POLITECNICO DI TORINO

Exploring the evolution and impact of integrative lighting on the design practice: from a systematisation of research methods to a case study application

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Corso di Laurea Magistrale in
Architettura per la Sostenibilità

Tesi di Laurea Magistrale

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The most important scale
is the people scale.

— Jan Gehl

Ai miei genitori,
trampolino di sogni
e rifugio sicuro.

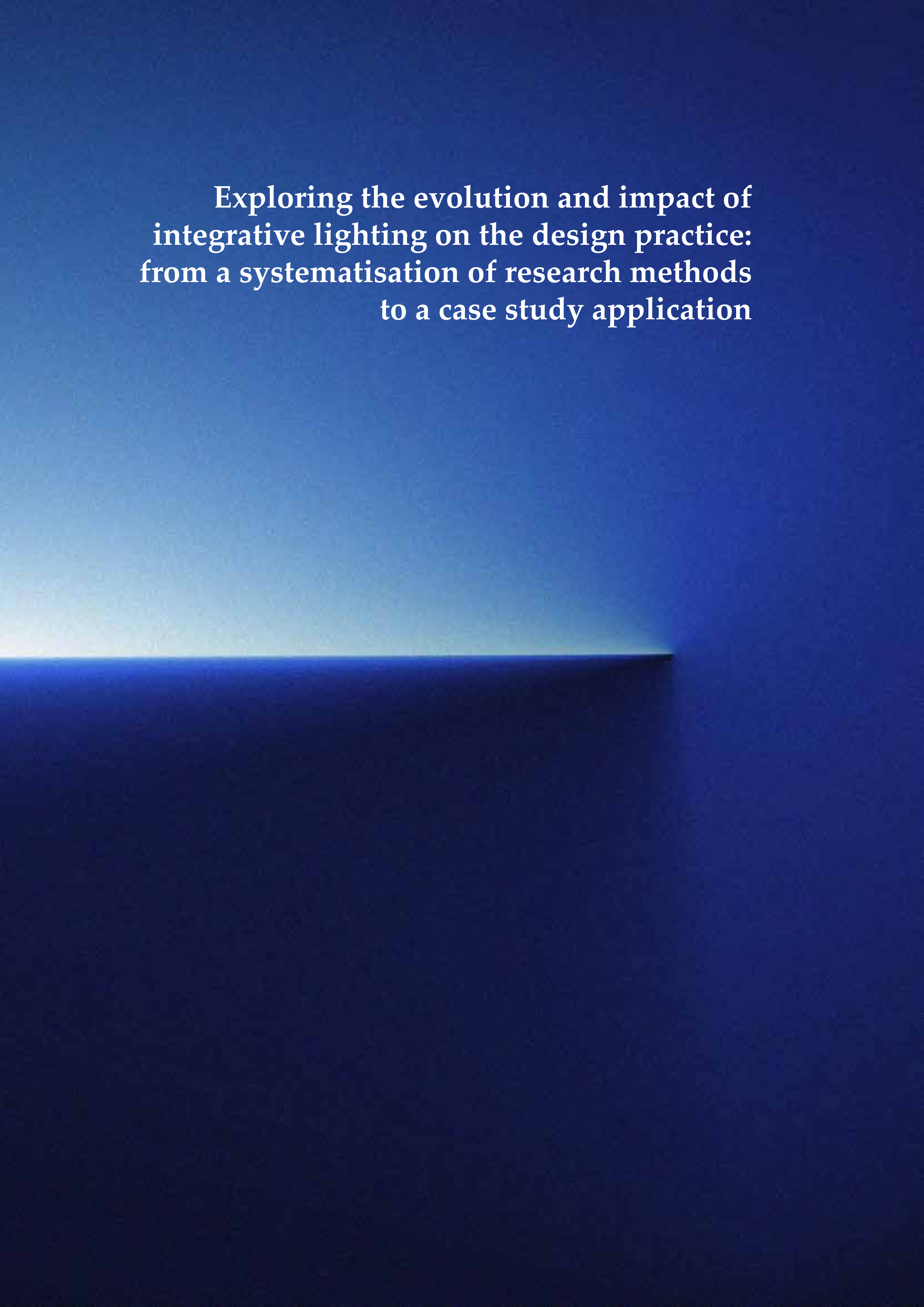
Abstract/EN

Light as a physical phenomenon affects the human organism and its photosensitive systems, leading to a range of visual and non-visual responses. The recently developed discipline of Integrative Lighting considers both visual and non-visual effects of light on humans to facilitate visual tasks but also support overall health and wellbeing. This paradigm shift in lighting practice is underpinned by the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) and the photopigment melanopsin, playing a Non-Image-Forming (NIF) role, which promped a number of studies aimed on enhancing human non-visual wellbeing in indoor environments and developing recommendations in the matter. This relatively recent research is based on a range of methodologies with very different characteristics. As light is able to influence numerous and intrinsically different variables, ranging from environmental factors and conditions to physiological and psychological processes, it is evident that a need exists for the organisation and systematisation of these methods in order to provide research with a suitable tool. This thesis proposes such a tool for standardising research approaches in Integrative Lighting. The tool was then applied in a real case study at the Politecnico di Torino offices; field measurements were taken and daylight and electric light simulations were carried out in order to approach the current recommendations in the practice of Integrative Lighting, which are gaining ground in the most recent lighting standards, currently oriented towards the holistic wellbeing of the person in the built environment.

Abstract/IT

La luce, in quanto fenomeno fisico, influisce sull'organismo umano e sui suoi apparati fotosensibili, provocando una serie di risposte visive e non visive. La disciplina dell'Integrative Lighting, sviluppatasi di recente, considera questi effetti visivi e non visivi della luce sull'uomo per facilitarne le attività visive ma anche per favorirne la salute e il benessere generale. Questo cambiamento di paradigma nel campo dell'illuminotecnica è dovuto alla scoperta delle cellule gangliari retiniche intrinsecamente fotosensibili (ipRGC) e del fotopigmento melanopsina, i quali svolgono un ruolo Non-Image Forming (NIF) che ha dato il via a una serie di studi volti a migliorare il benessere non visivo dell'uomo negli ambienti interni e a sviluppare raccomandazioni in materia. Questa ricerca relativamente recente si basa su una serie di metodologie con caratteristiche molto diverse. Poiché la luce è in grado di influenzare numerose variabili fondamentalmente diverse, che vanno dai fattori e dalle condizioni ambientali ai processi fisiologici e psicologici, è evidente la necessità di organizzare e sistematizzare questi metodi per fornire alla ricerca uno strumento adeguato. Questa tesi propone uno strumento di questo genere, volto a standardizzare gli approcci di ricerca nel campo dell'Integrative Lighting. Tale strumento è stato successivamente applicato in un caso studio reale presso la sede del Politecnico di Torino; sono state effettuate misurazioni in campo e simulazioni di luce diurna ed elettrica per approfondire le attuali raccomandazioni nella pratica dell'Illuminazione Integrativa; queste ultime si stanno affermando nelle più recenti norme illuminotecniche, attualmente sempre più orientate al benessere olistico della persona nell'ambiente costruito.

Exploring the evolution and impact of integrative lighting on the design practice: from a systematisation of research methods to a case study application



Index

Purpose of the thesis

The purpose of this thesis is to examine the discipline of Integrative Lighting in its fundamental characteristics, its evolution and its impact on the design guidelines of the future. As an evolving discipline, Integrative Lighting requires ongoing research; however, in order to achieve valuable findings, a standardised approach to research methodologies, to be applied to real case studies, is essential. Overall, the research undertaken should be able to provide guidelines for architectural and lighting practice to the designers of the future.

1. Theoretical background

Detailed index

1.1. Introduction

Light can be defined as radiant energy that propagates in the form of waves and corpuscular particles. However, the interaction between human beings and light generates a series of processes that lead to just as many disciplines, ranging from physics, biology, anatomy and behaviour to well-being and architectural design, including a multidirectional correlation between them.

What generates vision is, indeed, the intricate interaction between photons of light and the ocular receptors within the human eye. And this is the science beyond the fact that, for millennia, cultures and civilizations have linked light with symbolic and spiritual meanings, shaping narratives, traditions, or artistic expressions. Nowadays, light and vision play a central role in architecture, going beyond mere functional necessities to become essential components of design and human experience, since it is able not only to illuminate spaces, but also to shape them interacting with their form and textures, changing the perception of spaces and evoking emotions within occupants, thus characterising an environment. Beyond visual aspects such as aesthetics, the quality and distribution of light profoundly influence human well-being, affecting circadian rhythms, mood, and productivity. Architects therefore use light as a versatile tool, exploiting its inner properties to design environments both visually appealing and generally beneficial for occupants.

In this first chapter of the thesis, the issues of light as a physical phenomenon and its interaction with the human organism, which can generate both visual and non-visual effects, are explored in depth.

1.2. Understanding Light as a Physical Phenomenon

Nature of light

Light radiation has a dual nature: corpuscular and undulatory. This statement dates back to the 17^{th} and 18^{th} centuries, when two theories of light, still in use today, were formulated: C. Huygens proposed his Undulatory theory in 1678, according to which light is transmitted and behaves as longitudinal waves; while, in his 1704 volume "*Opticks: Or a treatise of the reflections, refractions, inflections, and colours of light*", I. Newton proposed a model of propagation of light in rectilinear motion in the form of corpuscles.

The wave theory was later deepened by the Scottish physicist J.C. Maxwell in 1870 who specified that light is a wave of electromagnetic nature. Two studies were the precursors of Maxwell's four electromagnetic field equations: in 1820, the physicist H.C. Ørsted carried out an experiment in which he observed that a wire carrying an electric current generated a magnetic field. In 1831, M. Faraday wanted to study the relationship between these two phenomena and did so by placing an electric circuit in a magnetic field and varying the strength of the field: an electric current was generated in the circuit. Conversely, in 1861, Maxwell noticed how variations in the electric field produced a magnetic field. This correlation, combined with the two observations that: light travels at the same speed as electromagnetic waves, which is $3 \cdot 10^8$ m/s in a vacuum[1], and is a transverse[2] wave, just like electromagnetic waves, led to the electromagnetic wave theory, according to which light consists of electromagnetic waves.

At the beginning of the 20th century, since the electromagnetic theory couldn't explain the phenomenon of photo electric effect, Plank introduced an innovational concept according to which energy isn't emitted or absorbed continuously but in specific, through countless of “pockets of energy”, indivisible units known as Quantum. Building on this, Einstein, in 1905, defined these energy packets as photons. Nowadays, the understanding is that photons display a dual nature: behaving as particles in case of higher energy and as waves in lower energy areas.

Figure 1.1. Corpuscular and undulatory and quantum theories, a visual simplification.

[1] The speed of light was already known in 1851, when the French physicist Hippolyte Fizeau was able to calculate it in moving water, thereby providing evidence for the wave theory of light.

[2] Waves can be classified as either transverse or longitudinal based on whether the direction of oscillation is parallel or perpendicular to the direction of propagation. Longitudinal waves, like sound waves, results from successive compressions and rarefactions of the medium. In a transverse wave the direction of oscillation and of propagation are perpendicular to each other. Transverse waves are all electromagnetic waves, such as light, X-rays, or radio waves.

Characteristics and properties of light radiation

In general, to describe purely optical phenomena such as diffraction, reflection, refraction, scattering, and more, the wave theory can be used.

In this case, light is depictable as sinusoidal curves quantifiable using:

- Wave Period (T): Time needed for two successive crests to pass a specified point;
- Wavelength (λ): Distance between adjacent crests. In the case of visible light, the wavelengths are expressed in nanometres (nm), units of 10^{-9} m. The metric used to represent the wavelength is expressed through the greek letter lambda λ;
- Width: Difference between maximum (crest) and minimum (trough) values;
- Frequency (f): Number of complete oscillation cycles occurring in each second, measured in hertz [Hz]. Frequency is inversely proportional to the period.

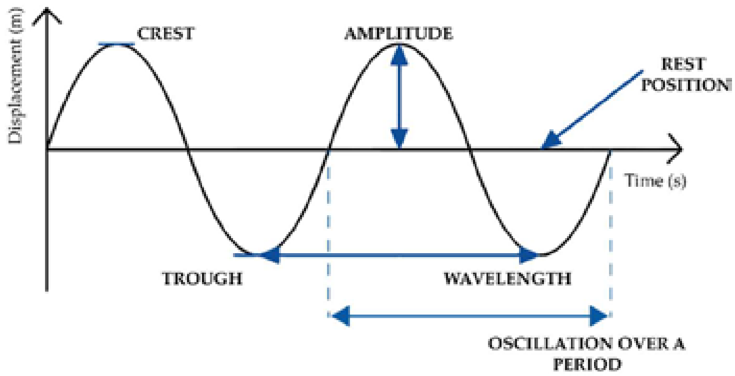


Figure 1.2. Wave properties (Personal manipulation of the Wave Definitions Image from "thescienceandmathszone.com").

Electromagnetic radiation is normally composed of radiation of different wavelengths and is caused by the simultaneous propagation of periodic perturbations of an electric field and a magnetic field oscillating in mutually orthogonal planes.

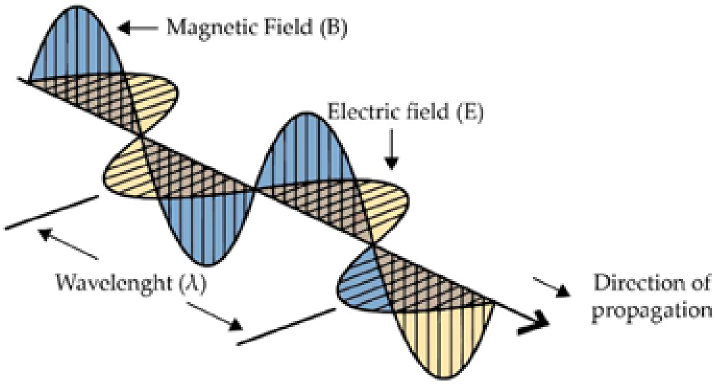


Figure 1.3. Magnetic and electric field of a light photon.

Light as a form of electromagnetic radiation takes part in the electromagnetic spectrum, that represents the totality of electromagnetic radiation.

> *The electromagnetic spectrum is traditionally divided into a number of spectral ranges that differ in the techniques used to analyse the radiation: X (XR), 0.001 nm to 1 nm; Ultraviolet (UV), 0.001 µm to 0.4 µm; Visible (V), 0.4 µm to 0.7 µm; Near-InfraRed (NIR), 0.7 µm to 3.0 µm; Mid-InfraRed (MIR), 3.0 µm to 30 µm; Far InfraRed (FIR), 30 µm to 1 mm; Millimetric, 1 mm to 10 mm; Microwave (MW), 10 mm to 1 m; Radio, 1 m to 10 m"* (Palladino, 2018).

Light is the portion of the spectrum between 380nm and 750nm.

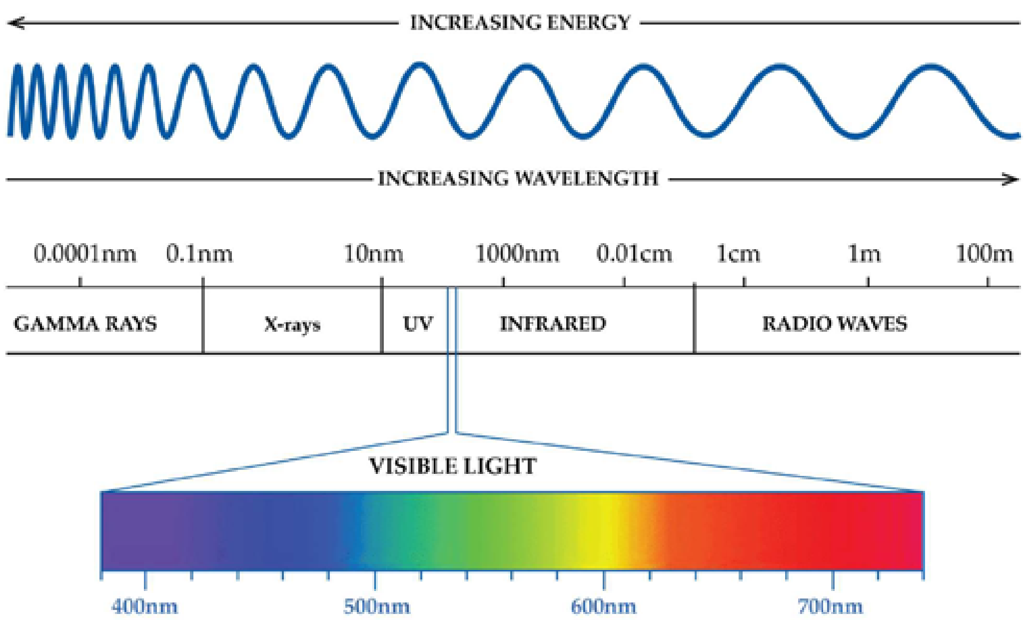


Figure 1.4. Electromagnetic and visible light spectra.

Moreover, other properties of light refer, for example, to its way of propagation: when unobstructed, light propagates in a straight line (proven by how shadows form), instead, it can be deflected in case of obstacles. This introduces the topic of the interaction between light and matter. Said interaction results in a series of phenomena: absorption, diffraction, scattering, interference, polarisation, reflection, refraction, transmission[3].

Optics

The discipline that studies light as a luminous phenomenon, its characteristics and properties and the interaction between light and matter, is optics, whose etymology comes from the Greek word *optikḗ* (*tékhnē*), meaning the art of visual things.

[3] Discussed in more detail in the following section.

As previously described, four different optical models have been developed through the years to describe the complex nature and countless phenomena associated to light: the ray model, the wave model, the electromagnetic model and the quantum model. Each refers to one of three branches of optics: geometric optics - which studies optical phenomena by assuming that light propagates in straight lines; physical optics - which exploits the wave-like character of light as electromagnetic radiation; and quantum optics - which describes light and its interaction with matter according to the postulates of quantum mechanics[4].

In brief, different models refer and explain different interactions between light and matter, as an example, taking the case of the ray model, a ray incident on a surface produces three phenomena: absorption, reflection and transmission.

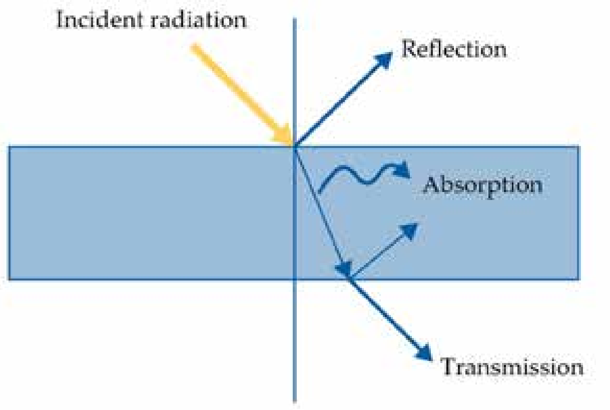


Figure 1.5. Incident radiation split into reflected, absorbed and transmitted components.

Radiometric quantities

Radiometric quantities are physical quantities describing a series of phenomena related to the emission and propagation of electromagnetic waves, thus related to energy per time, the most important of which are Radiant Emittance (M), Radiance (L), Irradiance (E).

These quantities and the laws that led to their theorisation have their origin in the fundamental blackbody theory:

> "A blackbody is defined as an ideal body that allows all incident radiation to pass into it (zero reflectance) and that absorbs internally all the incident radiation (zero transmittance)." [5]

[4] **Quantum mechanics** is a scientific discipline about the behaviors of matter and light at the atomic and subatomic levels. It focuses on properties and interactions of fundamental particles such as electrons, protons, neutrons, and more complex entities like quarks and gluons. This study explains how these particles interact with each other and with forms of electromagnetic radiation, including light, X-rays, and gamma rays. (Squires L.G., 2023, "quantum mechanics", Encyclopedia Britannica, https://www.britannica. com/science/quantum-mechanics-physics).
[5] Encyclopedia of Physical Science and Technology, Third Edition, 2003.

The black body is useful as a theoretical model because it is a perfect emitter: in simple terms, the energy it absorbs is equal to the energy it emits. This concept has been fundamental to the development of physical laws such as the Stefan-Boltzmann law (which allows us to understand the relationship between the energy emitted and the temperature of a black body) and Wien's law (which describes the density of emitted energy as a function of wavelength).

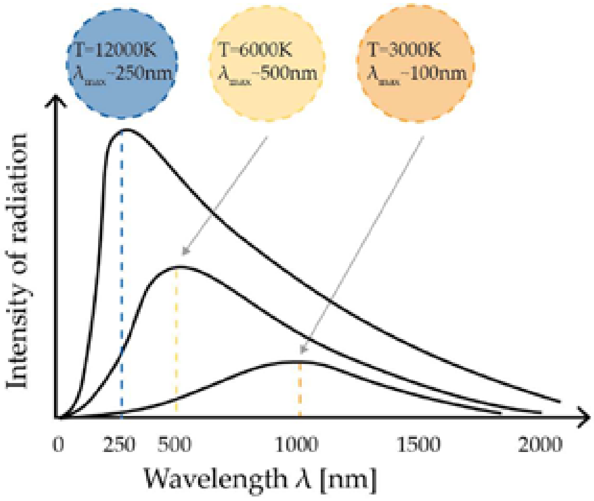


Figure 1.6. Visualisation of Wien's Law: relationship between wavelength and radiation intensity.

- **Radiant Emittance (M):** represents the radiant flux emitted by a body, measured in watts [W]. To limit the analysis on the visible spectrum, the value of Radiant Spectral Power Density ($M\lambda$) is adopted, whose curve indicates the amount of each radiation present in a given light; objectively characterising the chromaticity of a light, not considering the subjective feeling of a possible observer.

- **Radiant Intensity (I):** is the radiant flux emitted by a point source in a conoid of a unit solid angle, the axis of which points in a given direction. The SI unit for radiant intensity is the watt per steradian (W/sr).

