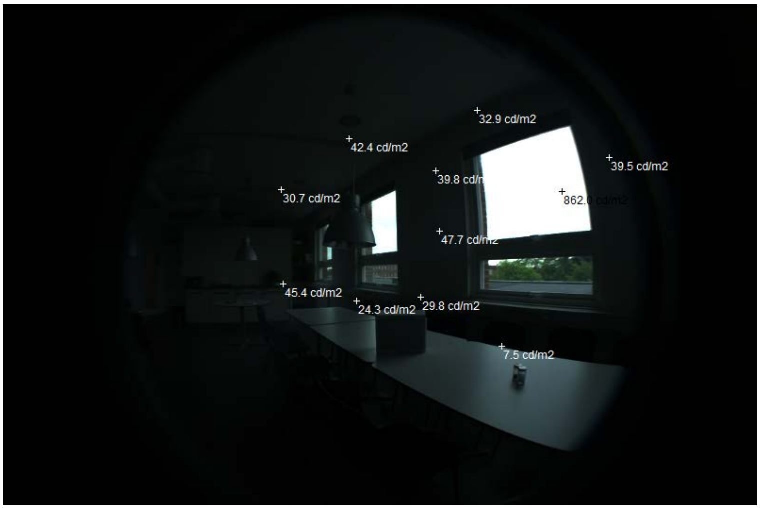


Figure 10 Example of a HDR image produced using WebHDR and opened in the Radiance image viewer.

Programs for obtaining UGR and DGP from HDR images

To obtain glare from HDR images, the programs Evalglare or Findglare can be used, where it is possible in both programs to use fish eye- as well as rectangular images as input. Note however that in Findglare, the light sources that are not in the images but that the eye can see in the peripheral vision will be missed if a non-fisheye image is used. In Evalglare, it is necessary to specify the illuminance value measured at the camera point (corresponding to the vertical illuminance at the eye) and directed parallel to the view direction except if a 180 degree fish eye image is used. Note that in this case Evalglare is more accurate than Findglare, but still it is not as accurate as when using fish eye images. Using rectangular images together with measured vertical illuminance level at the eye is an acceptable method by most experts in the field.

Evalglare

Evalglare (Wienold, 2010) allows calculating the DGP, in addition to the UGR (unified glare rating) and many other glare indices. This program can be installed from the following address: http://www.ise.fraunhofer.de/de/geschaeftsfelder/energieeffiziente-gebaeude/themen/lichttechnik/fue-leistungen/lichtsimulation/radiance. Care needs to be taken, however, to ensure that DGP calculations are not performed for electric light sources, and that standard UGR calculations are not performed for very small or very large electric light sources or daylight scenes, as this would result in inappropriate ratings. It is therefore most appropriate to assess daylight and electric light sources separately at different times. Electric lighting can be best assessed at night or with all windows blocked. The DGP is relevant for working environments with use of computer screen.

Once Evalglare is installed, the .hdr image can be copied in the C: Radiance\bin folder and the following lines can be written in the command line executer (e.g. DOS Shell Prompt) or as a batch (.bat) file:
evalglare image.hdr > image.dat
evalglare -c test.pic image.hdr

The image.dat file contains all the glare indices (DGP and UGR included). Note that there is a restriction on the size of the image, which must be less than 800 by 800 pixels so the pfilt command may have to be used prior to these commands in order to reduce the image size. Note also that the last command line above allows mapping the glare source on the initial HDR image, for visualization purposes.

Findglare

The UGR may also be obtained by using the program glarendx.exe, which is one of the basic Radiance programs. The .hdr image should be copied in the C: Radiance\bin folder and the following lines can be written in the command line executer (e.g. DOS Shell Prompt) or as a batch (.bat) file:
findglare -p image.hdr > image.glr
glarendx -t ugr image.glr > image.dat

The file image.dat contains the value of ugr calculated in the image provided. More information about this application may be found at this address: http://radsite.lbl.gov/radiance/man_html/glarendx.1.html.

7.5. Directionality

The method proposed to evaluate directionality in this protocol is based on a model proposed by Cuttle (1971) called the ‘flow of light’. This flow of light is determined by calculating the vector-to-scalar illuminance ratio (Ashdown, 1998). In this ratio, the vector illuminance (Ev) is described by a direction and a value. The value of the vector illuminance is the difference between the highest illuminance at the surface of the sphere, E(max), and the illuminance measured at the opposite side of the same object, E(-max). The vector direction is from the point of E(max) to the point of E(-max). The scalar illuminance (Es) is defined as the mean illuminance at the surface of the diffuse sphere.