- **Radiance (L):** the radiant flux (W) is the amount of radiant energy emitted, transmitted, or received per unit time, radiance is then the radiant flux density emanating from a surface per unit solid angle [W/m^2sr]. The radiance within the visible spectrum is referred to as the spectral radiance ($L\lambda$).

- **Irradiance (E):** Irradiance is the density of radiant power per unit area. Its version dealing with the visible spectrum is spectral irradiance ($E\lambda$).

Light sources

Light is a form of energy and, as such, is produced by a source. According to their origin, light sources can be categorised in a binomial way; natural light sources and artificial light sources.

Natural light sources, on earth, are limited to the sun. The sun belongs to the spectral class of yellow stars (also labelled as G2), a classification based on surface temperature, since, similar to a black body, it has a temperature of the emitting layer around 5800K; approximately 99% of solar radiation emerges from this layer[6]. The spectrum of solar radiation, an energy in the form of electromagnetic waves, is between 230 and 4000nm, emitting in both the visible and non-visible spectra, with a specific repartition corresponding to 7% ultraviolet radiation, 40% visible radiation and 53% infrared radiation[7], and emitting continuously at each wavelength in the visible. Dealing with the interaction between the sun and the earth, it is essential to acknowledge the celestial vault; the sun's radiation, in fact, as it passes through the earth's atmosphere, is split into three components: reflected, absorbed and diffused. Diffusion is due to the composition of the celestial vault containing oxygen and nitrogen molecules.

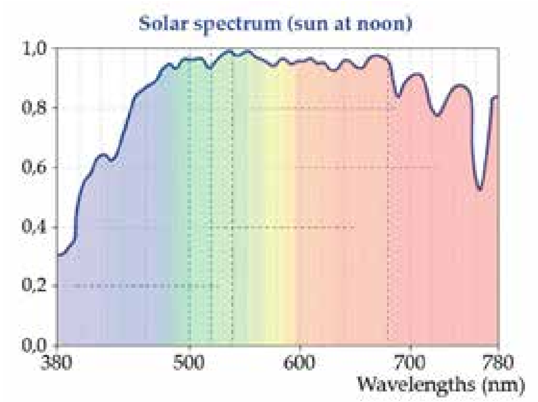


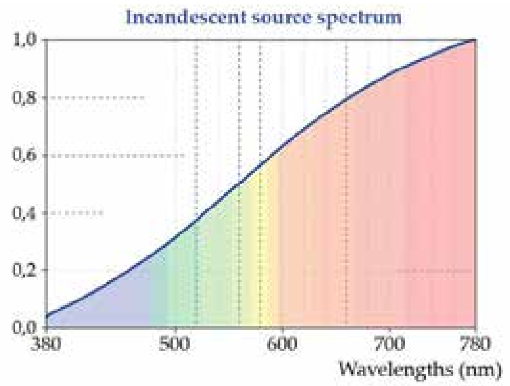
Figure 1.7. Solar emission spectrum.

One of the main characteristics of natural light is the fact that it is dynamic, not controllable. This characteristic is due to several factors including the position of the sun, both on the celestial vault and in relation to the observed surface and its orientation, as well as differences in sky conditions, the air moisture content that affects its diffusion, etc. The solar radiation incident on earth varies by the hour, day and year due to the inclination of the earth's axis and its rotation.

Modern artificial light sources are all the result of the development of technologies capable of transforming electrical energy into a luminous flux. A classification of electric light sources is based on their generative technology and the characteristics of the emitted radiation; in this context, the most relevant are incandescent, fluorescent and LED sources.

[6] (Coddington et al., 2016).
[7] (Degl'Innocenti, 2008).

The functioning of incandescent lamps is based on the Joule effect: an electric current passing through a conductor causes its heating. While fluorescent lamps are based on the concept of transforming ultraviolet radiation into visible radiation. In numerical terms, lifetime and efficiency are the main values in which large differences can be identified between the two types of lamps: an incandescent lamp emits an average of 1000 hours as opposed to the 60000 hours of a fluorescent lamp. Similarly, the efficiency of an incandescent lamp is approximately 12 lm/W[8], which is very low, in contrast to that of a fluorescent lamp which can exceed 120 lm/W[8], considered as particularly high.



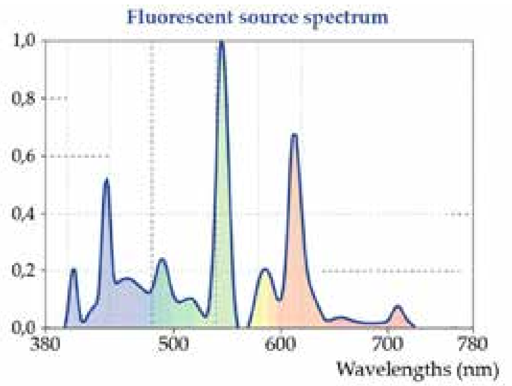


Figure 1.8. Incandescent source spectrum. Figure 1.9. Fluorescent source spectrum.

LEDs are based on electroluminescence, the emission of light from a semiconductor carried by electricity. Depending on the composition of the semiconductor (which may consist of zinc selenide, gallium phosphate, aluminium, arsenic, etc.) different emissions corresponding to different colours occur; the chip of a power led consists of several layers of doped semiconductor (i.e. with impurities added to change its conductivity properties) designed to maximise the emitted flux. The specific properties of LEDs have enabled their widespread use and asserted them as the primary option in the field; in particular thanks to the luminous efficiency which can be as high as 200 lm/W[8], long lifetime and its flux decay, and extremely low power consumption and versatility.

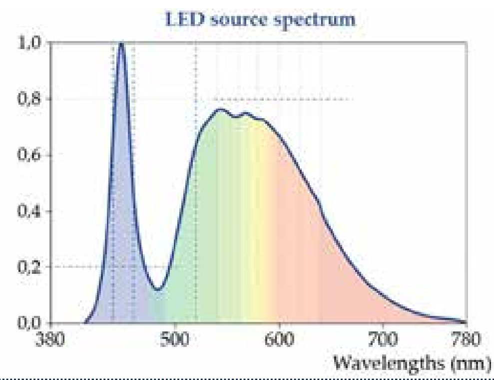


Figure 1.10. White light LED source spectrum.

[8] (Palladino, 2018).

1.3. Interaction between Light and Humans

Introduction

Light has always been a fundamental element of human existence, taking part in countless aspects of life. First and foremost, light facilitates vision, granting us the ability to perceive the world around us and to navigate it by interpreting our surroundings. Beyond mere sight, light plays an indispensable role in sustaining life itself, as it is the basic element for photosynthesis, the process by which plants exploit the energy coming from the sun to convert carbon dioxide and water into oxygen and glucose: the basis of the food chain and therefore our sustenance. Light is also able to affect our well-being, regulating circadian rhythms and influencing mood and productivity. Beyond these physical-biological aspects of the interaction between light and humans, thinking about disciplines related to art, culture and spirituality, we realise how light actually shapes and is indispensable to each of them. Thus, from nourishing our bodies to balancing our wellbeing, light is an essential element in almost every aspect of human life.

Referring only to the scientific side of human perception, researchers P. Boyce and M. Rea have come up with an intuitive and conceptual scheme taking account both the visual system, the circadian system and the perceptual system and displaying how light can influence human performance through them:

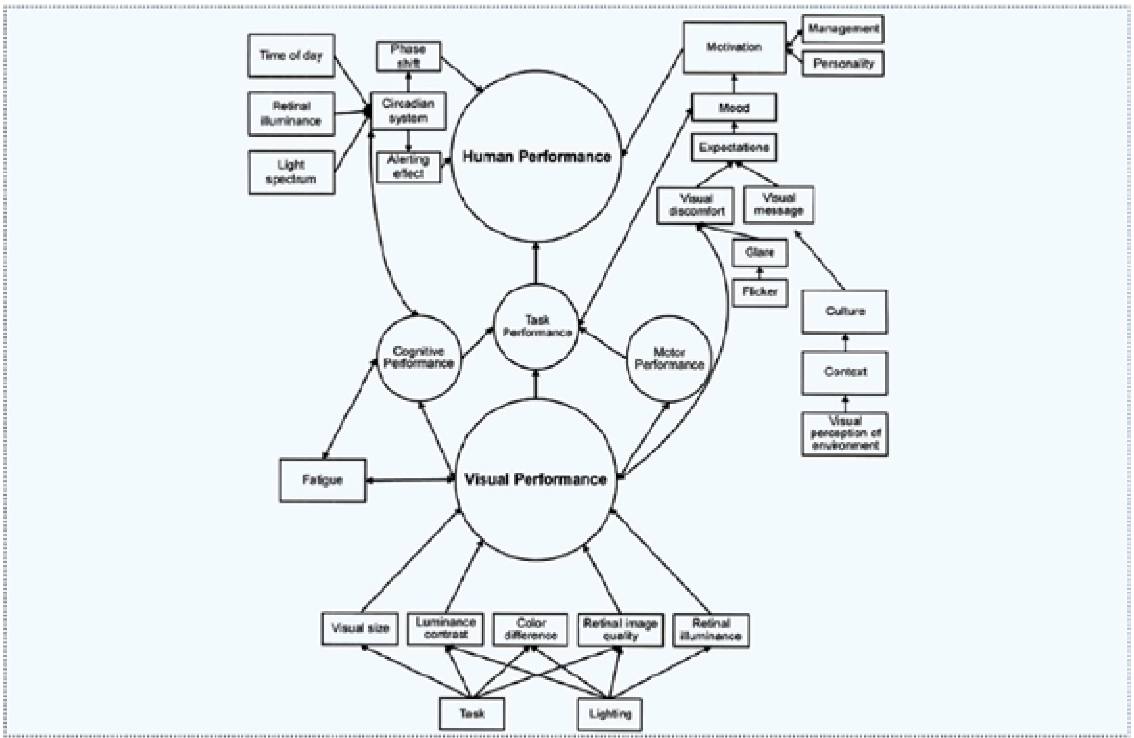
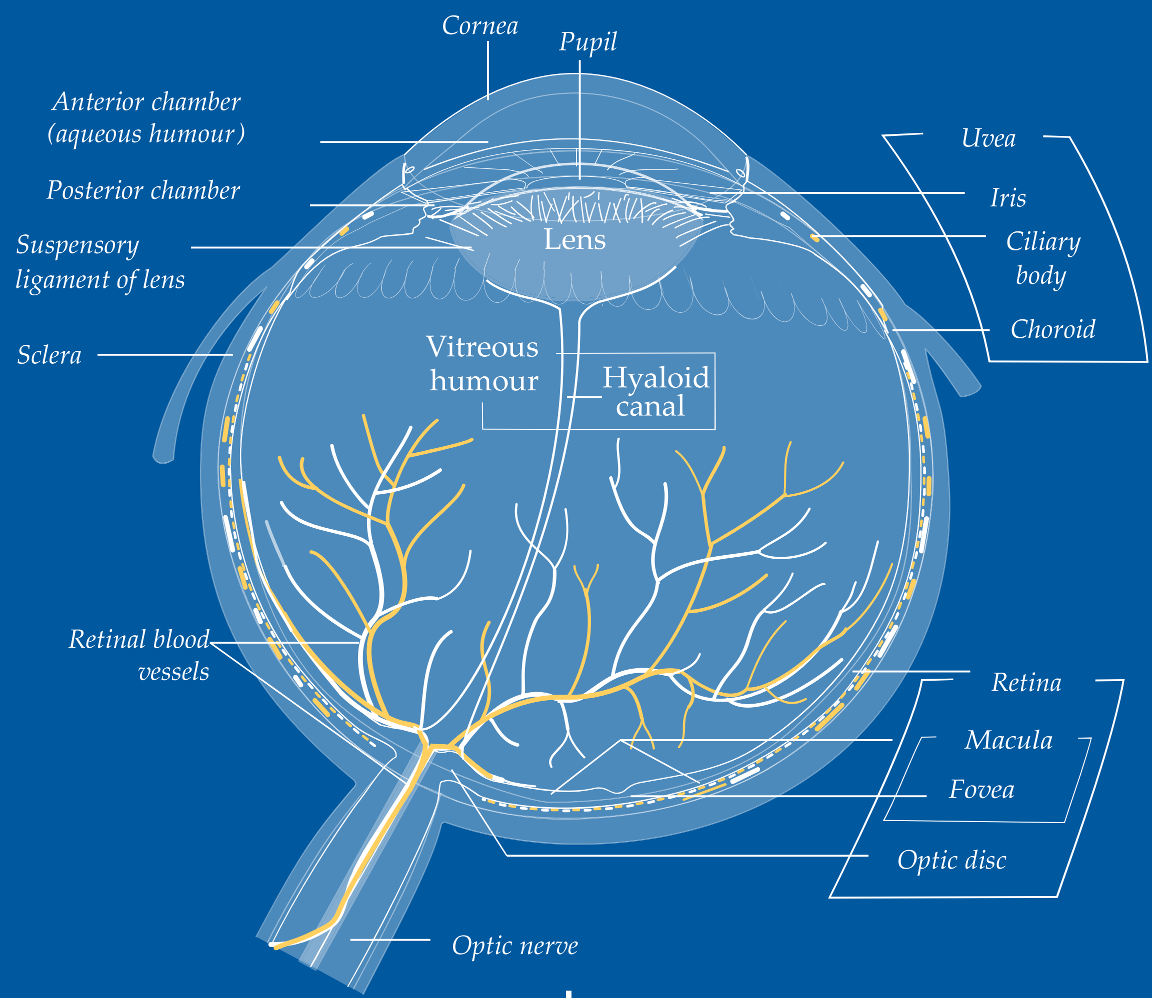


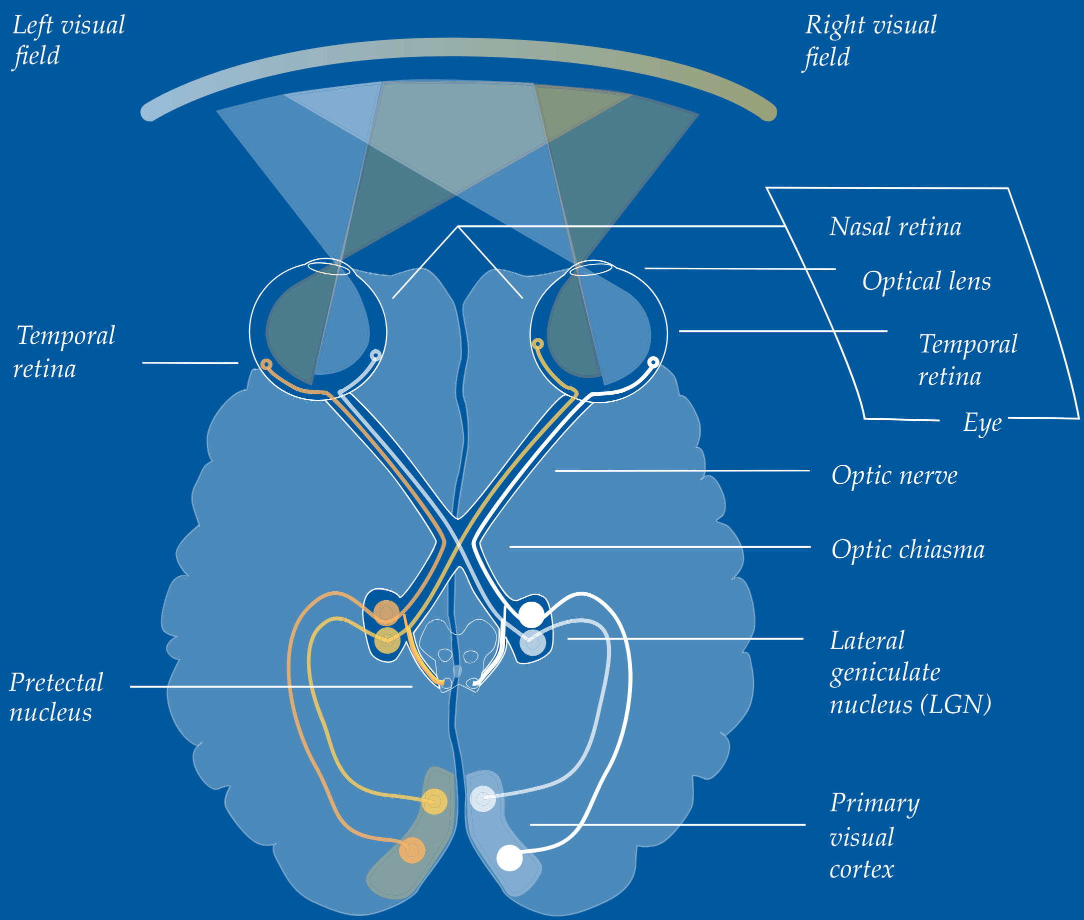
Figure 1.11. A conceptual framework setting out the routes by which lighting can influence human performance. The arrows indicate the direction of the effects (Boyce and Rea, 2001).

EYE ANATOMY

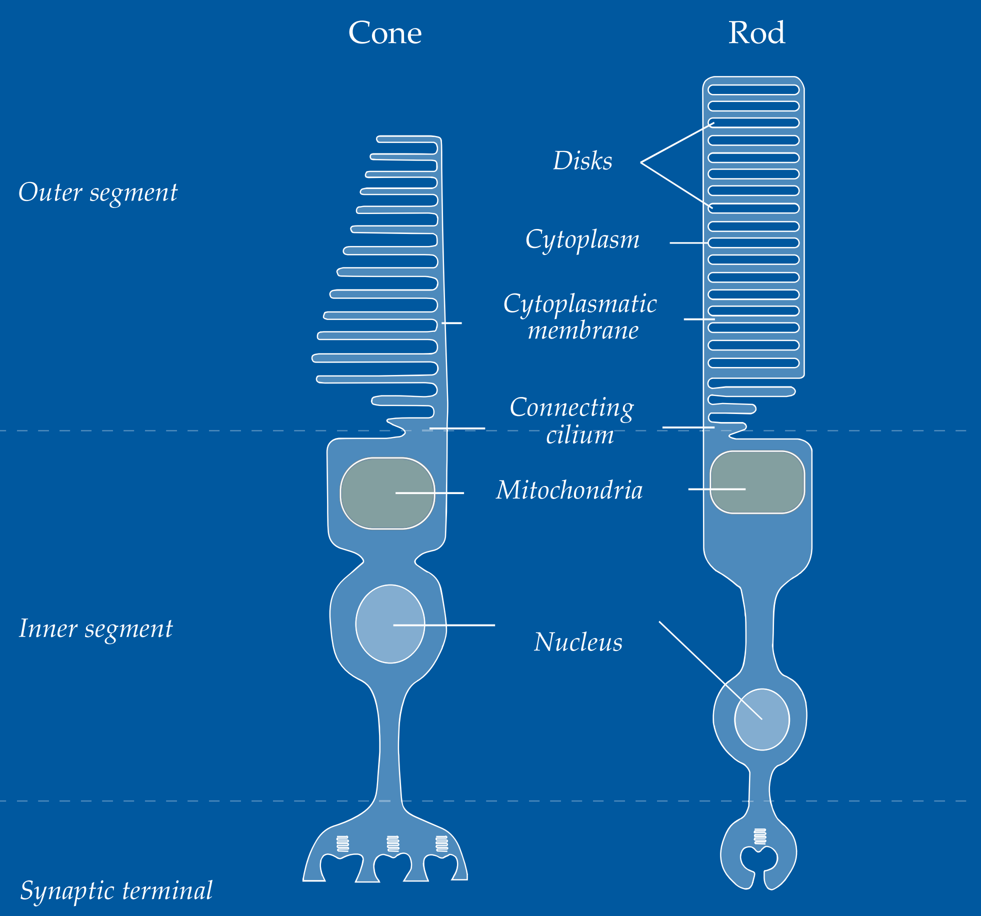


The visual system

VISUAL PATHWAY

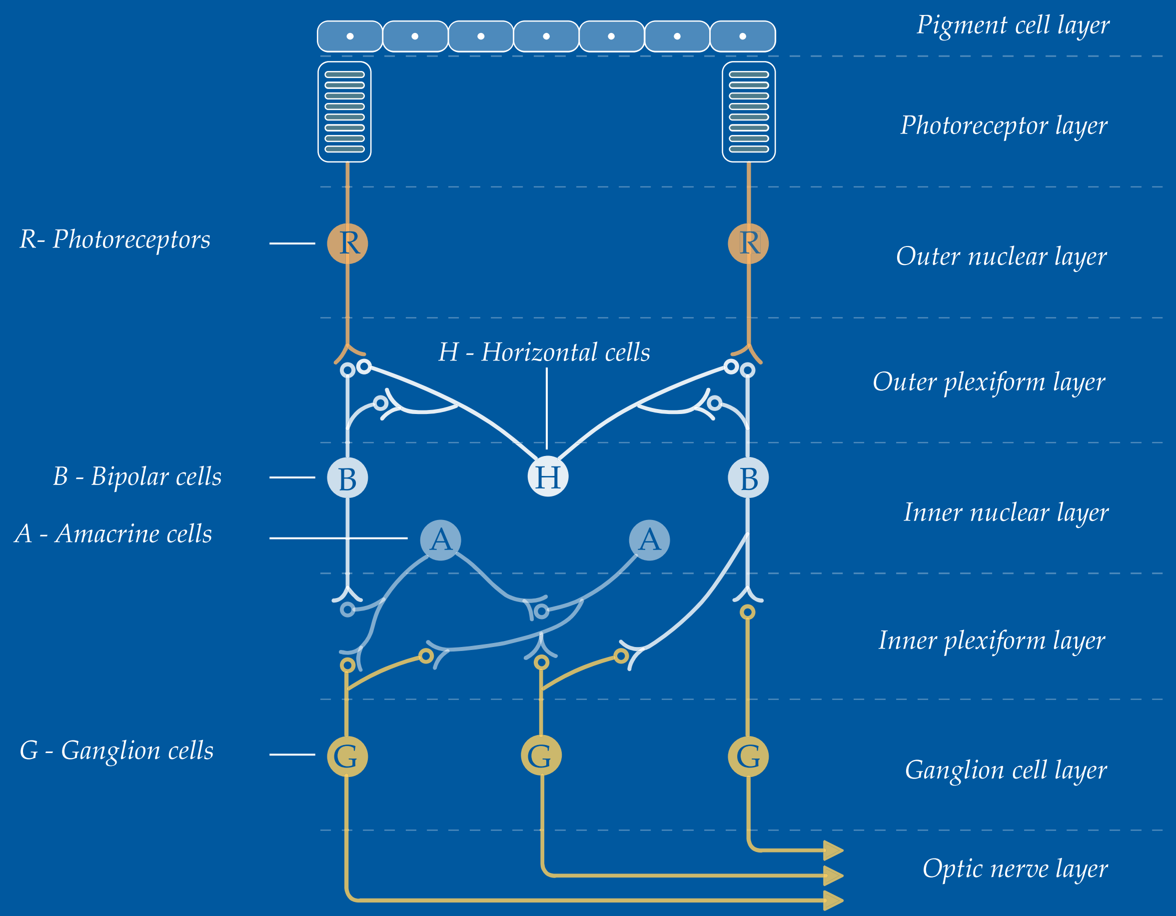


PHOTORECEPTORS



Photoreception

LAYERS OF THE RETINA



1.3.1. Visual Effects of Light on Humans

The visual system

The visual system is the detector that transforms radiant power into luminous sensation. "Hence, one may say that a burning candle emits radiation, but that the radiation does not become light unless a human perceives it" (Sterken & Manfroid, 1992). (Schreuder, 2008)

Several anatomical structures interact in the visual system in order to activate the process that converts photons of light into electrical signals, which the brain then translates into representations of our surroundings.

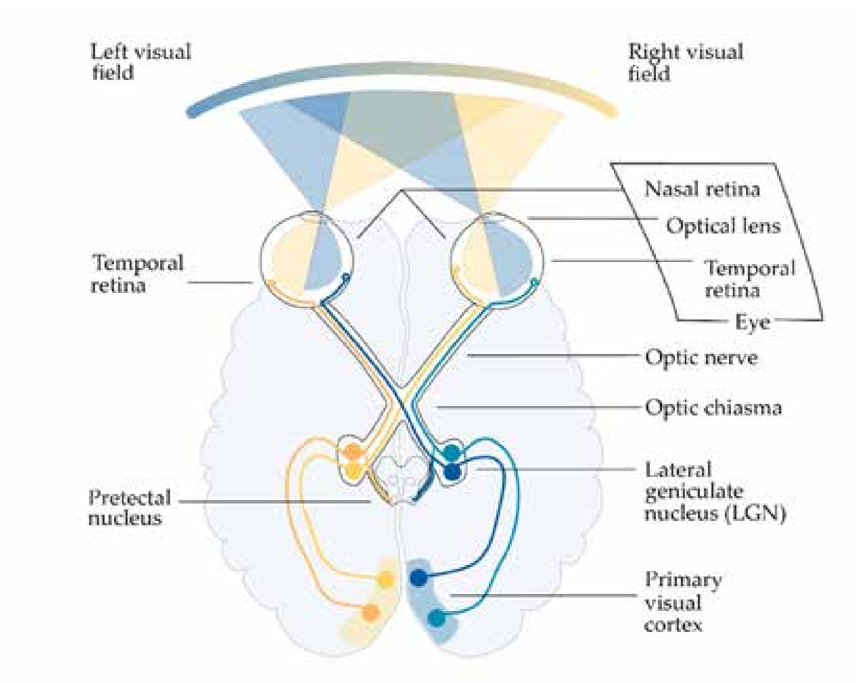


Figure 1.12. Visual pathway (Personal manipulation of A simplified schema of the human visual pathway by Miquel Perello Nieto, 2015).

Specifically, in humans, the primary visual cortex, a layered structure of neurons within the cerebral cortex, is the initial area responsible for processing visual information, which travel along a pathway connecting the retina to the brain. Such information come from the retina's light-sensitive elements, rods and cones, to the optic nerve, formed by a bond of axons. At the optic chiasm the nerve fibres cross over to the opposite hemisphere so that each half of the visual field is processed by the opposite side of the brain. Thereafter, at the end of the optic tract is located the lateral geniculate nucleus (LGN) of the thalamus which refines visual signals prior to their transmission to the cerebral cortex; the primary visual cortex then serves to integrate given inputs from both eyes, creating a map of such visual inputs in the brain.

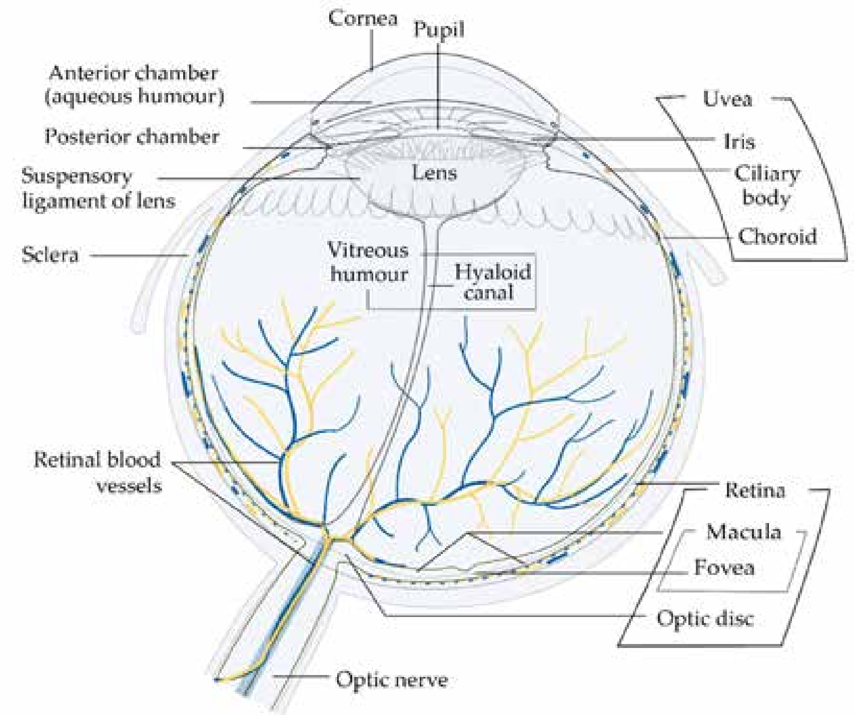


Figure 1.13. Eye anatomy (Personal manipulation of Diagram of the human eye in English. It shows the lower part of the right eye after a central and horizontal section by R.H. Castilhos and J.Marchn, 2007).

The eye is the sensory organ that allows vision in the organism. It is possible to subdivide the organ into three concentric layers, a first fibrous layer containing the cornea and sclera, a central vascular layer housing the iris and choroid, and an inner neural layer belonging to the retina. Another subdivision consists of the anterior and posterior chambers, the anterior chamber includes fundamental elements such as the lens, which concentrates and focuses thanks to the contraction of muscles and the pupil that regulates the brightness of the image that arrives upside down on the retina. Instead, the vitreous humour, a transparent fluid that occupies the space in between the lens and the retina, is located in the posterior chamber

Within the visual process, the retina plays a fundamental role as it contains a receptive field, in other words, it is entirely covered by a surface of photoreceptors. However, the retina's wiring is made up of 50 distinct cell types[9] arranged on eight successive levels. In the outer layer epithelial cells called pigments serve to absorb light. The photoreceptor layer, outer nuclear layer and outer plexiform layer contain the photoreceptors rods and cones, their nuclei and their synapses with interneurons. Such interneurons of various kinds are found in the inner nuclear layer and their synaptic elements are confined in the inner plexiform layer. The ganglion cell level contains, as its name indicates, ganglion cells, the output-containing cells of the retina. Finally, the ganglion cells, which are composed of neurons, axons and synapses, constitute the optic nerve through the connection of said axons, this part of the retina is called optic nerve layer.

[9] (Masland, 2001b).

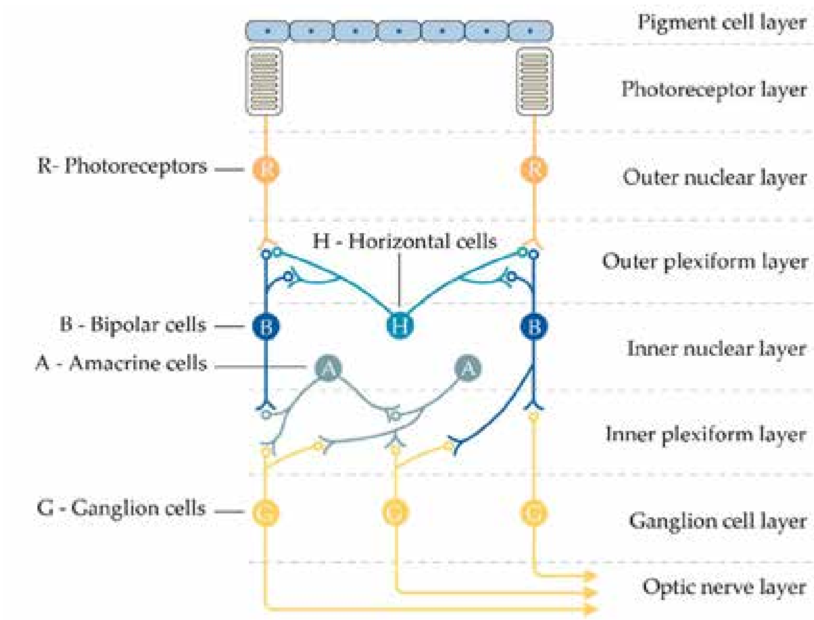


Figure 1.14. Retina structure (Personal manipulation of Layers of the retina from "doctorlib.info").

Of this entire system, a key role is played by photoreceptors, a mosaic[10] of cells distinguished in cones and rods that take on different functions in translating the light signals to be transmitted to the brain.

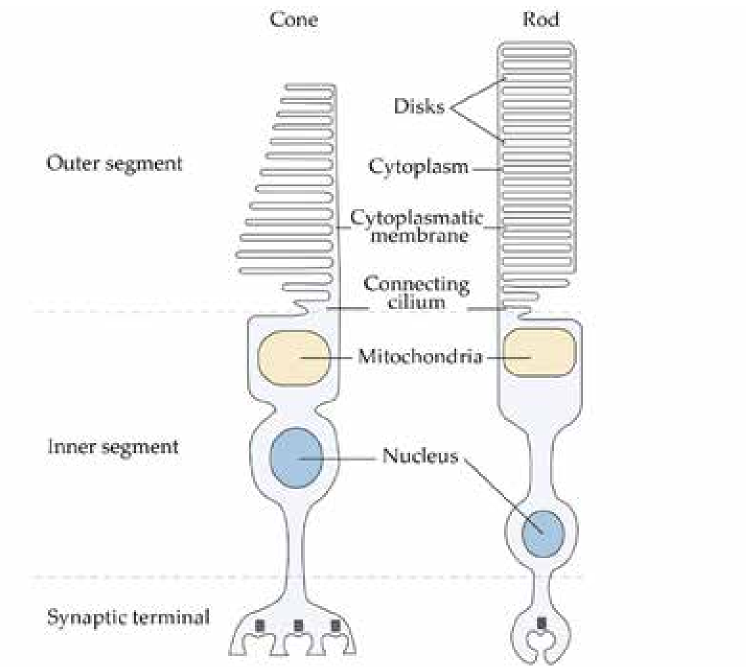


Figure 1.15. Photoreceptors (Personal manipulation of Schematic diagram of vertebrate rod and cone photoreceptors by Rick H. Cote, 2006).

[10] (Schnapf and Baylor, 1987).

Cones and rods are responsible for mediating photopic and scotopic vision, respectively. Rods are highly sensitive to low-intensity light, making them crucial for vision in dim conditions, or scotopic vision. They show low visual acuity and do not contribute to colour vision. In contrast, cones function optimally under bright conditions and are responsible for photopic vision; moreover, cones provide high visual acuity and enable colour perception. The structure of these photoreceptors is specialized for their functions; rods contain the pigment rhodopsin and are designed to operate in low light, while cones, with their three types of pigments sensitive to different wavelengths, are adapted for daylight and colour detection. Both photoreceptors function by hyperpolarising in response to lighting stimuli.

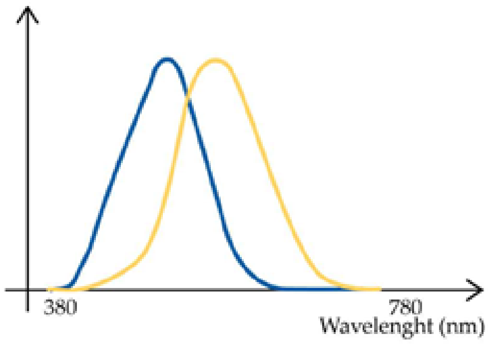
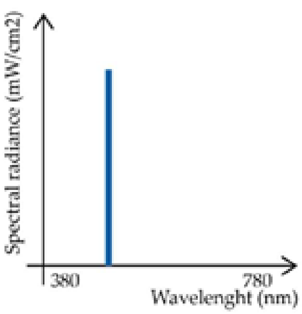


Figure 1.16. Photopic (yellow) and scotopic (blue) curves.

However, as mentioned in the previous section, the human visual system is only sensitive to a very narrow range of frequencies on the electromagnetic spectrum; portion called visible spectrum and delimited between the values of 380nm and 780nm. The human eye therefore perceives the individual radiations within this range as different colours because each radiation corresponds, through the visual system, to a different colour sensation. The radiation that reaches the eye can be monochromatic, containing a single wavelength, or polychromatic, or a combination of several wavelengths in the visible spectrum; the latter is the reason why humans are able to distinguish shades of colour, as well as white, grey and black (although these do not correspond to a single wavelength). This is because the eye is a synthetic instrument that receives a series of wavelengths and synthesises them into a single perception.



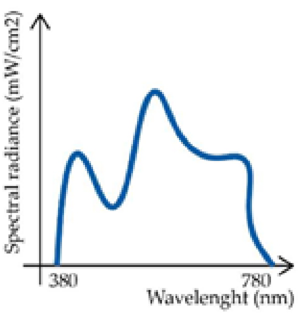


Figure 1.17. Monochromatic radiation. Figure 1.18. Polychromatic radiation.

Visual effects of light on humans

The visual system

Photometry

The purpose of photometry is to measure light in a way that takes the sensitivity of human visual system into account. While radiometry measures light in all spectral regions, including ultraviolet and infrared, photometry only measures in the visible spectral region from 360 nm to 830 nm, where human eyes are sensitive. Thus, photometry is essential for evaluation of light sources and objects used for lighting, signaling, displays, and other applications where light is intended to be seen by humans. (C. Miller, Y. Zong, Y. Ohno, 2009)

Photometric quantities

In contrast to the radiometric quantities, specific for energy but not capable of declining according to the sensitivity of the human visual system, photometric quantities weight the radiated energy in the visible spectrum according to the spectral sensitivity curve of the human eye. For this reason, each radiometric quantity corresponds to a weighted photometric quantity: what in optics is the spectral radiant emittance (Mλ), in photometry is the luminous flux (Φ); the same applies to spectral irradiance (Eλ) and illuminance (E) and explains the correspondence between spectral radiance (Lλ) and luminance (L).

Energy quantities weighed according to the photopic sensitivity of the human eye are:

- **Luminous flux (Φ):** luminous flux is the time rate of flow of radiant energy, evaluated in terms of a standardized visual response [lm][11].
- **Luminous intensity (I):** It is the luminous flux per unit solid angle in a specified direction[11], measured in candela [cd].
- **Illuminance (E):** Again, starting with the fundamental luminous flux, the illuminance represents the areal density of the luminous flux incident at a point on a surface; it is measured in lux [lx] and is formulated as: $E=d\Phi d/S$[11].
- **Luminance (L):** Luminance applies to any specific surface and depends on its physical characteristics and the position of the observer. It defines the luminous intensity emitted or re-emitted by a surface in a given direction and quantifies the luminous impression on the observer. Luminance is considered fundamental for glare assessment. Its unit of measurement is the candela/square metre [cd/m²].

Measurement techniques

In ancient times, the phenomenon of light was simply assessed through the eyes of an observer and quantified by comparation between different light sources or the luminances of different surfaces. The first example comes from astronomical photometry: the *Commentary on Aratus and Eudoxus* of the Greek astronomer and mathematician Hipparcus (190-120BC) who catalogued the stars of different constellations by comparing their brightness. This took a turn with the invention of the telescope, through such instrument stars could appear a lot brighter than what was previously assessed.

[11] ANSI/IES LS-1-22, Lighting Science: Nomenclature And Definitions For Illuminating Engineering.

It was, however, at the middle of the 19th century that Steinheil, Zollner and Pickering invented what are considered the most important visual comparative photometers. Late into the 19th century scientist began to experiment through photocells of the first kind, or photovoltaics, and of the second kind, or photoconductive. Anyway, interest in these elements was soon lost as it was diverted to photoelectric cells, also referred to as photocells of the third kind; these cells detected photoelectrons[12] released when certain elements absorbed light and then measured using a sensitive electrometer[13], allowing researchers in astronomical photometry to identify the brightness variations of stars. Thanks to photography at the beginning of the 20th century two photometric systems, each specifically sensitive to a different predominant wavelength, were already largely used; subsequently to the 9th General Assembly of the International Astronomical Union (Dublin, 1955) came the standardization of two-colour photometry. The development of the earliest photomultiplier tubes (PMTs) led to the possibility to count individual photons, being able to "convert light into an electrical signal" [14]. This discovery was one of the key events that gave rise to modern photometry, where today's sensors known as detectors (or photocells) transform incident electromagnetic radiation into a corresponding electrical signal, measuring light radiation more precisely.

The fundamental measuring instruments for current photometry will be analysed below:

- **Luxmeter**: The luxmeter is used to measure illuminance and is based on a photoelectric cell that generates an electric current proportional to the illuminance received by the instrument.
- **Photometric bench**: The photometric bench is the instrument capable of providing luminous intensity values of an unknown source using a reference one.
- **Goniophotometer**: Another instrument used to measure light intensity is the goniophotometer. Equipped with a photocell, it is used by taking several measurements of illuminance at different distances from the light source; given the values of illuminance and distance, the light intensity is calculated.
- **Ulbricht's sphere**: This interesting instrument, consisting of a concave metal sphere, larger than the light source to be measured by placing it inside, allows the light flux to be measured. Its operation is based on the principle that the source, placed inside the sphere, produces a series of reflections that result in a constant illuminance on all points of the sphere's surface; from the illuminance value, the flux value is obtained.
- **Luminance meter**: The luminance meter consists of a photoelectric cell and an optical system that projects the image of the surface to be measured onto the surface of the cell, providing the luminance value of that surface.

[12] A photoelectron is an electron emitted when electromagnetic radiation, such as light, hits a material (the process itself is called photoelectric effect).

[13] "An instrument for detecting or determining the magnitude of a potential difference or charge by the electrostatic forces between charged bodies". In: Collins English Dictionary, HarperCollins Publishers, (https://www.collinsdictionary.com/dictionary/english/electrometer).

[14] (Flyckt et al., 2002).

Statistical studies indicate that humans perceive with hearing at a rate of 12%, touch and taste at 2%, smell at 3%, and sight at 83%; of what has been perceived the memory records 20% of what has been heard and 40% of what has been seen[15]. These findings introduce the topic of visual dominance:

An interesting 2019 investigation by Professor F. Hutmacher of the University of Regensburg, Germany, on research related to sensory perception noted that the sense of sight plays a more prominent role than the other four human senses. With the support of a previous research on the same topic by Gallace and Spence (2009), he was able to produce a statistic on the number of studies focusing on the five human senses and their correlation with memory, finally providing extremely comprehensive graphs on the distribution of research in the field.