Both vector and scalar illuminances can be obtained from the luminance values retrieved in HDR photographs of the sphere (one on each side), assuming a perfectly Lambertian (diffusing) surface. A white diffuse sphere measuring about 120 mm in diameter may be used. The surface of the sphere could be divided into 24 evenly distributed small areas using elastic bands and pins to define measurement points in the middle of each area, see Figure 11.

Figure 11 Diffuse white sphere with surface divided into 24 similar areas using elastic bands and pins and luminance values retrieved from the HDR image of the sphere.

The luminances at the measurement points can be retrieved from the HDR pictures and illuminances can be calculated afterwards from the luminance values since the reflectance of the sphere is known or can be determined. To enable a luminance measurement at all points in the presence of daylight, the pictures have to be taken from two (or more) opposite sides simultaneously. If it is difficult to take two luminance pictures simultaneously due to lack of measuring devices, it is also possible to take them one after another, using the grey reference surface to adjust the values.

In this protocol, it is suggested to assess light directionality in space using the concept of ‘vectorial to scalar’ illuminance ratio (Ev/Es), see also (Cuttle, 1971, 2003; Ashdown, 1998). In this ratio, the vectorial illuminance (Ev) is obtained by adding all illuminance vectors incident on a sphere placed at a particular point of interest in the space while the scalar illuminance (Es) is defined as the average illuminance on the sphere. The Ev/Es ratio always results in a value between 0 and 4 due to geometrical and mathematical considerations.

This model was tested by studying the preferences of people about the appearance of human faces in an interview situation, see Cuttle et al. (1967) via Cuttle (2003). Ev/Es ratio between 1.2 and 1.8 were generally preferred and a table of interpretation was proposed, see Table 19. In addition, it was found that people preferred a lateral orientation than a more vertical orientation for this so-called ‘flow of light’ and a light vector with an altitude between 15° and 45°. This is probably due to the fact that humans are used to view objects lit by the sun, which is above objects that they are viewing.

In practice, the vector-to-scalar illuminance ratio may be determined by retrieving the luminance value at the center of each small surface area L(p) from the luminance pictures of each side of the sphere. The illuminance at the respective surface points can be calculated using:

$$E = \pi * L(p)/\rho \tag{10}$$

were ρ is the reflectance of the sphere material.

When the illuminances for all surface-points are calculated, the mean value is calculated using:

$$E(s) = \text{MEAN}\ (E(1) + E(2) + E(3)......) \tag{11}$$

Note that a minimum of 20 surface points are needed.

The vector illuminance can then be determined by:

1. Finding the lowest L(min) and the highest L(max) surface-point luminances, which should be perfectly opposite.These points coincide with the illumination vector, with the vector direction - the flow of light - going from maximum to minimum luminance.

2. From L(min) and L(max) it is easy to calculate E(min) and E(max) using equation 10.

3. Calculate the illuminance vector E(v) = E(max)-E(min)

Vector-to-scalar illuminance ratio should then be calculated as:

$$E(V)/E(s) \tag{12}$$

and compared to the assessment from Table 19.

Table 18 Vector-to-scalar illuminance ratio versus perceived directionality, according to CIBSE (1984).

Ev/Es	Typical assessment
3.0	Very strong
2.5	Strong
2.0	Moderately strong
1.5	Moderately weak
1.0	Weak
0.5	Very Weak

7.6. Colour

7.6.1. Correlated colour temperature (CCT)

The European standard SS-EN-12464-1 (2011) provides a table for the interpretation of the apparent colour of a lamp, based on the measured CCT, see Table 21.

Table 19 Apparent colour as a function of CCT (K).

Apparent colour	CCT
Warm	< 3300 K
Intermediate	3300-5300
Cold	> 5300

7.6.2. Colour rendering

In order to provide an objective indication of the colour rendering properties of a light source, the general colour rendering index CRI or Ra has been introduced. The maximum Ra is 100 and this figure decreases with decreasing colour rendering quality (SS-EN-12464-1, 2011). The CRI measures how well a given light source renders a set of test colours relative to a reference source of the same correlated colour temperature as the light source in question (CIE, 1987). The general CRI of the CIE is calculated as the average of special CRIs for eight test colours. The reference light source is a Planckian radiator (incandescent type source) for light sources with CCT below 5000 K and a form of a daylight source for light sources with CCT above 5000 K. The higher the general CRI, the better the colour rendering of a light source, with 100 as the maximum value. Note that the CIE recommends the development of a new colour rendering index (or a set of new colour rendering indices), which should be applicable to all types of light sources including white LEDs, see CIE technical committee TC1-69 Colour Rendering of White Light Sources.