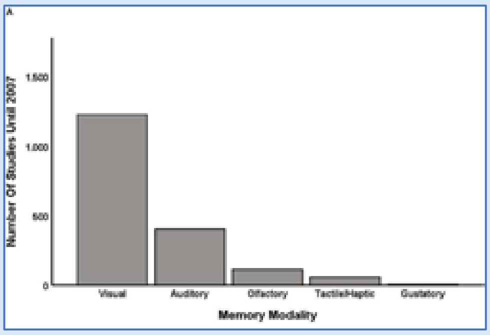


Fig. A: Number of Studies Until 2007

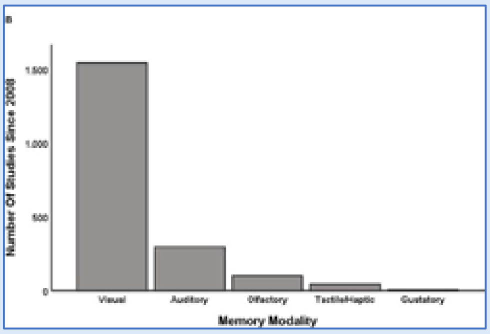


Fig. B: Number of Studies Since 2008

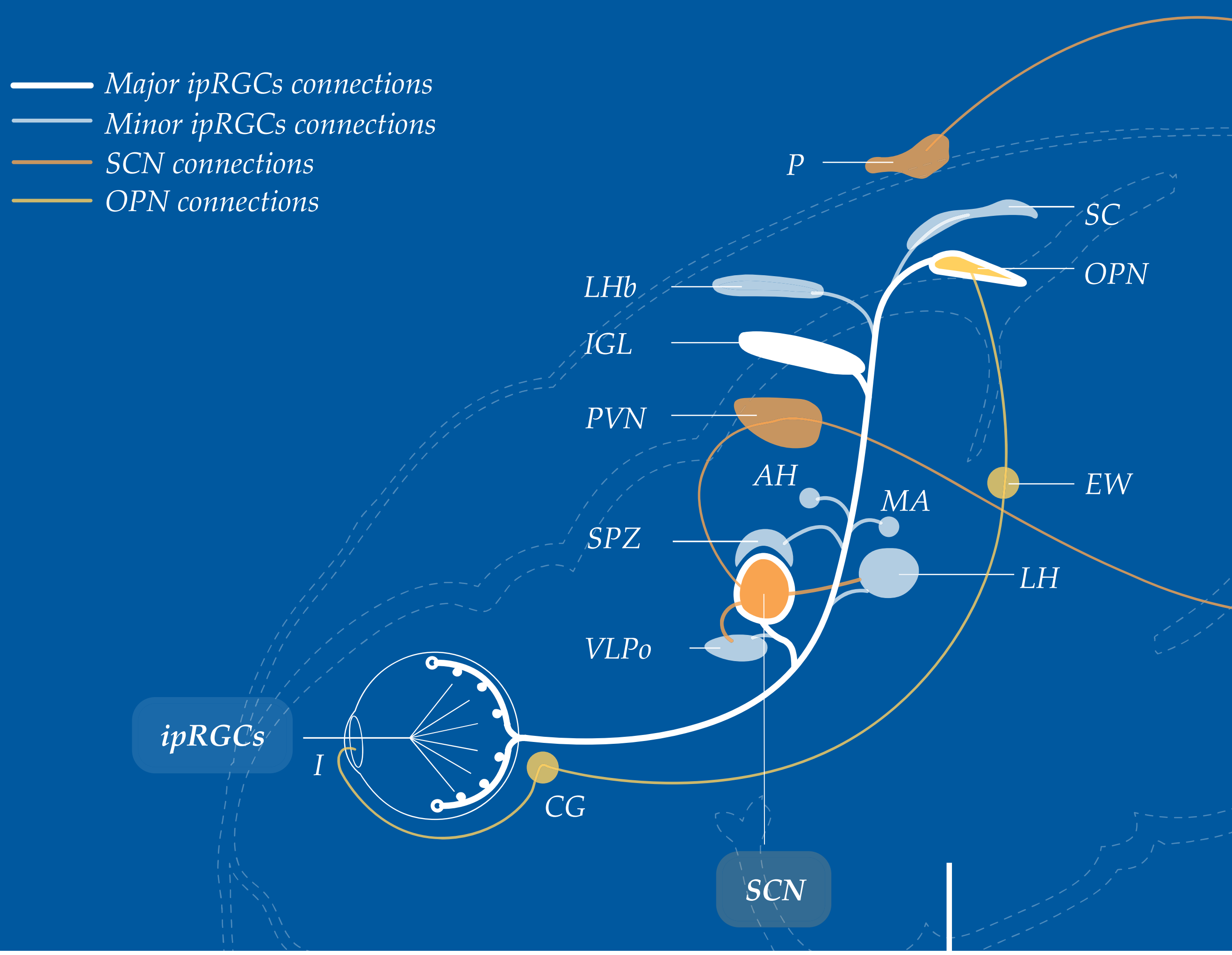
"The number of studies on the different sensory modalities published until the end of 2007 is depicted in panel (A); the number of studies on the different sensory modalities published since the beginning of 2008 is depicted in panel (B)."

After evaluating both the subjective and empirical importance of the different sensory modalities, Hutmacher argued that "*vision is first of all our most important sensory modality, but also the most complex*", due to the fact that a larger part of the human neocortex is dedicated to visual processing than to other sensory functions.

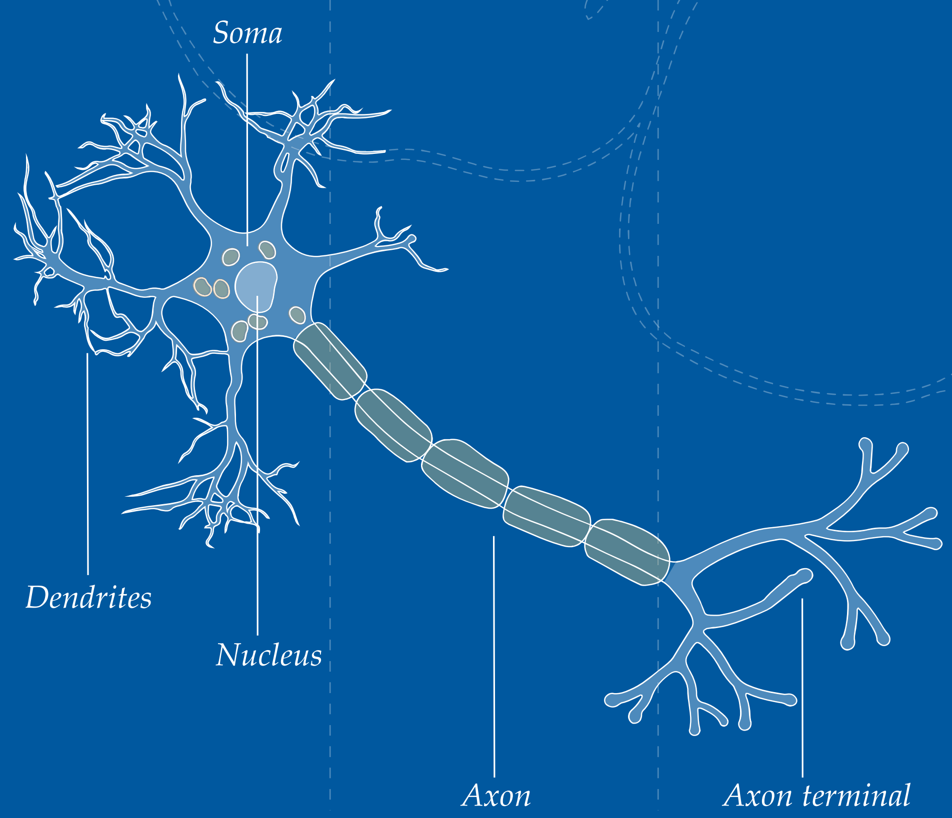
The same topic has been addressed from different perspectives in other studies. A research on the macaque neocortex revealed that a significant 54% of it is dedicated to processing visual information, while only a 3% is specialised in auditory processing, for example[16]. Another study estimated that the number of sensors, afferents and amount of information transmitted is significantly higher for vision than for any other sense in humans[17].

[15] (Posner, 1967).
[16] (Van Essen et al., 1991).
[17] (Zimmerman, 1989).

ipRGCs BRAIN TARGETS

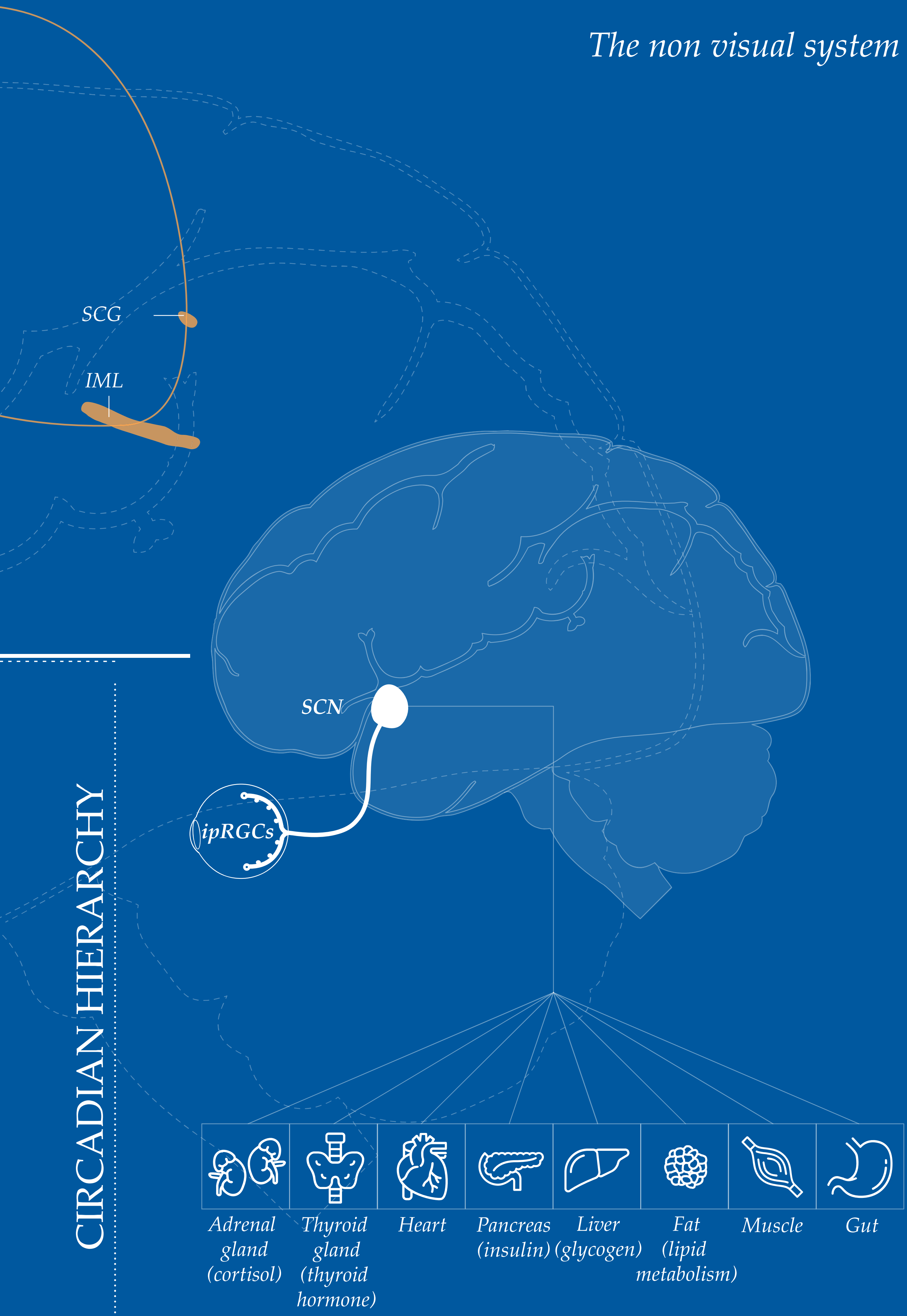


ipRGCs PHOTORECEPTOR



CIRCADIAN HIERARCHY

The non visual system



1.3.2. Non-Visual Effects of Light on Humans

Light, as previously discussed, is fundamental to vision, activating the visual organs and their components to create the perception of images. However, it also plays crucial non-visual roles, influencing a range of physiological phenomena through mechanisms distinct from image formation, often referred to as "non-image-forming responses" or "non-visual effects of light". Such non-visual effects of light regulate the human internal circadian clocks, synchronized with the 24-hour environmental cycle, and thus affect a myriad of physiological functions. In fact, while natural illumination serves as a reliable indicator of the time of day, aligning the internal circadian clock with the external environment, artificial lighting in modern environments has disrupted this relationship, leading to potential misalignments of circadian rhythms and associated physiological processes and thus enhancing the need to study the non-visual.

In detail, the term "non-visual" includes a variety of light-induced effects, such as the regulation of circadian rhythms, melatonin suppression, pupillary constriction, increased heart rate, modified core body temperature and stimulation of cortisol production. Additionally, light acts as a neurophysiological stimulant, helping to maintain a state of alertness and readiness in humans and mammals in general. One of the most significant non-visual responses, however, is the light-induced phase resetting of endogenous circadian clocks, which are intrinsic to nearly every physiological, metabolic, and behavioural system. The process of synchronization between light-dark natural cycle and the human body's circadian rhythm is known as photoentrainment. Physically, the eye retina processes light information through dedicated pathways involving intrinsically photosensitive retinal ganglion cells (ipRGCs), these cells then transmit light signals to brain regions responsible for regulating circadian rhythms and other physiological functions.

This section will explore the mechanisms by which light influences non-visual pathways, the role of ipRGCs and the resulting impacts on human health and behaviour. At last, an analysis about the researchers approach to define metrics for such non-visual effects is carried out.

The non-visual system

As previously described, the retina of the eye presents an entire surface of photoreceptors which allows the perception of visible light waves. However, within the ganglion-containing region of the retina, additional rare photosensitive neurons have been identified and designated as intrinsically photoreceptive retinal ganglion cells (ipRGCs), which drive non-visual behaviours. As they belong to the class of retinal ganglion cells (RGCs) they differ significantly in both form and function from the photoreceptors rods and cones; they express a unique photopigment, melanopsin, as well as having a completely different connective structure, since they project to various brain regions influencing circadian and homeostatic functions, including the sleep-wake cycle, pupil movements, core temperature and emotional aspects.

Firstly, in terms of its structural composition, ipRGCs cells are neuronal cells and, as such, present the typical structure of a soma (the central part containing the nucleus), minor fibres that ramify from it called dendrites, an axon and its axon terminal. The dendrites of the ipRGCs cells are sparsely distributed, irregularly shaped and extend over long distances. In general, the field formed by all the dendrites of this type of neuron is the largest known in primate RGCs cells[18]. Given the heterogeneity of the ipRGC population, these neurons have been further categorised according to their "*dendritic morphology, melanopsin expression, gene expression, and central projection locations*"[19]. This has led to the identification of six main types of ipRGC in primates, which have been codified as M1 to M6.

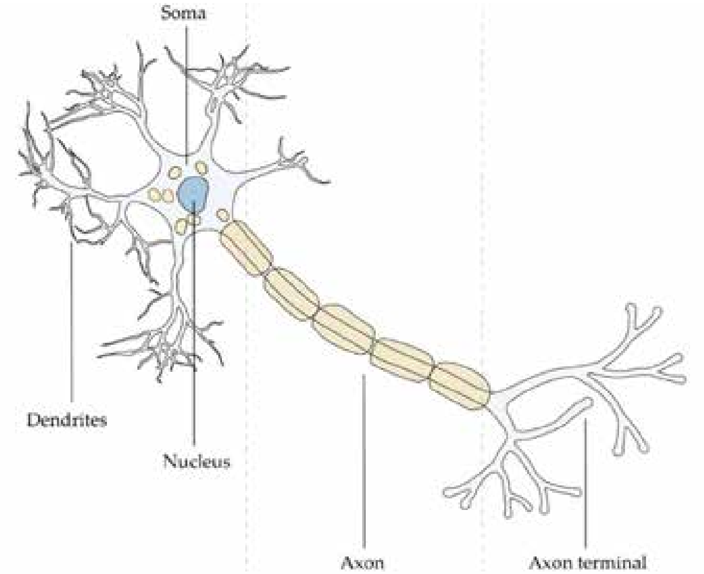


Figure 1.19. Intrinsically photosensitive retinal ganglion cells (ipRGCs) structure.

With regard to the functioning process, ipRGCs work through the expression of a photopigment called melanopsin, named from the dermal melanophore cells of frog skin in which it was first isolated[20]. Discovered by Provencio and colleagues, melanopsin belongs to the class of opsin photopigments, which include rhodopsin and cone-opsin for rods and cones; consequently, it is structurally and functionally similar to all known opsins, which are molecules working as sensory receptors that detect light and, through chemical transduction, generate a biological signal. The expression of melanopsin is, then, the key through which ipRGCs achieve their photoreceptive capacity, since the protein distributes throughout the cell membrane and is found both on the dendrites and the soma; additionally, a small portion of it can be localized in the axon, resulting in a relatively weak photosensitivity of it. As ipRGCs are the sole cells expressing melanopsin, and vice versa, melanopsin is only present in such neurons, the cells can also be found with the designation of melanopsin cells or melanopsin RGCs.

[18] (Do & Yau, 2010).
[19] (Berry et al., 2023).
[20] (Provencio et al., 1998).

Melanopsin is particularly responsive to short wavelengths, or the blue portion of visibile light, and its action spectrum shows a peak at approximately 480 nanometres. When such light interacts with the human system, intrinsically photosensitive ganglion cells respond to it by depolarising, i.e. firing nerve impulses at a higher rate, which appears to be the opposite of the hyperpolarisation observed in the visual photoreceptor cells; they also differ regarding the velocity of such light response, where rods and cones have a fast hyperpolarisation, while ipRGCs show a slow reaction. Sensitivity to light levels is another distinguishing feature between photoreceptors[21][22]; rods have high sensitivity to low light levels, cones have moderate sensitivity and are involved in color vision, while ipRGCs have low sensitivity to light, which suffices for their role in detecting ambient light levels for non-visual functions. In the light spectrum rods are most sensitive at 555nm, cones show a peak at around 510nm while ipRGCs, depending on melanopsin, are most sensible at 484nm[23], to be exact.

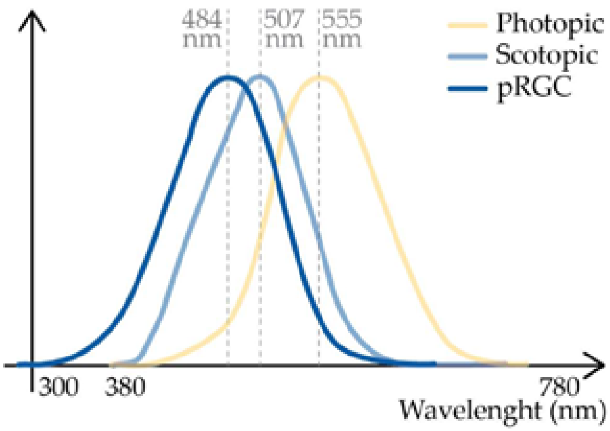


Figure 1.20. Sensitivity curves of rod (photopic), cones (scotopic) and ipRGCs cells (pRGC).

The receptive fields of these photoreceptive cells also vary: rods and cones have very small receptive fields, allowing for high spatial resolution and detailed vision, while the receptive fields of ipRGCs are very large, which suits their function of measuring overall light intensity rather than detailed images. The inputs of ipRGCs come primarily from bipolar and amacrine cells, with contributions from rod–cone photoreceptors, with whom they synapse through the dendrites. Whereas, ipRGCs, being ganglion cells, connect and send outputs directly to numerous brain regions.

The dominant projection site of ipRGCs, connected through the retinohypothalamic tract (RHT), is the suprachiasmatic nucleus (SCN) of the hypothalamus, known as the master circadian clock; the SCN, in fact, coordinates circadian rhythms by synchronizing the body's internal clock with the external light-dark cycle. This pathway ensures that the SCN receives consistent light information expressed by the melanopsin photopigment.

[21] (Brainard et al., 2001).
[22] (Rea et al., 2002).
[23] (Berson et al., 2002).

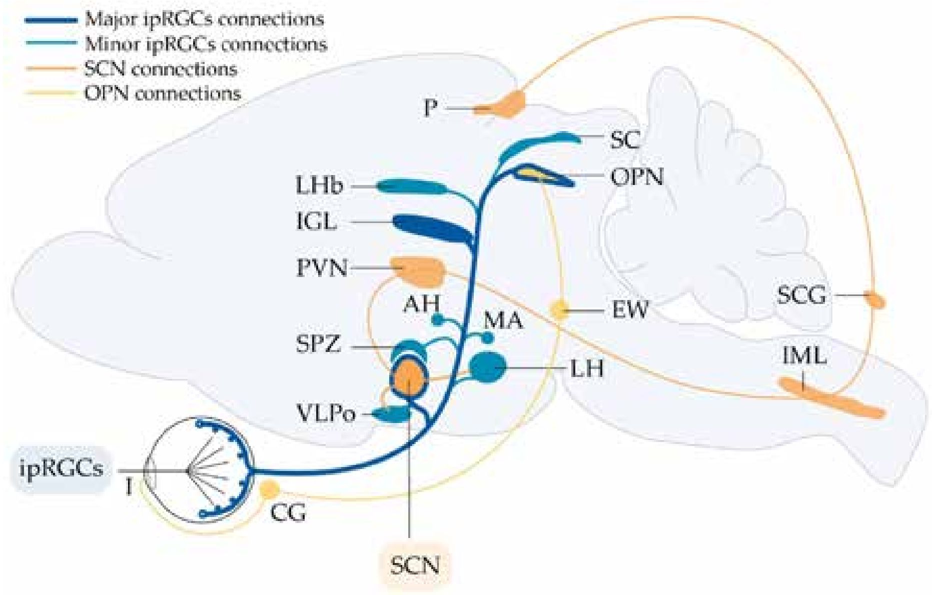


Figure 1.21. Schematic representation of ipRGCs major and minor connections, suprachiasmatic nucleus (SCN) connections and olivary pretectal nucleus (OPN) connections in different brain regions of a mouse. (Personal manipulation of Schematic summary of brain regions and circuits influenced by intrinsically photosensitive retinal ganglion cells (ipRGCs) by David M. Berson, 2003 and of Intrinsically Photosensitive Retinal Ganglion Cells by Michael T. Hoang do and King-Wai Yau, 2010).

In regard to other major targets, ipRGCs project to the intergeniculate leaflet (IGL), another important centre for circadian entrainment. The IGL modulates the signals received by the SCN, contributing to the fine-tuning of circadian rhythms. Together, the SCN and IGL act as irradiance detectors, integrating light signals to maintain stable entrainment to environmental light conditions. The olivary pretectal nucleus (OPN) is another fundamental target of ipRGCs, the OPN is essential for the pupillary light reflex, which adjusts pupil size in response to light intensity. This reflex helps protect the retina from excessive light and optimizes visual function. The pathway includes synaptic connections in the Edinger-Westphal nucleus (EW), ciliary ganglion (CG), and iris muscles (I), ensuring a rapid and efficient response to changes in light. Minor targets of ipRGCs include the ventrolateral preoptic nucleus (VLPO), involved in sleep regulation, and the ventral sub-paraventricular zone (vSPZ), a portion of the subparaventricular zone of the hypothalamus (SPZ) that is densely connected to the suprachiasmatic nucleus, with which it performs circadian regulation functions. These areas contribute to diverse non-visual responses, including modulation of mood, alertness, and body temperature. The ipRGCs also projects to a weaker extent to the perihabenular nucleus which is implicated in mood regulation. Furthermore, ipRGCs influence the regulation of melatonin release, an hormone of the family of neurotransmitters, secreted from the pineal gland (P). This polysynaptic circuit involves projections from the SCN to the paraventricular nucleus (PVN) of the hypothalamus, the intermediolateral nucleus (IML) of the spinal cord, and the superior cervical ganglion (SCG). Light information processed by this pathway modulates melatonin secretion, thereby regulating sleep-wake cycles and seasonal behaviours.

In summary:

> *These ipRGCs are a morphologically and physiologically heterogeneous population that project widely throughout the brain and mediate a wide array of visual functions ranging from photoentrainment of our circadian rhythms, to driving the pupillary light reflex to improve visual function, to modulating our mood, alertness, learning, sleep/wakefulness, regulation of body temperature, and even our visual perception.* (Aranda & Schmidt, 2021)

Ultimately, dealing with the structure of the non-visual system and its connections, further clarification on the suprachiasmatic nucleus and its definition as the human biological clock is necessary: the SCN, indeed, operates as an internal pacemaker that synchronizes the body's daily cycles with the 24-hour environmental light-dark cycle by secerning hormones, regulating core temperature and human sleep. Actually, the SCN intrinsic period does not correspond exactly to the duration of the solar day[24], however this is compensated by its synchronization through sensory inputs of light from, again, the ipRGCs. Interestingly, the rhythmic activity of the SCN is evident even at the cellular level, SCN neurons exhibit circadian patterns of electrical activity, and these rhythms persist even when the neurons are cultured in isolation outside the body[25]. For these reasons, it is considered to be responsible for the generation of circadian rhythms, working as a leader in the hierarchy of circadian organization of the body and modulating peripheral clocks in various organs, including liver, pituitary gland, heart, and kidneys.

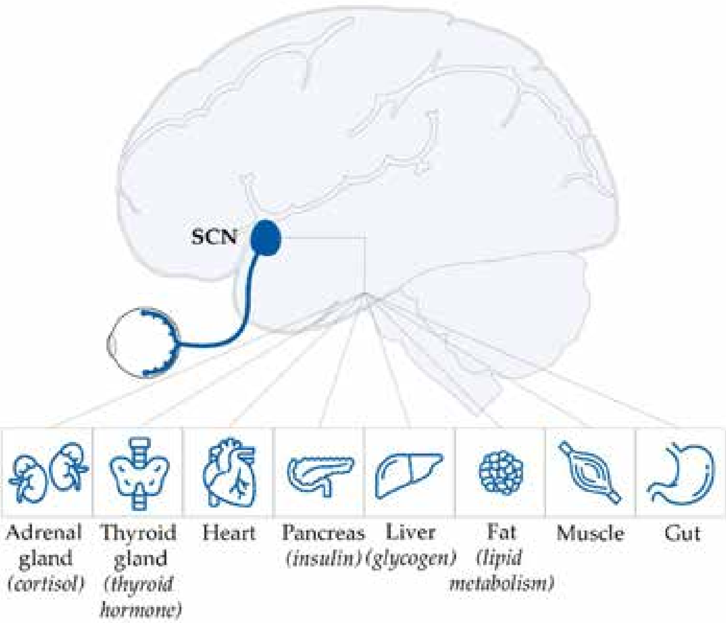


Figure 1.22. Scheme of the circadian hierarchy.

[24] (Richter, 1971).
[25] (Takahashi et al., 1980).

Circadian cycle

The circadian cycle, also known as circadian rhythm, derives its terminology from the Latin words *circadian*, meaning "around", and *diem* meaning "day", since it represents the physiological oscillations of the body repeating every 24 hours, with slight variations. Such physiological processes regulate a variety of body functions, as previously discussed in relation to the connections between the suprachiasmatic nucleus and the different organs. These include the sleep-wake cycle, a series of hormonal secretions, body temperature, the meal pattern connected to appetite and body digestion, and so on. Actually, it can be stated that, when analysing the human body, almost every organ and tissue has its own circadian rhythm, and their combination defines the circadian cycle.

The main zeitgeber[26], or external clue, for this cycle is light. In particular, daylight is able to properly synchronize the human biological clock. Daylight is, in fact, a dynamic source whose characteristics of intensity and colour temperature[27] vary throughout the day, caused by the sun's position in the sky. Following a clear pattern, the colour temperature of daylight shifts from warm hues during dawn and dusk to cooler, neutral tones at midday.

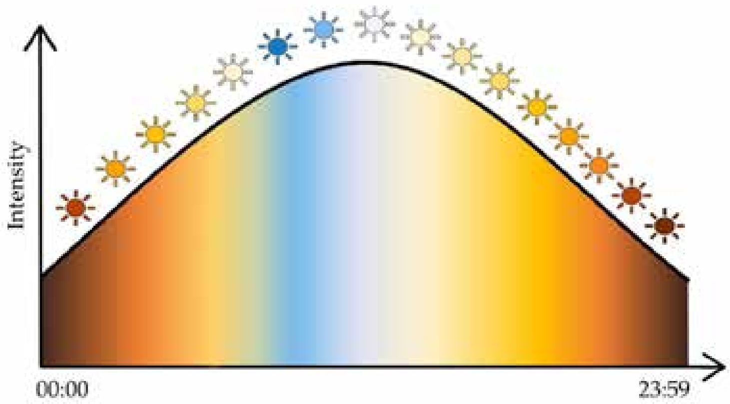


Figure 1.23. Light colour intensity variations during the day. (Personal manipulation of A schematic representation of light color and intensity change using Human Centric Lighting by Vizulo, 2022).

[26] "*Zeitgeber: It is a term derived from the German words Zeit, time, and Geber, giver. It was adopted by Jürgen Aschoff, one of the fathers of modern chronobiology, to indicate any type of signal capable of modifying the phase of an endogenous biological oscillation and thus synchronising the biological clock that generates it with the external environment. In nature, for a majority of organisms on earth, the most important and most effective Zeitgeber is undoubtedly light and its cyclical variations*". From Enciclopedia della Scienza e della Tecnica, R. Costa (2008).

[27] Color temperature is a physical quantity associated with the hue of light, or more precisely, an index that measures its chromatic appearance. It is expressed in degrees Kelvin (K) and, conventionally, certain ranges have been defined in which light temperature is referred to as warm, between 2700K and 3500K; neutral, corresponding to the range from 3500K to 5000K; or cool when greater than 5000K. (Coakley, 2022).

The variation in the colour of sunlight across the day is a consequence of light scattering when passing by minuscule particles in the atmosphere. This scattering process, or dissipative process, is influenced by the Sun's angle relatively to the horizon; depending on this angle, light is dispersed in different directions, which results in certain wavelengths being deviated and consequently not reaching the observer's eye[28].

In response to such changes in light intensity, sensed by its ipRGCs photoreceptors, the suprachiasmatic nucleus sends inputs to the hypothalamus and pituitary gland, among others, prompting the secretion of cortisol and melatonin, respectively, hormones of crucial roles in regulating wakefulness and sleep. Cortisol, often referred to as the "stress hormone" is produced in the region of the adrenal cortex and works by increasing blood sugar levels, providing energy, and enhancing the immune system[29]; however, prolonged high levels of cortisol can lead to exhaustion and inefficiency. Cortisol follows a diurnal pattern, with levels peaking in the morning, to help the body wake up and activate for the daily functions, and gradually decreasing throughout the day, reaching their lowest point around midnight. This arousal hormone, in fact, is significantly activated in the presence of blue light (the most sensitive light to melanopsin.). On the contrary, melatonin production is stimulated by darkness and inhibited by light, particularly in the blue wavelength range, yellow and orange light also contribute to melatonin production. Melatonin is secreted primarily by the pineal gland in the brain but is also found in the retina, lens and gastrointestinal system[30]. This hormone works by inducing sleepiness and enabling relaxation. Melatonin is considered as the key regulator of the sleep-wake cycle but not only, since its receptor have been found in numerous organs such as the primate adrenal gland and the kidney[31], for example.

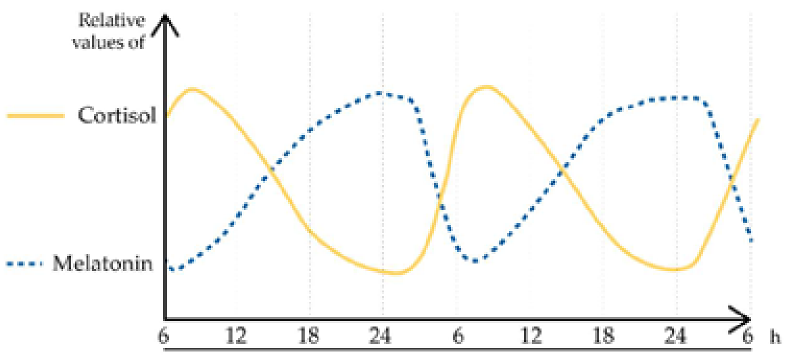


Figure 1.24. Cyclic variation of cortisol and melatonin hormones. (Personal manipulation of Double plot of typical daily rhythms of body temperature, melatonin, cortisol, and alertness by Wout van Bommel, 2004).

This hormonal balance ensures that that circadian rhythm is maintained, allowing for optimal daytime alertness and nocturnal rest, promoting overall well-being.

[28] (Vizulo, 2022).
[29] (van Bommel & Beld, 2004).
[30] (Zamanian et al., 2013).
[31] (Koch, 2009).

Figure 1.25 illustrates a typical human circadian cycle. However, numerous factors, including seasonal and daylight variability, as well as individual differences, can result in slight variations in the timing of this cycle between individuals, yet without disrupting it. The concept of chronotype (also called circadian pattern) fits into this topic: unlike the circadian cycle, synchronized primarily by environmental cues, a chronotype refers to an individual's natural sleep preferences and tendencies[32]. It has a significant genetic component, but it can also be influenced by age, lifestyle, and environmental factors. For instance, individuals with an early chronotype, also known as "morning people," tend to have a more conventional circadian cycle, as the one illustrated.

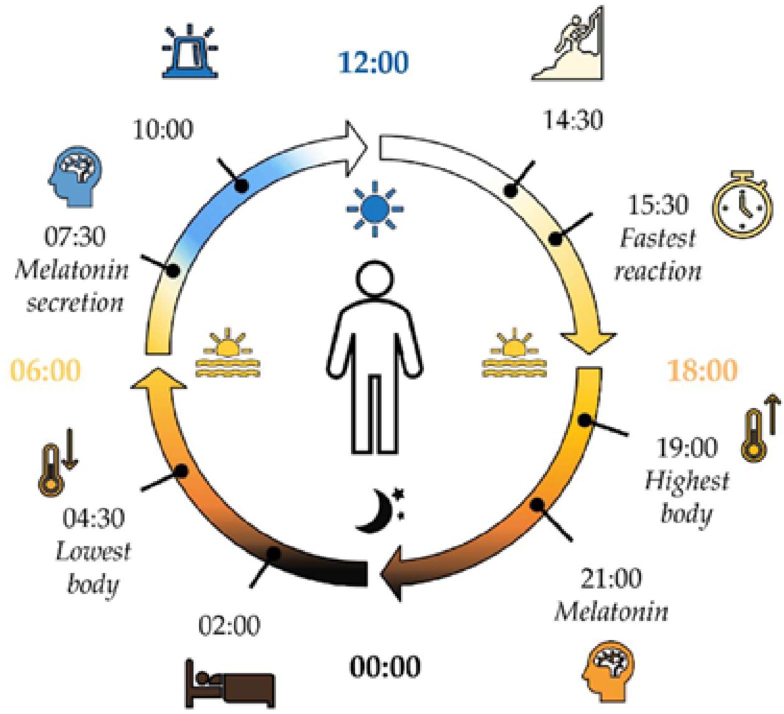


Figure 1.25. Human circadian system. (Personal manipulation of Human Circadian Rhythm schematic diagram by Vizulo, 2022).

In addition to the circadian cycle there are other biological rhythms, which can be classified according to duration: it is possible to distinguish the Diurnal[33], a cycle referring to night and day, the Ultradian of less than 24 hours, the Infradian or Circalunar ruling over 1 month and, finally, the Circannual corresponding to 1 year.

[32] (Chauhan et al., 2023).

[33] "The term diurnal is used to refer to rhythms that cycle once daily. Circadian rhythms are diurnal rhythms based on endogenous, cyclic events that occur approximately once each day. To be classified as circadian, a diurnal rhythm must be synchronized to environmental cues, but not driven by them." (Clifton & Steiner, 2009).

Disruption of circadian cycle and light affective disorders

The advent of electric lighting and the fact that people spend an average of 90%[34] of their time indoors, with little or no opportunity to interact with daylight and its spectrum, has the potential to trigger hormonal secretion processes, causing their deviation and consequently disrupting the circadian cycle. Also, nighttime exposure to artificial light, is one of the crucial factors in the disruption of the circadian cycle in humans[35]. In general, both light exposure but also eating habits and other environmental cues are able to maintain or disrupt biological rhythms[36]. A disruption on the circadian cycle can cause behavioral, health and psychiatric consequences[37]. There have been countless studies in this field over the past decade, the following is a list of the results obtained after analysing the positive and negative influence of light on humans:

- Seasonal Affective Disorder (SAD) is a depressive disorder that recurs annually in patients, predominantly in the winter period, and then decreases or disappears in the spring and summer months, due to the variation in daylight exposure[38].
- Artificial Light At Night (ALAN) has been demonstrated to suppress the natural secretion of the sleep-supportive hormone melatonin, increase sleep onset latency (SOL), and enhance alertness. Additionally, it has been shown to impair cardiometabolic function[39,40]. Addressed also by the World Health Organization which was the first to suggest long-term shiftwork being a carcinogen[41]. On the contrary, more daytime light exposure can reduce the alerting and sleep-disruptive impact of evening/nighttime light exposures[42].

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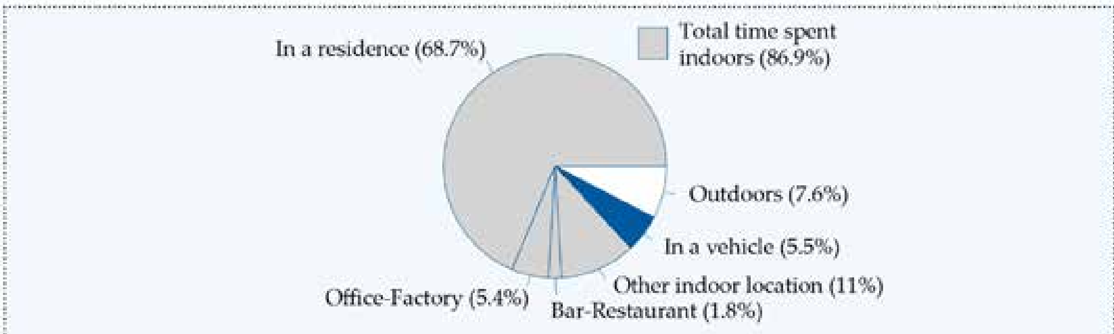

Figure 1.26. Pie chart showing the mean percentage of time the NHAPS responders spent in six different locations in the diary day (weighted). From Klepeis N. et al. (2001). The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants.

35 (Cho et al., 2015).
36 (DerSarkissian, 2023).
37 (Walker et al., 2020).
38 (Rosenthal et al., 1984).
39 (Cho et al., 2015).
40 (Mason et al., 2022).
41 (Fernandez, 2022).
42 (te Kulve et al., 2019).

- The presence of low daylight levels has been demonstrated to delay the onset of sleep and sleep quality, furthermore it increases inter-individual differences in sleep timing[43,44]. This is happening more and more commonly, consequently, being sleep essential for health, performance and wellbeing, the prevalence of sleep pathologies has reached alarming proportions, with an estimated 70 million individuals in the United States alone affected[45]. Some of these pathologies are the_Shift Work Disorder (SWD), the Delayed Sleep Phase Disorder (DSP) and the irregular sleep-wake rhythm disorder. While travelling through different times zones, for example, entails a possibility of Jet Lag Disorder.
- Evening types report poorer sleep quality and higher levels of work-related fatigue than morning types[46].
- Individuals with a later chronotype and greater social jet lag have been found to exhibit a higher prevalence of depressive symptoms[47].
- While individuals who spend more time outdoors during the day are at a reduced risk of developing depression over the course of their lifetime[48].
- In general, disruption and misalignment of circadian rhythms have been linked to adverse effects on mood, sleep, and a range of other physiological functions, including cardiovascular, reproductive, metabolic, and immune processes[49,50].
- Specifically, exposure to blue light at night, through both an illuminating system but also mobile devices and laptop monitors, leads to a sudden decrease of melatonin levels, disrupting the circadian rhythm resulting in difficulties related to falling asleep and daytime sleepiness[51].
- The presence of light at night has also been demonstrated to negatively impact wild organisms and the functioning of ecosystems[52].

Having recognised that all these problems are due to incorrect exposure to light or to a specific spectrum of it, light itself has been used as a treatment for countless disorders, such as non-seasonal depression, menstrual-cycle-related problems, bulimia nervosa, and cognitive and fatigue problems associated with senile dementia, chemotherapy and traumatic brain injury[53], also, extending the photoperiod with bright artificial light has been shown to induce an antidepressant effect[54].

[43] (Papatsimpa et al., 2021).
[44] (Wams et al., 2017).
[45] (Roenneberg, 2013).
[46] (Martin et al, 2012).
[47] (Levandovski et al., 2011).
[48] (Burns et al., 2021).
[49] (Cho et al., 2015).
[50] (Bedrosian et al., 2016).
[51] (Filipović et al., 2023).
[52] (Irwin, 2018).
[53] (Lucas et al., 2014).
[54] (Rosenthal et al., 1984).

Chronobiology

As discussed, the human body and a variety of its functions are regulated through a series of biological rhythms, or cycles, working as an internal clock, due to the fluctuation on light and temperature caused by the rotation of the Earth around its axis approximately every 24-h. The science that studies these phenomena and the human responses to it is chronobiology, a discipline that has both extremely ancient origins and is still evolving today.

> *Chronobiology is a relatively new name for a very old subject. It is the discipline which involves investigation of biological rhythms occurring in some prokaryotes and in all eukaryotes from fungi to humans […]. The most ubiquitous of these rhythms are the circadian rhythms which are also called biological clocks.* (Chandrashekaran, 1998)

An history overview:

Ancient observations & 18th and 19th Centuries: Initial Scientific Interest

Although it is know that ancient populations[55] observed how both plants and animals presented patterns leading to regularly timed cycles; the subject of biological rhythm was firstly addressed in the 18th century, firstly in 1729 in a research conducted by the French scientist Jean-Jacques d'Ortous de Mairan who studied a 24-h periodical pattern in nature, where the leaves of a mimosa lowered and rose cyclically through 24-h even in absence of light[56-57] even though not realizing the implication of this discovery; a few years later Carolus Linnaeaus made a 'flower clock', or *Horologium Florae* as he called it in his *Philisophia Botanica* (Vienna, 1751), in which he catalogued a series of flower species based on the time they opened and closed their petals.

Early 20th Century: Formal Recognition

In the early 20th century, scientists from different fields started conducting controlled experiments to study biological rhythms systematically; key discoveries included the identification of circadian rhythms, of approximately 24-hour cycles, in various organisms, from plants to humans. In this short paragraph, the European and American research binomial is illustrated, in which different theories and timeframes eventually led to a univocal conception.

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[55] "The first recorded circadian rhythm was for the sleep movements of the leaves of the tamarind tree by the Greek philosopher Androsthenes when he joined Alexander of Macedon in his march on India in the fourth century BC." (Chandrashekaran, 1998).

[56] (Wulund, Reddy, 2015).

[57] D'Ortus de Mairan observed that the mimosa plant, beyond being a *heliotrope* -naturally tilting towards the position of the sun-, exhibited another intriguing behavior: its leaves would drop at nightfall and go back up during the day. De Mairan then thought of placing a mimosa plant inside a dark cupboard to explore its reactions without light. Upon periodic checks, he noticed the plant's leaves continued their rhythmic opening and closing, as if mimicking its own day and night. Even in the absence of natural light, the plant's leaves still wilted during its 'night' and got up during its 'day'. This experiment revealed that the mimosa had an internal rhythm or rather, a biological clock. (Foster, Kreitzman, 2014).

European studies

From the second half of the 19th century from the mid-20th century onwards, particularly in Germany and in general across all Europe, almost every branch of biology started to emphasise the researching on biological rhythms. Some of the most prominent European exponents and researchers in this field were, for instance, German botanist Wilhelm Pfeffer (1845-1920) pioneer in the study of plant physiology[58] and of interest for his laboratory, *"built at the University of Leipzig nearly 100 years ago, which even by today's standards was modern and state-of-the-art. That […] had rooms with automatic switching to provide alternating light and dark periods, including simulation of dawn and dusk conditions"*[59]. German biologist Julius Sachs (1832-1897), in his seminal monograph "Experimental-Physiologie der Pflanzen" (Experimental Physiology of Plants) (1865), demonstrated that the rhythmic of the opening and closing of the flowers is influenced by two components: a hereditary one securing a rhythmically running movement, and a controlling one that fixes the beginning of the rising-lowering-cycle[60]. Another researcher on the topic, although being a physicist, Jagadish Chandra Bose (1858-1937), born in India, who studied and became a researcher in England, thoroughly observed and experimentally studied[61] the plant's tropic movements, including photonastic[62] responses and the day/night rhythmic movements of petals and leaves, providing great scientific publications about daily movements in relation to light and darkness. Or again Dutch botanist Antonia Kleinhoonte (1929) investigated the periodicity in leaf movements and pointed out the synchronisation, in plants, with light-dark cycles[63]. Eventually, Erwin Bünning and Kurt Stern in 1930 studied, at the Botanical Institute of the Universität Jena, plants under constant temperature conditions and a specific light cycle and proved that: "This experimental setting secured that the movements of the plants were indeed autonomous, i.e. controlled by an endogenous rhythmic, that is itself regulated by the extern signal light. As soon as the control is discontinued, the length of the period diverges significantly (dependent on species and individual) from the 24 hours, so that it must be talked about a circadian rhythmic"[64].