7.7. Flicker

Flicker is produced by the fluctuation of light emitted by a light source. Light sources that are operated with AC supply, produce regular fluctuations in light output. The visibility of these fluctuations depends on the frequency and modulation of the fluctuation. Flicker can even be a hazard to health for some people (IEA, 2010).

At the ‘comprehensive’ monitoring level, a technique proposed by Osterhaus, Stoffer & Erhardtsen (2014) and Kitsinelis et al (2013) could be used. These authors observed that video recordings and still images taken of various light sources with a mobile phone (screen refresh rate of 30 frames per second) clearly exposed photometric flicker of light sources, see Figure 12. This can be used at the ‘comprehensive’ monitoring level, and at this level, flicker can only be detected using the mobile phone with an embedded camera.

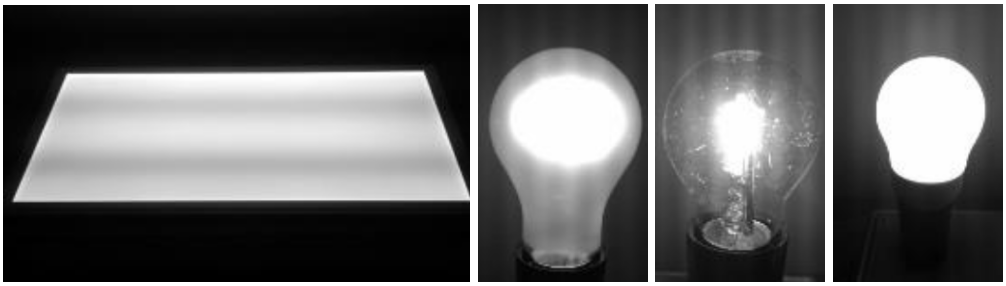


Figure 12 Photographs of flickering light sources taken with a mobile phone camera.

7.8. View

The width of the view (α view) and the approximate view distance (depth) should be registered. The width of view is the sum of the horizontal view angle of all transparent glazing in one facade seen from a reference location in the space, typically from the position of a work place. Movable daylighting systems are withdrawn when the width of the view is determined. At the basic monitoring level, the width of the view is calculated for the center of the selected space using equation 1.

The quality of the view can be evaluated by using the parameters specified in Table 21.

A good view should have a width larger than 28°, a view distance larger than 20 m; it should include a minimum of two layers, and secure the access to the following information: time, weather, location and one of: nature or people.

Table 20 Quantitative view quality parameters.

Parameter	**insufficient**	**sufficient**	**good**	**excellent**
Width of view window(s)	< 14°	> 14°	> 28°	> 54°
Distance of the view	< 6 m	> 6 m	> 20 m	> 50 m
Number of layers: - **sky** - **landscape** (both urban and nature) - **ground**	only sky or only ground	landscape layer is included	Minimum: two layers are included	all layers are included
Environmental information: - **location** (orientation regarding water, food, heat, sunlight, escape routes, destination) - **time** (environmental conditions which relate to our innate biological clocks) - **weather** (need for clothing, need for shelter, heating/cooling, opportunities for sunbath) - **nature** (the presence of trees, bushes plants, insects, birds and other animals) - **people** (the presence of people and their activities)	time and weather	time weather and location	time, weather, location and one of: nature and people	all

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Appendix A – General questionnaire

Dear Sir/Madam,

This questionnaire is part of a research project about lighting retrofit solutions. Lighting plays a central role in guaranteeing a healthy work environment and reducing energy consumption. Your opinion is important, so we would very much appreciate your feedback.

Answers are provided anonymously. At the end of each section you will find a space for additional comments you might wish to provide.

Building: ________________________________ **Room Number or Room ID:** _____________

Date: ________________ and **Time**: _____________ of Questionnaire Completion

GENERAL SATISFACTION WITH THE FOLLOWING ASPECTS OF THIS ROOM

		Very dissatisfied	*Somewhat dissatisfied*	*Neutral*	*Somewhat satisfied*	*Very satisfied*
1.	Daylight	☐	☐	☐	☐	☐
2.	Electric lighting	☐	☐	☐	☐	☐
3.	Noise Level	☐	☐	☐	☐	☐
4.	Odour/Smell	☐	☐	☐	☐	☐
5.	Ventilation	☐	☐	☐	☐	☐
6.	Temperature	☐	☐	☐	☐	☐
7.	Window Size	☐	☐	☐	☐	☐
8.	Privacy	☐	☐	☐	☐	☐
9.	Size of Space	☐	☐	☐	☐	☐
10.	View	☐	☐	☐	☐	☐
11.	Total Room Impression	☐	☐	☐	☐	☐

Additional comments

GENERAL APPRAISAL OF THIS ROOM

How would you rate the total size of all façade windows and/or roof windows in this room?