American belief

Concurrently, in the United States, biological rhythms became a popular subject in physiology only around sixty-seventy years ago[65], this was mainly caused by the previously widespread acceptance of the Homeostasis theory (Bernard, 1878; Cannon, 1939)[66-67], stating that:

[58] Britannica, The Editors of Encyclopaedia, (2023), "Wilhelm Pfeffer", Encyclopedia Britannica.
[59] (Chandrashekaran, 1998).
[60] (Sengbusch, 1996-2004).
[61] (Chandrashekaran, 1998a).
[62] Movements induced by light.
[63] (Kein, 2007).
[64] Ibidem.
[65] (Sollberger, 1971).
[66] (Cannon, 1939).
[67] (Bernard, 1878).

Homeostasis is the in-built tendency of a living organism to maintain stable equilibrium among its internal components while interacting with the external environment.[68]

This concept holds that living organisms possess self-regulating mechanisms to assess their stability: when such stability is disturbed, these mechanisms react to the deviations in order to establish a new equilibrium. Implying, therefore, that internal rhythms may not exist. This belief finally changed thanks to new studies coming from advancements in cybernetics on the real nature of homeostasis (that can be found, in particular, in "*An introduction to Cybernetics*" (1958) by W.R. Ashby, "*Cybernetics*" (1961) by N. Wiener or "*Regulation and Control in Living Systems*" (1966) by H. Kalmus); experts realized that both mechanical and biological systems often work with rhythmic patterns, and talking about biochemistry, are controlled through enzymes or hormones.

Mid to Late 20th Century: Advances in Understanding

Dr. Franz Halberg[69], Nobel Prize in Physiology and Medicine's multiple nominee and among the founders of modern chronobiology, coined in 1959 the term "circadian", coming from the Latin words *circa* (about, approximately) and *dies* (day, 24h); circadian refers, in fact, to oscillations of 24h periodicity[70].

The year 1960 stands as a crucial moment in the history of chronobiology: in the State of New York is held the XXVth edition of the Cold Spring Harbor Symposia on Quantitative Biology[71] around the topic of "Biological Clocks". Organized by Professor Arthur Chovnick, pioneer of modern genetic analysis in higher organisms, the symposium was attended by 150 scientists, practically everyone in the field at the time, who contributed to the shaping of subsequent discoveries concerning the cellular and molecular mechanisms of biological clocks and "signalled the beginning of the modern age in rhythm research"[72].

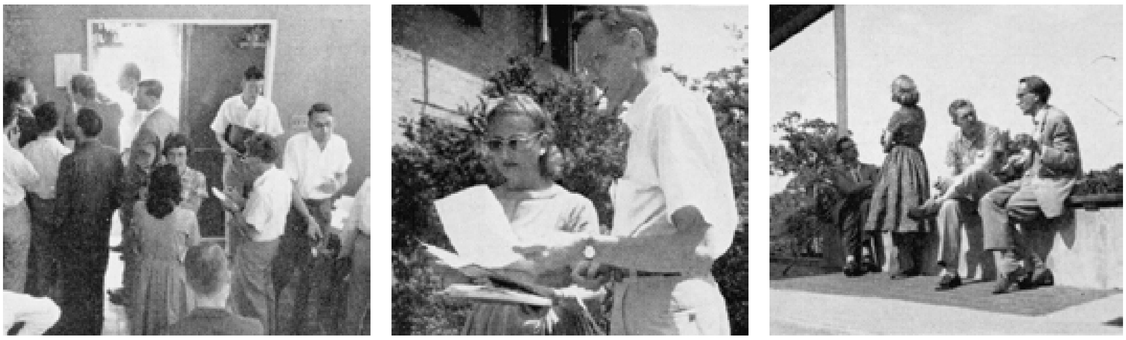

Figure 1.27. Photos of the 1960 Symposia. Courtesy of Cold Spring Harbor Laboratory Archives, New York.

[68] (Marks, 2015).
[69] Franz Halberg is seen as the leader of the school of thought generally labelled "chronobiology";
[70] (Eckel-Mahan, Sassone-Corsi, 2013).
[71] (Witkowski, 1960).
[72] (Chandrashekaran, 1998).

These were the years where the development of tools like continuous monitoring devices and genetic techniques revolutionized chronobiology. The turning point was, in fact, reached in the 1970s when the suprachiasmatic nucleus (SCN) was identified in the brain, as part of the anterior hypothalamus, and considered as the primary biological clock in mammals, regulating circadian rhythms. The experiments leading to this discovery, published in 1972, showed that if that area was damaged, a loss of circadian rhythms was observed: the discovery of the SCN happened, in fact, simultaneously by two separate laboratories led by Robert Y. Moore (University of Chicago) and Irving Zucker (University of California,Berkeley), stating that the Suprachiasmatic Nucleus serves as a significant circadian pacemaker in rodents (Moore et al., 1971-1972) and subsequently in other mammals (Moore, 1973). Moore's interest in the SCN originated from his studies on monoamines, leading to the identification of the retinohypothalamic tract (RHT), a visual pathway to the hypothalamus. On the other hand, Zucker and Fred Stephan were exploring how light and circadian rhythms influence neuroendocrine functions. Both research groups showed that perception of light by circadian system is independent from the neural routes in the brain that process visual information; and converged on the SCN as a critical component of the circadian system, concluding that its destruction disrupted rhythmicity[73].

Late 20th to 21st Century: Interdisciplinary Growth

However, the SCN is not the only thing that controls the biological clock: its discovery as a pacemaking structure came before the application of genetic approaches[74] to the topic, introduced by Konopka and Benzer on *Drosophila* in 1971[75] and by Dunlap and Feldman regarding *Neurospora* in 1988[76]; their techniques, such as genetic screens in model organisms and molecular biology approaches, were fundamental to prove the series of network of genes, proteins and feedback loops[77] governing circadian rhythms.

[73] (Weaver, 1998).

[74] (Menaker, 2007).

[75] Konopka and Benzer study aimed to understand the genetic basis and mechanisms causing circadian rhythms in Drosophila melanogaster (fruit flies). Because of their short lives, thus fast generational replacement, researchers performed genetic screens on them, identifying mutant flies with altered circadian rhythms, all mutant rhythms appeared to come from mutations in a single functional gene located on the X chromosome. This study's findings show that multiple genes are responsible for circadian rhythms. (Konopka, Benzer, 1971).

[76] Dunlap and Feldman aimed to understand how protein synthesis can affect circadian rhythms of Neurospora crassa, to set up the experiment, the researchers used various concentrations of cycloheximide (CHX) to inhibit protein synthesis and observed its effects on the circadian rhythms of different Neurospora types, which were measured based on spore formation patterns and other characteristics. Analysing the results, it was seen that most of the Neurosporas showed significant phase shifts in response to CHX, except for the frq-7 mutant, meaning that its circadian rhythm is less affected by protein synthesis inhibition. This imply that specific proteins or enzymatic activities, rather than their synthesis rates, might play crucial roles in maintaining the circadian rhythm. (Dunlap, Feldman, 1988).

[77] Feedback loops are biological mechanisms that help maintaining homeostasis, ensuring stability in the organisms.

Subsequently, timing mutation were studied in hamsters (Ralph M. and Menaker M., 1988), mice (Vitaterna et al., 1994) and other strategies were applied to discover *clock-genes "in both prokaryotic and eukaryotic systems, including cyanobacteria, fungi, plants, insects, and mammals. Even human rhythms are potently altered by clock gene mutations (Jones et al. 1999)"*[78]

In general, the end of the 20th century and the beginning of the 21st century saw, in a multi-disciplinary approach, an interrelationship between chronobiology and other disciplines such as genetics and neuroscience, whose advances in the field have enabled scientists to understand the genetic and molecular mechanisms that drive biological rhithms.

Latest discoveries, Implications and Applications

Over the last 20 years the field of chronobiology and circadian rhythms has seen great developments in understanding the molecular mechanisms previously discussed, as well as introducing health implications and societal impacts regarding biological clocks. On the developments of molecular biology, despite the identification of 'clock-genes' for many years now, emerging evidences in recent years support the claim of an interaction between circadian system and redox homeostasis[79] of the cell. How this correlation works was explained by Lisa Wulund and Akhilesh B. Reddy from the Department of Clinical Neurosciences at the University of Cambridge:

> *Circadian rhythms […] are orchestrated by a network of core 'clock genes' that are organised into transcription–translation feedback loops (TTFLs), producing oscillations with a period of approximately 24h. The modern understanding of circadian timekeeping has revolved around the TTFL paradigm. Recently, however, this has been challenged by new findings that redox reactions persist in the absence of gene transcription, and that cycles of oxidation and reduction are conserved across all domain of life. These results suggest that non-transcriptional processes such as metabolic state may interact and work in parallel with the canonical genetic mechanisms of keeping circadian time.*[80]

Following this discovery, researchers have been able to further investigate on a new pathway, moving away from the dogmatic and centered view related to the circadian clockwork. However, research into the relationship between circadian and redox systems is still in its early stages and many questions are still unanswered.

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[78] (Kuhlman, Craig, Duffy, 2018).

[79] Cellular redox homeostasis is a process able to balance oxidation–reduction reactions in a cell or organism (commonly known as redox reactions, they involve the transfer of electrons: the loss of electrons makes a cell or organism oxidized, while the gain of electrons labels it as reduced), in this way it regulates a series of biological responses in the organism. Redox homeostasis ensures that the cellular environment remains stable by regulating the levels of reactive oxygen species (ROS) and antioxidant defences, in fact, when the system detects shifts in those levels it can adjust the metabolic functions in charge. Imbalances in redox homeostasis can lead to oxidative stress, which is associated with various diseases such as cancer, cardiovascular diseases and neurodegenerative disorders.

[80] (Wulund, Reddy, 2015).

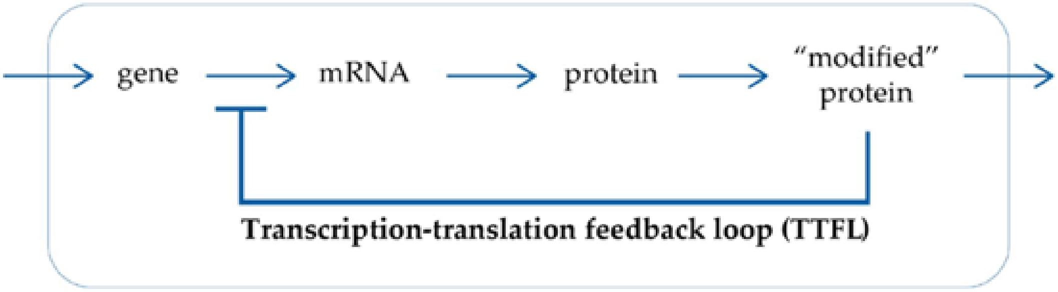

Figure 1.28. Schematic workflow of TTFL. (Personal manipulation of Schematic summary of The Transcription-Translation Feedback Loop (TTFL) by J.C. Leloup, 2009).

Today: Broad Applications on various disciplines

Moreover, thanks to the extensive knowledge gained about the biological mechanisms that govern our circadian rhythms, nowadays it has been possible to apply it on various fields and understand its implications. As an example, the impact on health is certainly the most widely discussed issue: disruptions on circadian rhythms can be linked to various health issues, including sleep disorders[81], neurodegenerative disorders[82], mood disorders[83-84] and even certain types of cancer[85]. Notably developments regarded also technological aspects that, such as genetic editing tools like CRISPR-Cas9, have enabled researchers to manipulate genes related to circadian rhythms. As well as medical treatments as in Chronotherapy[86]. And, with particular reference to recent years, has encountered numerous studies dedicated to the application of artificial light in architecture and design, as it has been discovered how blue light greatly impacts circadian systems[87]; this has led to the development of disciplines such as integrative lighting and human centred lighting; on top of that, an attempt is being made to quantify the impact of light on biological rhythms so that design recommendations can be made (although this will be dealt with in more detail in other sections).

Considerations

In summary, chronobiology has evolved from ancient observations to a scientific-driven and sophisticated interdisciplinary field, offering broader implications for health, behaviour, and well-being.

[81] (Boubekri et al, 2020).
[82] (Abbott, Malkani, Zee, 2020).
[83] (Lazzerini Ospri, Prusky, Hattar, 2017).
[84] (Walker et al. 2020).
[85] (Meng, 2023).
[86] "*Chronotherapy, a medical treatment, aims to restore the proper circadian pattern of the sleep–wake cycle, through adequate sleep hygiene, timed light exposure, and the use of chronobiotic medications, such as melatonin, that affect the output phase of circadian rhythms, thus controlling the clock.*" (Cardinali, Brown, Pandi-Perumal, 2021).
[87] (Wahl et al., 2019).

Melanopic quantities

The influence of light on non-visual responses requires to be quantified, both for researchers and designers in light and architectural fields. To do so, specific quantities, also referred to as circadian metrics, addressing the sensitivity of the non-visual system are needed. As previously mentioned, the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) and the photopigment melanopsin has revolutionized the understanding of how light influences human biology. In particular, melanopsin, the photopigment found in ipRGCs, is particularly sensitive to blue light with a peak sensitivity around 480 nm[88]. Moreover, "*the established photometric quantities used to describe brightness and luminous sensation as perceived by humans do not adequately reflect the spectral sensitivity of any melanopsin-dependent responses to light*"[89], since accounting for rods and cones sensitivity.

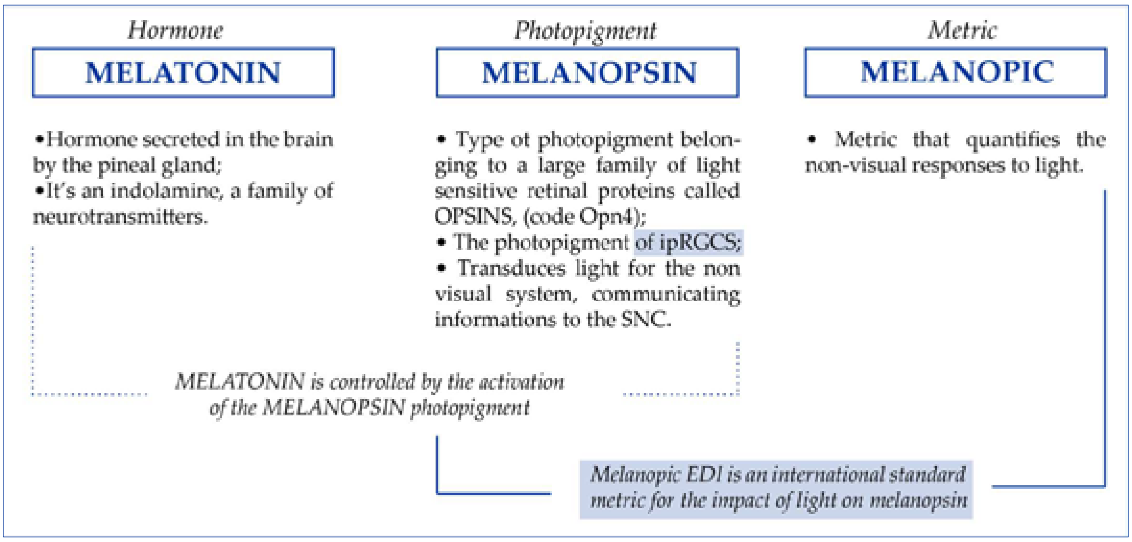

Figure 1.29. Melatonin, Melanopsin and Melanopic. Description and correlations of terms.

To understand the correlations between such elements: melanopic suppression by monochromatic light is predominantly driven by melanopsin, and it can be initiated at extremely low melanopic lux levels. Moreover, being melanopsin highly sensitive to blue light, this sensitivity is taken into account in melanopic metrics.

A first attempt in defining a suitable metric occurred in 2013, when a group of researchers were able to weight irradiance in accordance with the sensitivity of five opsin proteins (melanopsin, rhodopsin, S-, M- and L-cone opsin)[90], a system subsequently approved by the CIE and partially included in the CIE publication S 026:2018. Although Lucas et al. model permits the calculation of all α-opic illuminances,

[88] "*Blue light is also called high energy visible light (HEVL) because it has rays of the shortest wavelengths, but also of the highest energy in the whole spectrum of visible light*" (Filipović et al., 2023).
[89] (Brown et al., 2022).
[90] (Lucas et al., 2014)

the circadian response is assessed exclusively through the melanopic one, given the dominant role of melanopsin-expressing ipRGCs in the circadian phototransduction process. Originally, this quantity was designated as **EML (Equivalent Melanopic Lux)**, being the product of photopic illuminance and melanopic ratio:

$$EML = E \cdot MR$$

Where:

$$MR = \frac{\text{Melanopic content}}{Photopic\ content} \cdot 1.218$$

EML unit is melanopic lux (sometimes indicated as m-lux), which is not a standard unit of measurement. In fact, EML, being an equivalent α-opic illuminance, cannot be expressed in lux. The lack of a clear and official unit can lead to confusion and inconsistencies in reporting and interpreting such lighting measurements. This parameter therefore required improvement, which was made and published by the International Commission on Illumination in "CIE S 026/E:2018 - *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*". The new proposed metric was defined as **melanopic Equivalent Daylight Illuminance (abbreviated in mel-EDI)** and can be described as following: "*Given a specific source, the mel-EDI is the photopic illuminance at the eye due to D65 radiation required to obtain the same ipRGCs stimulus as the considered source. Therefore, the mel-EDI is expressed in lux (lx)*"[91], thus complying with the SI International System of Units. To calculate mel-EDI values, melanopic Daylight Efficacy Ratio (mel-DER) is needed:

$$mel\text{-}EDI = E \cdot (mel\text{-}DER)$$

Where:

$$mel - DER = \frac{\text{Melanopic Luminous Efficacy of Test Light Source}}{Melanopic\ Luminous\ Efficacy\ of\ D65}$$

The principal difference between the EML approach and that of the CIE S 026 lies in the illuminant employed for the calculations; the CIE standard employs the CIE standard illuminant D65 (with a correlated colour temperature of 6500 K), whereas the methodology proposed by Lucas et al. utilises an equal energy source illuminant. In any case, as the EML and mel-EDI are based on the same calculation model, the mel-EDI can be readily obtained by multiplying the value of EML by 0.9058[92], furthermore MR is a scalar multiple of mel-DER and can be obtained by multiplying it by 1.103[93].

This approach has been endorsed by both the CIE and the WELL Building Standard, each of which has recommended specific values of such metrics. With the difference that the CIE employs melanopic equivalent daylight D65 illuminance (m-EDI), while the WELL Building Standard utilizes equivalent melanopic lux (EML).

[91] (Bellia et al., 2023).
[92] (Englezou & Michael, 2023).
[93] (Esposito & Houser, 2022).

As an alternative to the proposed metrics, Circadian Stimulus (CS) and Circadian Light (CLA) were developed to address a multi-photoreceptor approach, since researchers recognize that not just ipRGCs but also other visual photoreceptors, like rods and cones, contribute to light-induced melatonin suppression. Both being calculation procedures based on a published mathematical model of human circadian phototransduction, proposed by Rea et al in 2005. In brief, CLA measures the light reaching the eye, adjusted for how sensitive the human circadian system is to different wavelengths of light, based on how much it suppresses melatonin after one hour of exposure. While, CS, which ranges from 0.1 to 0.7, indicates how effective this light is at suppressing melatonin[94].

At present, popular metrics for "circadian illuminance", such as equivalent melanopic lux (EML) and melanopic equivalent daylight D65 illuminance (m-EDI), are based solely on melanopic illuminance. In support of this Brown's 2019 research article can be cited, where several studies are analysed to determine the most appropriate metric to quantify and predict the non-visual effects of light. The studies concerned melatonin suppression in subjects with dilated pupils or undilated pupils, circadian phase resetting in humans, alerting responses and sensitivity range of melanopsin. In conclusion, it was recognised that all these phenomena in most cases are entirely accounted for by melanopic illuminance, even though it being a simplification of underlying biology: "*presently available data indicate that for most commonly encountered real world simulations […] melanopic illuminance provides a robust predictor of non-visual responses with widespread utility*"[95], making melanopic illuminance the best available predictor for responses of the human circadian system. However, doubts have recently been raised about the suitability and accuracy of such metric. Indeed, the melanopic illuminance approach excludes the contribution of visual photoreceptors, making it a simple approximation for a complicated problem. This raises questions about whether melanopic light levels are sufficient to predict circadian effects of light alone. Recent studies addressing these concerns have analysed, for example, the contribute of S-cone related cyanopic illuminance to light-induced circadian responses, finding positive feedbacks[96].

In the context of design practice, architects and lighting designers must consider five primary characteristics of light radiation that influence both visual and non-visual responses to light, such as intensity, spectrum, photic history and the temporal pattern of exposure, which encompasses both the time of exposure and its duration. Where "*intensity refers to how much light is received in the retina, whereas the light source spectrum refers to the amount of spectral irradiance at each wavelength within the visible spectrum. The timing of exposure regards the time of day or different seasons throughout the year during which an occupant is exposed to the light source. Duration is about how much time someone is exposed to the light source, and photic history is mainly about the different light exposure someone had*

[94] (Busatto et al., 2020).
[95] (Brown, 2020).
[96] (Huang et al., 2023).

before being exposed to a specific light source"[97]. These are the variables that can be managed when designing a lighting system.

Measurement techniques

Traditional measuring tools are capable of measuring melanopic illuminances, such as the spectrophotometer, which should normally be positioned 1.2m above the ground for measurements on a vertical plane, to simulate the view of a user sitting at a workstation, for example.

Employing inappropriate spectral composition and intensity of light can pose a risk to human health[98], this is one or the reasons why another fundamental measurement tool in this field is the spectroradiometer, able to measure the Spectral Power Distribution (SPD) of light sources, which outputs a graph of the energy levels of a light source measured through different wavelengths.

Melanopic metrics, however, require specific measuring instruments as visual and circadian systems respond very differently to optical radiation and in general show extremely different characteristics such as the circadian cycle displaying a considerably higher threshold and requires much longer exposures for activation. Additionally, it exhibits a peak spectral sensitivity at a wavelength that is much shorter than that which is optimal for the activation of the visual system. Of particular importance is, then, the differential sensitivity to light at different times of day[99]. For these reasons, in 2005, Bierman, Klein and Rea developed a prototype for a new device called Daysimeter, for circadian dosimetry. *"The Daysimeter is a light-weight, headmounted device that records radiation exposure estimates for both the visual and circadian systems, and is specifically designed for field use. In addition to logging spectrally weighted radiation measurements, it records head position and motion to be utilized as a representation of human circadian activity"*[100].

Moreover, circadian metrics, as opposed to photopic metrics, have the particular feature that they require longitudinal measurements, i.e. scanned in time. Longitudinal analysis has the distinct advantage over cross-sectional analysis of examining how processes in general evolve over time. This being the key reason why research is witnessing a development in wearable light monitoring technologies. At the moment a wide range of different technologies of light dosimeters exists on the market, like the Actiwatch Spectrum, the MotionWatch, etc. Personal light exposure is usually measured with lightweight wearable devices applied to glasses or watches, for instance[101].

Accurate measurements of melanopic variables are crucial for designing lighting environments that support human health and well-being. Some tools are already reliable while others still need development to address all the particular challenges posed by non-visual responses and melanopic metric.

[97] (Englezou & Michael, 2023).
[98] (Noor et al., 2023).
[99] (Bierman et al., 2005).
[100] ibidem.
[101] (Hartmeyer & Andersen, 2023).

Introduction

Integrative Lighting, also known as Human-centric lighting, is a design approach that aims to enhance indoor well-being by designing lighting systems that support both physiological and psychological needs. This approach integrates natural and artificial lighting to replicate the benefits of outdoor environments within indoor spaces. Traditional lighting design has primarily focused on creating optimal visual conditions to help individuals perform visual tasks efficiently, safely, and comfortably. However, light has significant roles beyond vision, affecting human physiological and psychological factors, which in turn influence performance and productivity[102], the aim of integrative lighting is to recognise these effects and comply with them.

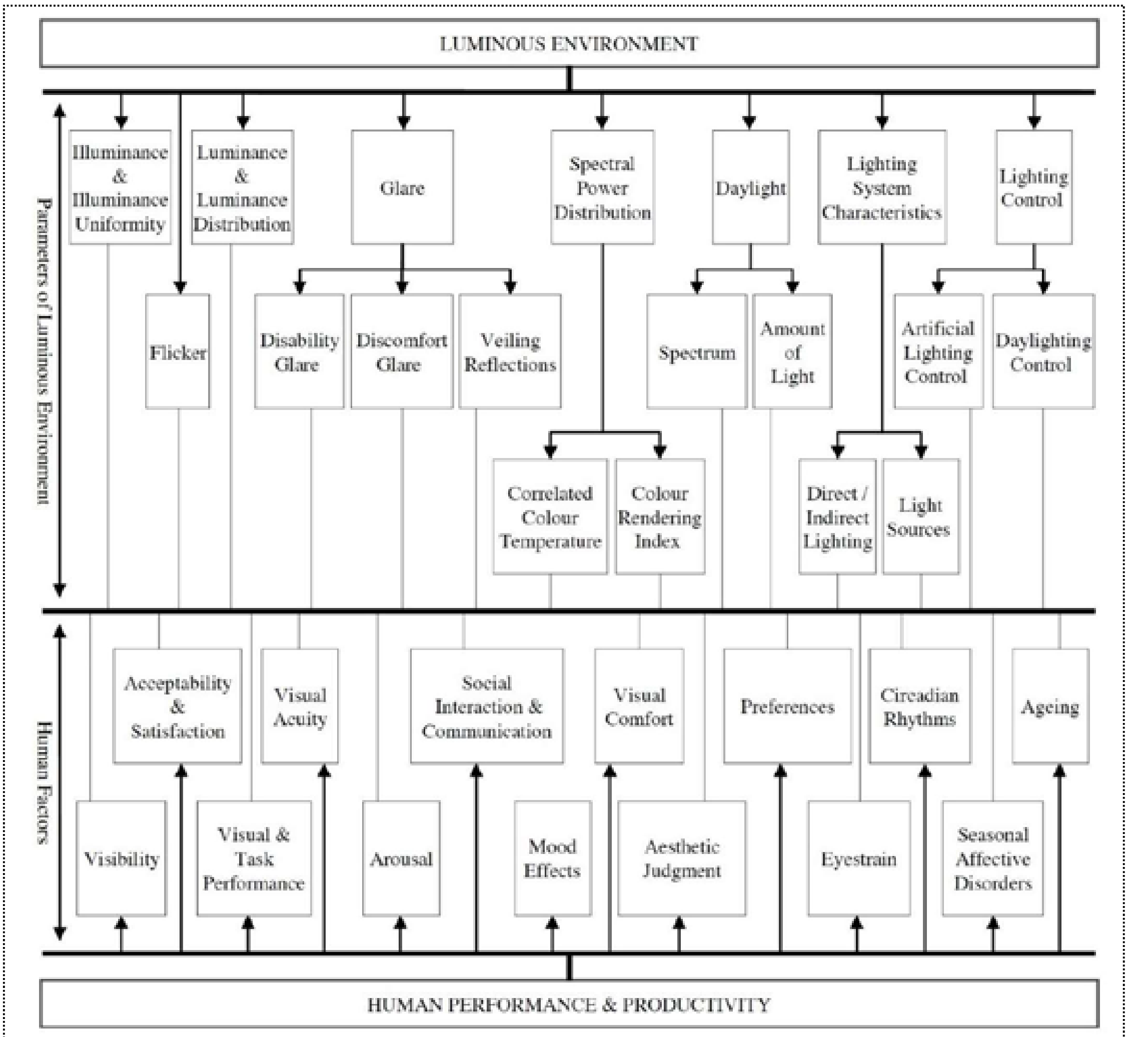

Figure 1.30. Visual and non-visual effects of the different characteristics of light. From: Viorel Gligor, Luminous environment and productivity at workplaces. Thesis, 2004, Helsinki University of Technology.

[102] (Gligor, 2004).

Integrative Lighting, in fact, acknowledges the non-visual or non-image forming effects of light. These include regulating physiological processes such as hormone production, influencing behaviour and mood, and maintaining circadian rhythms, which are critical for managing alertness, concentration, and sleep. By combining the visual and non-visual effects of light, Integrative Lighting aims to provide holistic benefits, supporting both the visual requirements and overall well-being of individuals[103].

The purpose of this chapter is to explore the concept of Integrative Lighting as a means of creating indoor environments that not only facilitate visual tasks but also promote overall health and well-being, aligning with the evolving needs of modern society; but to do so designers must adhere to specific reference values. While current standards provide countless reference values for design practice to ensure all visual functions, the parameters related to non-visual effects and their reference values are undergoing a development in recent years, research has led to the definition of some protocols, but the values are not yet present in any standards.

Visual requirements

The current standards for lighting include a series of values, expressed in tables, and recommendations that ensure visual performance. These standards enable people to see and move around safely in environments, to perform visual tasks efficiently, accurately, and without causing visual fatigue, and to create comfortable visual conditions. In order to achieve this, it is important to pay attention to both the quantity and the quality of light in the design, hence the introduction of several lighting parameters. As instance, the European standard "EN-12464-1:2021, *Light and lighting - Lighting of workplaces - Part 1: Indoor workplaces"*, provides a set of minimum values to be observed in order to properly conduct visual tasks, according to the specific setting, such as illuminance and its distribution on the task area and on the surrounding area. In order to comply with the regulation in the design practice, the average illuminance should not fall below the recommended values (in lux). As an example:

Parameter	Standard	Values
Illuminance	EN 12464-1	500 lux
(on work surface, horizontal)		Immediate surrounding illuminance: 300lux
		Background area illuminance: 100lux

Figure 1.31. Illuminance requirements in work areas.

A number of visual parameters have been defined at the national and international levels, indicating the required range of values for each, to support design practice.

[103] (Schlangen, 2022).

INDIVIDUAL NEED	
VISUAL PERFORMANCE	Illuminance (horizontal) on task area Illuminance (vertical) on task area Illuminance (horizontal) on computer (keyboard, mouse) Illuminance for drawing Illuminance of immediate surroundings Illuminance (vertical) on screens
VISUAL COMFORT	Luminance ratio on the task area (luminances on walls, ceilings, task plane) Ceiling luminance Maximum luminance from overhead luminaries Maximum wall luminance Maximum window luminance Recommended surface reflectances Specification of flicker-free light sources Illuminance uniformity on the task ârea Discomfort Glare Rating Discomfort glare in the case of use of Visual Display Terminals (VDT) Control of reflected glare and veiling reflections Possible specifications regarding lighting fixtures
COLOR APPEARANCE	Color rendering index (CRI) Correlated color temperature (CCT) Possible use of saturated colors Possible use of color variations of light
WELL-BEING	View to the outside Light quality through lighting modelling Directional lighting Biophilia hypothesis (daylight) maximization) Lighting quality / Aesthetics of space Aesthetics of lighting equipment Individual or programmed lighting and daylight control
NON VISUAL EFFECTS	Role of spectral power distribution Daylight exposure through value of daylight factor Daily exposure to daylight Frequency of light (Hz) UV(Ultra Violet) content of light Infra red exposure associated to lighting
SOCIAL NEEDS	
	Cost, budget User satisfaction (expressed by reduction of complaints) Impact of lighting quality on productivity through reduction of failures, higher satisfaction and less fatigue Reduction of maintenance through improved quality of equipment Impact of lighting on security issues Impact of lighting on feeling of safety
ENVIRONMENTAL NEEDS	
	Reduction of power consumption for lighting through efficient light sources and luminaries Ability of lighting system to minimize peak load demand (use of daylight, adjusted power consumption) Lighting controls (use of daylight, use of occupancy sensors) Reduction of harmonics and power losses in electricity distribution networks Reduction of resources for making lamps (increased life of sources) Reduction of environmental impact (low production of pollutants)

Figure 1.32. Visual parameters and recommendations addressed in lighting standards. Inspired from: Guidebook on energy efficient electric lighting for buildings, (2010), Edited by Liisa Halonen, Eino Tetri & Pramod Bhusal.

Non-visual recommendations in the international context

Recent advancements in lighting science have highlighted the importance of proper light levels in indoor lighting design to address non-visual responses. An international expert workshop on circadian and neurophysiological photometry recently published a set of light recommendations to best support such responses including human physiology, sleep, and wakefulness within indoor settings[104]. These recommendations have been expressed through melanopic equivalent daylight illuminance (mel-EDI), measured vertically at the eye level, aligning the detector orientation with the dominant direction of gaze.:

- Daytime: The recommended minimum melanopic EDI is 250 lux. This level of light exposure is necessary to support alertness, mood, and overall daytime functioning.
- Evening: Starting at least three hours before bedtime, the recommended maximum melanopic EDI is 10 lux. Lowering light exposure during this period helps in preparing the body for sleep by reducing stimulation of the ipRGCs.
- Sleep Environment: The sleep environment should be as dark as possible. The recommended maximum melanopic EDI is 1 lux[105], and for situations where some light is unavoidable (e.g., for safety or essential nighttime activities), the maximum should be 10 lux.

These guidelines are intended for healthy adults aged 18-55 with a day-active schedule. They are designed to complement, not replace, existing guidelines and regulations related to visual function, comfort, and energy consumption. By incorporating these recommendations, lighting design can achieve integrative solutions that address both visual and non-visual needs. In the same text, researchers even provide highly needed additional considerations and guidance to successfully accomplish integrative lighting solutions[106]. For example, it is recommended that daylight be given priority wherever possible. In the event that this is not possible, a polychromatic white source with a higher spectral irradiance in the short-wavelength part of the visible spectrum could be used as a supplement[107].

The development of publications such as the CIE S 026 and WELL protocol is the first step towards incorporating these non-visual considerations into lighting standards as required values.

[104] (Brown et al., 2022)
[105] Earlier researches addressing the topic of defining recommendations held the belief that a significant level of illuminance was required to suppress nocturnal melatonin in humans, with levels as high as 2500 lux being considered necessary; later studies, however have demonstrated that, under certain conditions as little as 1 lux or less can effectively suppress melatonin in humans. (Lucas et al., 2014).
[106] (Schlangen, 2022).
[107] (Englezou & Michael, 2023).

- CIE

As mentioned above, the CIE supported the introduction of mel-EDI as the melanopic unit of measurement and, in the international standard CIE S 026:2018[108], listed its recommended threshold values, quoting the guidance provided by Brown et al.: at least 250 lx m-EDI throughout the day, a maximum of 10 lx three hours before bedtime and a maximum of 1 lx during the night[109]. (A thorough description of the CIE body and its publications can be found in the fourth chapter of this thesis).

- Well Protocol

The WELL Building Standard consist of a document directed to design practitioners aiming to overall health and wellbeing guaranteed by means of the built environment. In order to achieve this, it gathers the best practices to be suggested, identifying 100 performance metrics, design strategies, and policies that can be implemented by the owners, designers, engineers, contractors, users and operators of a building. This process includes the scientific and technical review of a huge body of research to find the most critical discoveries about positive effects of spaces on individuals. The first ever publication of the WELL protocol, referred to as the first version or *v1* took place in 2014, as a result of 7 years of research, then revised 4 years later in a second version, *v2*. Such versions of the WELL are organized into seven categories of wellness, called "Concepts", in the *v1* (Air, Water, Nourishment, Light, Fitness, Comfort and Mind) and ten categories or concepts in the *v2*, comprising Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind and Community. There are 110 individual features distributed across the ten concepts of the second version, each feature is a specific, actionable item that contributes to achieving the goals of its respective concept. Features are once again divided into parts, which are more detailed requirements or actions necessary to fulfil the overall intention of the feature. These parts are often tailored to different building types (such as commercial, residential, or educational buildings) to ensure the applicability and relevance of the standards across various environments.

The WELL Building Standard also contains a certification system, consisting of a points-based system, with a total of 110 points available for each project, of which 100 points come from the ten concepts and an additional 10 value the innovation of the project. The levels of certification achievable are WELL Bronze, Silver, Gold and Platinum (the highest equalling to a minimum of 80 points). On the topic of light, a project that demonstrates an effective and integrative approach to lighting design can score up to 18 points.

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[108] The CIE S 026/E:2018 is an international standard developed by the International Commission on Illumination (CIE) that provides guidelines and metrics for assessing the non-visual effects of light on humans. This standard introduced the melanopic equivalent daylight illuminance (mel-EDI), a new metric that quantifies the illumination needed to stimulate intrinsically photosensitive retinal ganglion cells (ipRGCs) similarly to daylight. But also defined the spectral sensitivity functions, quantities, and metrics to describe the ability of optical radiation to stimulate each of the five photoreceptor types that can contribute to retina-mediated non-visual effects of light in humans.
[109] (Giovannini et al., 2023).

Figure 1.33. The 10 WELL v2's concepts and respective features. From: WELL Building Standard v2

The Light concept of WELL v2 "*promotes exposure to light and aims to create lighting environments that promote visual, mental and biological health, specifically providing a lighting environment that reduces circadian phase disruption, improves sleep quality and positively impacts mood and productivity*"[110]. The pivotal importance of incorporating Non-Image-Forming issues into architectural practice is underlined by the first line of the text dedicated to the concept of light in the WELL Building Standard v2, stating that "*Light is the main driver of the visual and circadian systems*"[111]. WELL gives recommendations about light over 9 topics:

1. **Light exposure**: provided indoor through daylight and electric light design;
2. Visual lighting design: provide visual comfort and enhance visual acuity for all users through electric lighting;
3. **Circadian lighting design**: support circadian and psychological health through indoor daylight exposure and outdoor view;
4. **Electric light glare control**: minimize glare caused by electric light;
5. **Daylight design strategies**: provide daylight exposure indoors through design strategies;
6. **Daylight simulation**: ensure indoor daylight exposure through daylight simulation strategies;
7. **Visual balance**: create lighting environments that enhance visual comfort;
8. **Electric light quality**: enhance visual comfort and minimize flicker;
9. **Occupant lighting control**: provide individuals with access to customizable lighting environments.

[110] WELL Building Standard v2. Version Q1 2023. International Well Building Institute.
[111] Ibidem.

A series of recommendations are given along these themes, which also contain thresholds to be accomplished, such as 218 lx of melanopic EDI in case of electric light only use, or 163 lx with daylight presence, specifically if specific daylight criteria are met. Important to note that such light intensities should be met for a minimum of 4 hours.

Here a schematic representation of the main recommendations in terms of values[112]:

1 point	3 points
• m-EDI > **136** lx	• m-EDI > **250** lx
or	*or*
• m-EDI > **109** lx • 70% of all workstations within 4.88m of glazing • Light transmittance T_v > 40%	• m-EDI > **163** lx • 70% of all workstations within 4.88m of glazing • Light transmittance T_v > 40%
or	*or*
• m-EDI > **109** lx • average $sDA_{300,50\%}$ >75% of regularly occupied floor area	• m-EDI > **163** lx • average $sDA_{300,50\%}$ >75% of regularly occupied floor area
Light level must be present on the vertical plane at eye level for at least 4 hours (beginning by noon at the latest)	

Figure 1.34. WELL recommendations in terms of circadian lighting. From Giovannini, L., Lo Verso, V. R. M., Valetti, L., Godoy Daltrozo, J., & Pellegrino, A. (2023, settembre). Integrative lighting in offices: results from field measurements and annual daylight simulations. https://doi.org/10.25039/x50.2023.OP016.

In addition, threshold values have also been defined for the Circadian Stimulus (CS) metric developed by Rea and Figueiro, found in "Model for Human Circadian Phototransduction proposed by the LRC". Again, the values are distributed over the different times of the day, such as in the CIE recommendation, and consist respectively of a Cricadian Stimulus value of 30% for daytime hours, a threshold pre-sleep 3 hours before habitual sleep corresponding to 10% and finally a CS value in the sleeping environment of 0%[113].

Conclusions

To achieve integrative lighting, a designer must balance lighting strategies to meet both visual requirements and non-visual recommendations. This involves carefully designing both electric lighting and daylight through reliable strategies. The result of such integration would consist in creating environments that support both the visual and non-visual needs of occupants.

[112] (Giovannini et al, 2023).
[113] (Rea et al., 2005).

List of illustrations, Chapter 1

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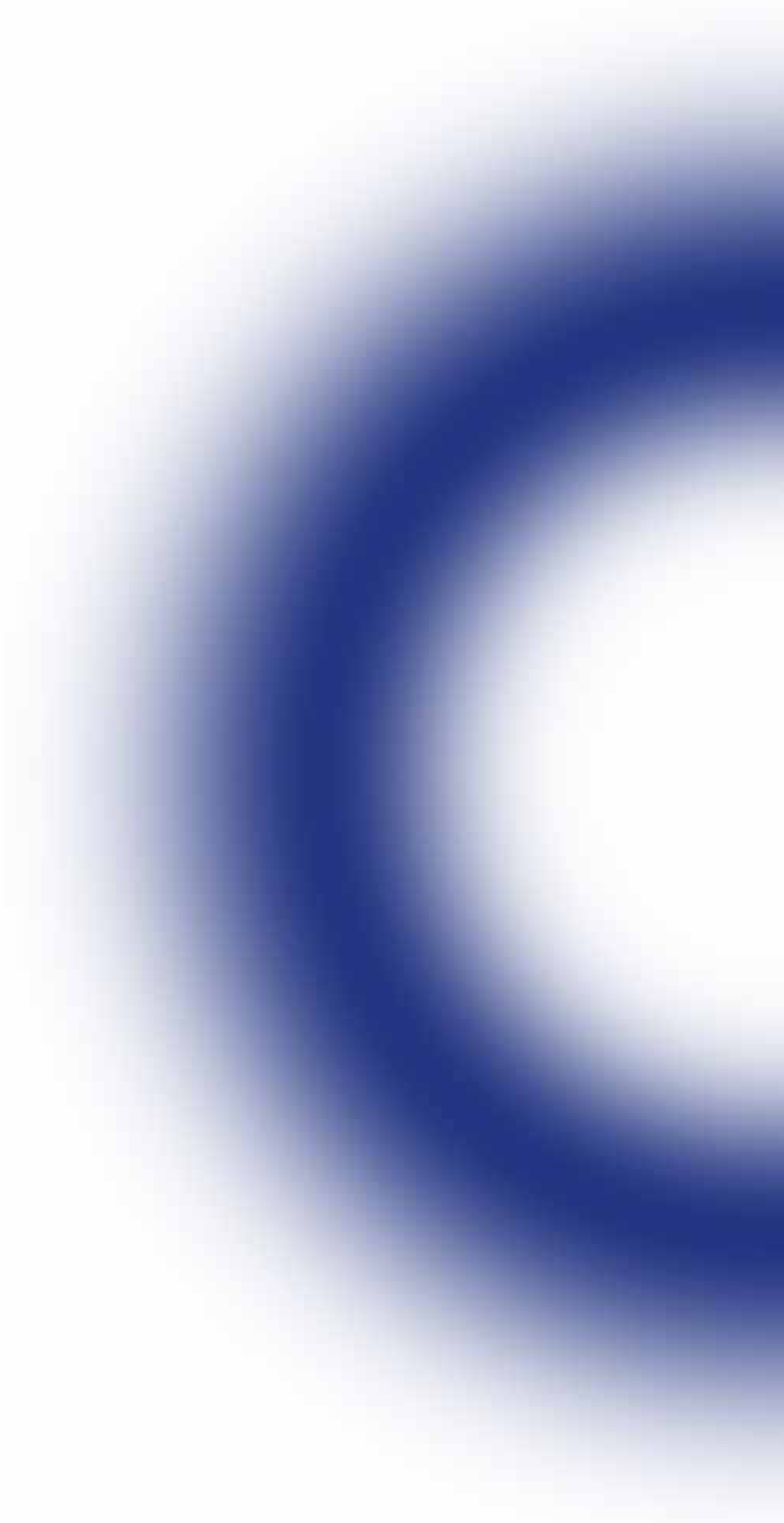


2. Literature review

Detailed index

2.1. Introduction:

In recent years, the field of lighting design, including its research component, has experienced a significant shift towards integrative lighting solutions that consider both the visual and non-visual effects of light on human well-being. Given that integrative lighting is a relatively new area of focus, it is essential to understand the methodologies employed in current research. This literature review aims to investigate the methods used in integrative lighting studies, examining how recent research is structured, including the approaches taken to evaluate both visual and non-visual effects of light and the metrics and measurement techniques utilized. The general idea is to systematise the different research methods by comparing a selection of studies, as well as relating them to one another and identifying potential areas for further methodological development.