12. Too small ☐ ☐ ☐ ☐ ☐ ☐ ☐ Too large

How would you rate the total size of those windows providing your view to the outdoors?

13. Too small ☐ ☐ ☐ ☐ ☐ ☐ ☐ Too large

How would you rate the transparency of the window glass with respect to your view out?

14. Too transparent ☐ ☐ ☐ ☐ ☐ ☐ ☐ Not transparent at all

How would you rate the transparency of the solar shading device(s) with respect to your view out?

15. Too transparent ☐ ☐ ☐ ☐ ☐ ☐ ☐ Not transparent at all

How would you generally rate the perceived brightness of this room when the electric lighting is turned off during daylight hours?

16. Never bright enough ☐ ☐ ☐ ☐ ☐ ☐ ☐ Always bright enough

Additional comments

GLARE EXPERIENCE

In general, how often do you experience glare from direct sunlight?

17. Very often ☐ ☐ ☐ ☐ ☐ ☐ ☐ Never

In general, how often do you experience glare from the electric lighting system?

18. Very often ☐ ☐ ☐ ☐ ☐ ☐ ☐ Never

Additional comments

ELECTRIC LIGHTING

How would you rate the appearance/atmosphere of the room under electric lighting?

19. Too cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ Too warm

Do you ever experience any flickering from the electric light sources in this room?

20. Yes, very much ☐ ☐ ☐ ☐ ☐ ☐ ☐ No, not at all

How often is the electric lighting switched on when daylight alone can no longer provide sufficient light to see?

21. Never ☐ ☐ ☐ ☐ ☐ ☐ ☐ Always

How is the electric lighting turned on or off?
22. Always manually by the user ☐ ☐ ☐ ☐ ☐ ☐ ☐ Always by an automated lighting control system

How would you describe the ease of operation of the electric lighting system?
23. Very difficult to operate ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very easy to operate

Does the lighting control system match your visual needs?
24. No, not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Yes, absolutely

Additional comments

ADDITIONAL INFORMATION ABOUT **<u>THE CURRENT SITUATION</u>**

How far away do you sit from the closest window?
25. ☐ Less than 3 meters away ☐ Between 3 and 6 meters away ☐ More than 6 meters away

Is the electric lighting switched on at this moment?
26. ☐ Yes, all of it ☐ Yes, some of it ☐ No

How would you describe the sky conditions outside at this moment?
27. Completely overcast sky ☐ ☐ ☐ ☐ ☐ ☐ ☐ Completely clear sky (no clouds)

ELECTRIC LIGHT AND DAYLIGHT IN THE ROOM **<u>AT THIS MOMENT</u>**

How would you rate the current overall light level in this room?
28. Too little light ☐ ☐ ☐ ☐ ☐ ☐ ☐ Too much light

How would you rate the current light level on your desk/table/workstation?
29. Too little light ☐ ☐ ☐ ☐ ☐ ☐ ☐ Too much light

Do you currently experience any areas in this room which you consider to be too dark (gloomy)?
30. Yes, many ☐ ☐ ☐ ☐ ☐ ☐ ☐ No, none

Do you currently experience any areas in this room which you consider to be too bright?
31. Yes, many ☐ ☐ ☐ ☐ ☐ ☐ ☐ No, none

How well can you see under the current lighting conditions in this room?
32. Very poorly ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very well

Additional comments

Personal Data

33.	Age	<19	19-29	30-39	40-49	50-59	60-69	>70
		☐	☐	☐	☐	☐	☐	☐

34.	Sex	M	F
		☐	☐

Do you use any visual aids (e.g. glasses, contact lenses, magnifying glass, etc.)?

35. ☐ Yes, always ☐ Yes, sometimes ☐ No, never

If you answered yes to the preceding question, please provide further details.

36.	I am shortsighted	I am farsighted	I am both shortsighted and farsighted	I wear bifocal lenses	I wear trifocal lenses	I wear progressive lenses
	☐	☐	☐	☐	☐	☐

Thank you for your contribution!