> "*The increased interest in the acute and circadian effects of light made it necessary to create a standard template for research approaches since many variables can be included, such as physiological or psychological processes, environmental factors or person-related.*" (Englezou & Michael, 2023)

2.2. Method

2.2.1. Data sources

Databases choice

In the initial phase of the literature review, the search was conducted across three major academic databases: ScienceDirect, Scopus, and ResearchGate, between the end of January and the beginning of February 2024. The decision to use these specific databases is driven by the following reasons: the large number of publications they offer, the simplicity of the search settings, the offer of "open access" papers and their scientific-technical approach.

2.2.2. Study selection

Selection criteria

This second phase involved formulating the input criteria for the database interface. Firstly, the search strategy consisted of a rigorous selection of terms, such as "integrative lighting", "measurements", and "melanopic", that could summarise the aim of the research and provide a broad selection of articles. Specifically, the combination of keywords used in all three databases was as follows: "*(integrative lighting) AND (melanopic) AND (non-visual effects)) AND ((simulations) OR (measurements) OR (recommendations)) AND ((lighting standards) OR (well) OR (cie))*".

To maintain focus and relevance to the specific objectives of the research and thus to provide an overview of the current state of research, one of the selection criteria was a specified timeframe, ranging from 2022 to 2024. This relatively narrow timeframe helped to achieve a balance between comprehensiveness and manageability: some attempts to use a more extended period of time actually resulted in a greater volume of literature, including a mix of relevant and less relevant content; this abundance of articles, while potentially comprehensive and useful, could have been challenging in terms of practicality and efficiency, in other words, analysing a large number of articles within the context of a single research project would be time-consuming and/or potentially overwhelming the capacity of an individual researcher. Substantially, after experimenting with different timeframes as search parameters in the three selected databases, the 2022-2024 period was identified as the most suitable for the reasons outlined above.

Regarding the typology of articles selected, a database setting provided the possibility of filtering out articles: letters to the editor, conference abstracts, encyclopaedia articles, book chapters and literature reviews were excluded, in order to focus exclusively on original research.

Databases output

In ScienceDirect a total of 30 research articles meeting the defined criteria were identified, excluding 6 review articles, 1 encyclopaedia entry and 4 book chapters. Similarly, in Scopus, 68 articles fitting the criteria were discovered, with 10 reviews, 7 conference papers, and 1 book chapter being excluded. The search in ResearchGate, on the other hand, was carried out in a slightly different *modus operandi* since, given the same selection criteria as above, the database initially identified a huge number of papers -in the order of hundreds of items- leading to a selection by title that yielded 22 articles matching the search criteria.

Moreover, to increase the comprehensiveness of the literature review, the reference lists of the identified articles were scrutinised, resulting in the identification of an additional 27 relevant articles.

ScienceDirect_2:		
	RESEARCH THERMS:	*((integrative lighting) AND (melanopic) AND (non visual effects)) AND ((simulations) OR (measurements) OR (recommendations)) AND ((lighting standards) OR (well) OR (cie))*
	YEARS:	2022-2023-2024
	ARTICLES TYPE:	Research article **(30)** [excluded: Review article (6), Encyclopedia (1) and Book chapter (4)]
Scopus:		
	RESEARCH THERMS:	*((integrative lighting) AND (melanopic) AND (non visual effects)) AND ((simulations) OR (measurements) OR (recommendations)) AND ((lighting standards) OR (well) OR (cie))*
	YEARS:	2022-2023-2024
	ARTICLES TYPE:	Research article **(68)** [excluded: Review (10), Conference paper (7), Book chapter (1)]
ResearchGate:		
	RESEARCH THERMS:	*((integrative lighting) AND (melanopic) AND (non visual effects)) AND ((simulations) OR (measurements) OR (recommendations)) AND ((lighting standards) OR (well) OR (cie))*
	YEARS:	2022-2023-2024
	TOTAL:	few hundred articles, selected by title.
	ARTICLES TYPE:	Research articles **(22)**
Reference list:		
	27 articles	

Table 2.1. Schematic visualisation of the selection criteria used as input for the three databases mentioned and the corresponding outputs.

The first phase of this literature review, consisting in the databases search process, together with the reference lists scanning, produced a total of 147 potentially relevant publications collected.

Selection process

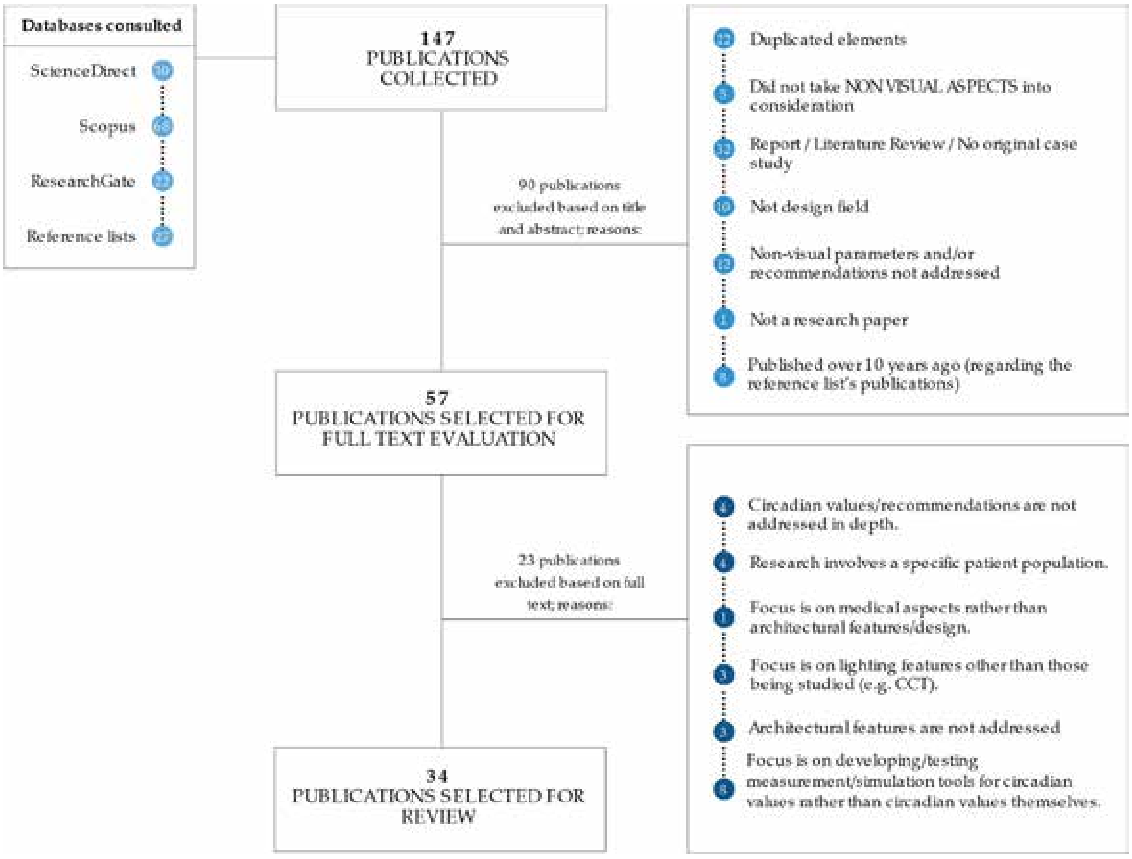


Table 2.2. Prisma diagram of the selection process.

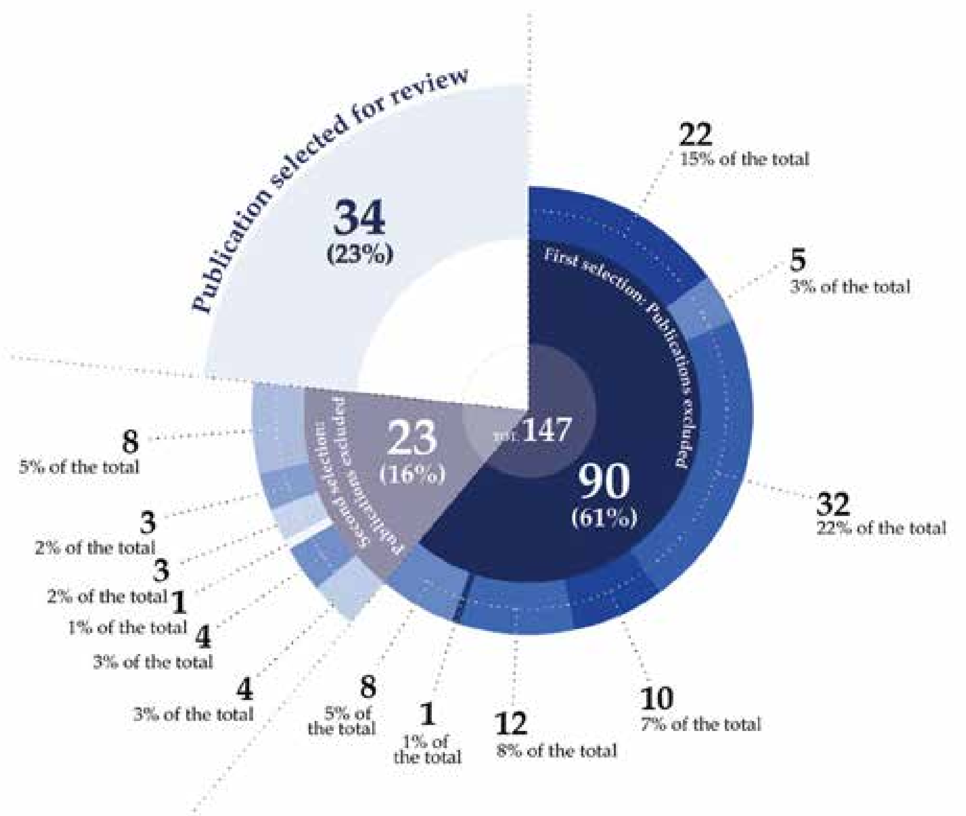
Being the topic of the review, the articles were selected when presenting a focus on integrative lighting research and, in particular, non-visual aspects of light, an explicitation of circadian and melanopic metrics, measured or simulated, and, in general the presence of a well-defined and clearly described research method. One of the primary inclusion criteria was, then, that the paper analysed had to be an original research article, providing explicit details about the methodology used. For this matter, reports, literature reviews and articles containing non-original case studies were excluded.

The selection process of the dataset was carried out in two steps. Firstly, the selection was made on the basis of the titles and abstracts of all 147 publications. This resulted in a subset of 57 publication. Of the remaining 90 publications, 22 were immediately excluded as duplicates, the majority (32 articles) were reports, literature reviews or did not include an original case study; in 12 articles non-visual parameters and/or recommendations were not addressed and 5 publications did not even consider non-visual aspects, 10 articles were not related to the field of design in any way and 1 could not be considered a research paper.

Lastly, 8 papers, among those coming from the reference lists, were excluded because their publication date was over 10 years ago; here it has to be pointed out that a specific rule was applied for the articles selected among the reference lists, the timeframe applied consisted, in fact, of 10 years, from 2014 to 2024, since the most recent publications could not cite other newer papers as references.

The remaining 57 publications were fully read in detail and 23 of them were furtherly rejected, main reasons being that most of them (8 articles) focused on developing/testing measurement/simulation tools for circadian values rather than measuring circadian values themselves; 4 of them did not address recommendations and/or circadian values in detail and 3 focused on lighting features other than those being studied (e.g. CCT), in 3 other architectural features were not specifically addressed and 1 paper related to the medical rather than the architectural field. Finally, 4 researches involved a specific patient population, whereas this review refers to a more general target population.

Therefore, the dataset of this literature review consists of 34 articles.

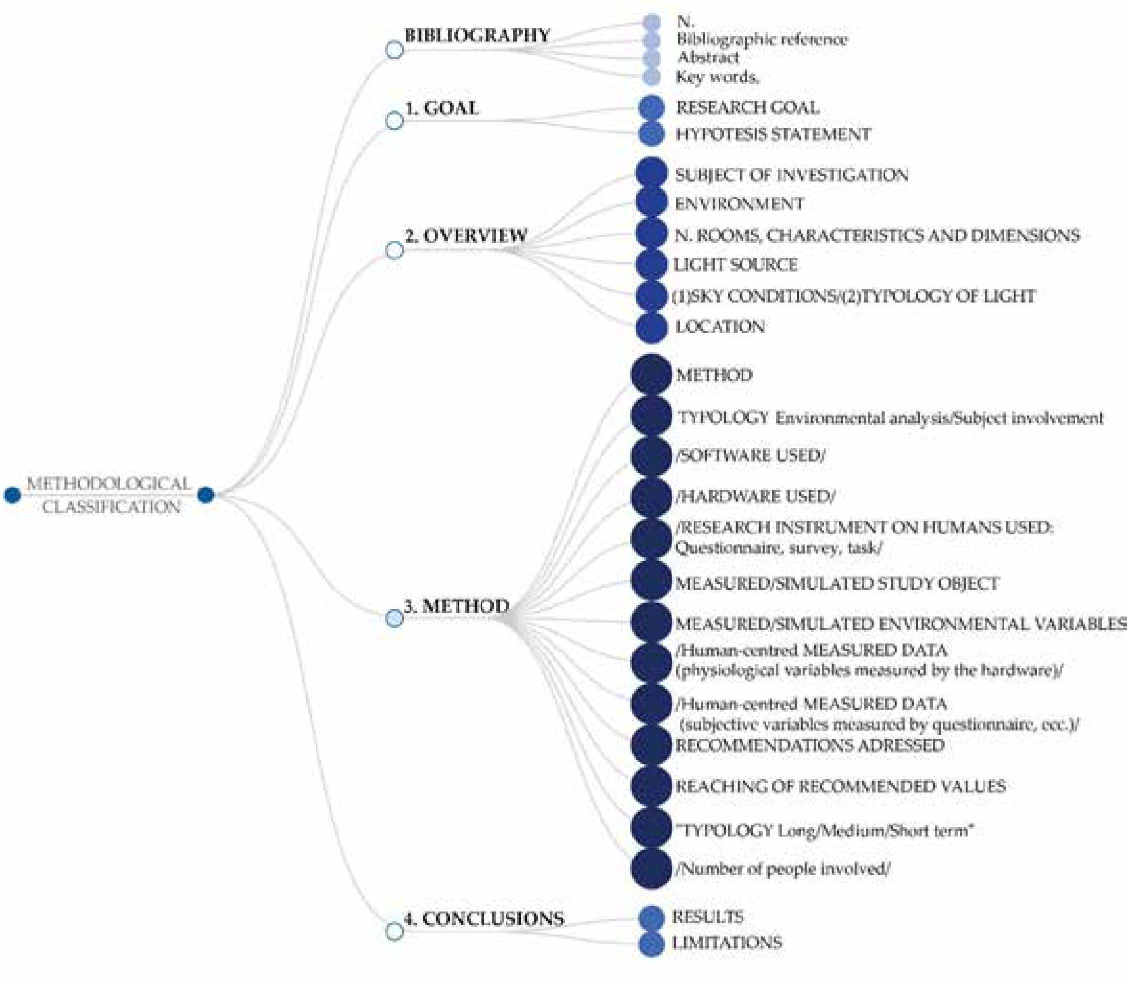


Graph 2.1. Pie chart of the literature review selection stages.

2.2.3. Analysis

Methodological classification

The second, main phase of this literature review consisted of a systematic methodological classification applied to the selected 34 articles: the data contained in each article were reviewed individually and recorded on a standardised form; consisting of 28 columns corresponding to 28 analysed characteristics; considering key dimensions such as the research goal, a general overview giving information about the environment the study was conducted in, such as the light sources or the location, the method, with an extensive analysis of its key features, in order to be able to compare the differences in the methods used from several points of view, and the conclusions drawn by the researchers.



Graph 2.2. Linear dendrogram of the methodological classification carried out for the literature review.

Analysis

Methodological classification

The categories included in the form are described in detail here:

- **BIBLIOGRAPHY:**
  - The classification starts by providing **bibliographic reference information**, including **abstracts** and **keywords**. Each research paper was numbered from 1 to 147 to simplify selection and organisational operations, reason for the presence of a column dedicated to this numerical information.

- **(1) GOAL:**
  - **Research goal**: Each article was scrutinized to identify and categorize its main research objective, allowing for a clear understanding of the primary focus of the study.
  - **Hypotesis statement:** A short paragraph describing the researchers' prediction of the results of their studies.

- **(2) OVERVIEW**:
  - **Investigated issue:** The primary element, which may be data or a property of a physical element, or a behavioural or biological aspect, whose information is analysed by the study.
  - **Environment:** The specific environment in which each case study was conducted was noted and categorized. This classification provided insights into the diverse settings where the research was carried out.
  - **N. Rooms, characteristics and dimensions**: Each study was conducted in a specific environment and due to the nature of the research, architecturally based, its architectural features are categorised.
  - **Light source:** A distinction is made between studies taking into account only electric light, daylight or both.
  - **Sky conditions / (2) Typology of light:** A description of the light adressed in the previous category is given.
  - **Location:** The city and country where the study takes place is an important factor when discussing the contribution of daylight, because of the orientation and position of the sun.

- **(3) METHOD**
  - **Method**: This section summarises the process in a few sentences as an overview of the approach adopted.

- "**Typology: Environmental analysis/Subject survey**": Here a distinction was made between studies primarily characterized by an environmental analysis and those emphasizing subject involvement, with human participants.
- **/Software used/:** A list of the software /if/ used.
- **/Hardware used/:** A list of the hardware /if/ used.
- **/Research instrument used on subjects: questionnaire, survey, task/:** A list of subject research instrument /if/ used, such as questionnaire, survey, task.
- **Measured/simulated study object:** A short sentence describing the object from which data were collected.
- **Measured/simulated environmental variables:** A list of the physical variables measured or simulated by the hardware or software mentioned.
- **/Subject measured data (physiological variables measured by the hardware)/:** /If/ adressed in the research, given the hardware used, a list is made of the physiological variables measured by it.
- **/Subject measured data (subjective variables measured by questionnaire, ecc.)/:** /If/ adressed in the research, given the research instrument used on subject, a list is made of the subjective variables measured by it through questionnaires, surveys or tasks.
- **Reaching of recommended values:** A distinction is made if the recommended values, from the adressed recommendations, are "MARGINALLY REACHED", "REACHED since the research environment was specifically designed to reach the recommended values", "EXCEEDED", "REACHED" or "NOT REACHED".
- **"Typology Long/Medium/Short term":** Articles were categorized according to the duration of the study, distinguishing between long-term, medium-term and short-term investigations. Short-term refers to a period of less than one week, medium-term refers to a period of between one week and six months, while long-term refers to a period of more than six months and up to one year or more.
- **/Number of people involved/:** /If/ the research involved human participants, the number of individuals engaged in the study was documented. This criterion provided an additional level of information on the size and scope of the research.

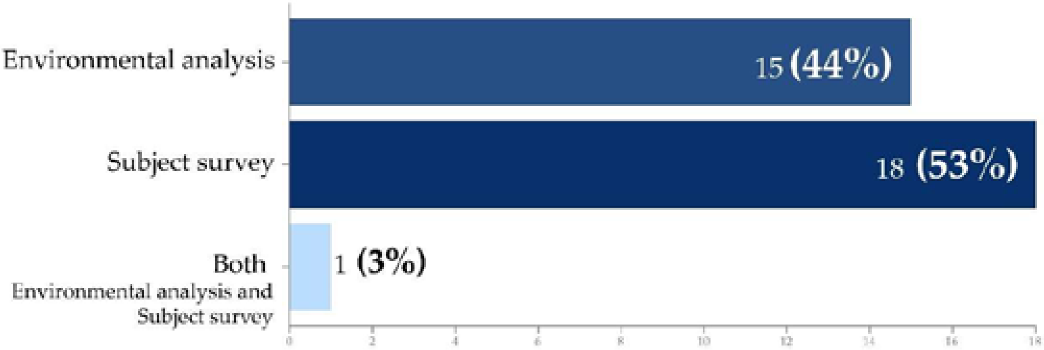
- **(4) CONCLUSIONS**
  - **Results:** A short paragraph describing the research findings.
  - **Limitations:** A list of limitations addressed by the researchers.

The form is included in its entirety in Appendix A of this thesis.

2.3. Results

2.3.1. Methodological categories

From the review of the individual research papers, a clear distinction emerged between two main methodological approaches: on the one hand, an analysis based exclusively on the environment chosen as a case study, consisting of measurements and/or simulations, defined as "Environmental analysis"; on the other hand, an analysis developed with the involvement of subjects, defined as "Subject survey".



Graph 2.3. Bar chart about method typology categorization.

The following review is based on this distinction.

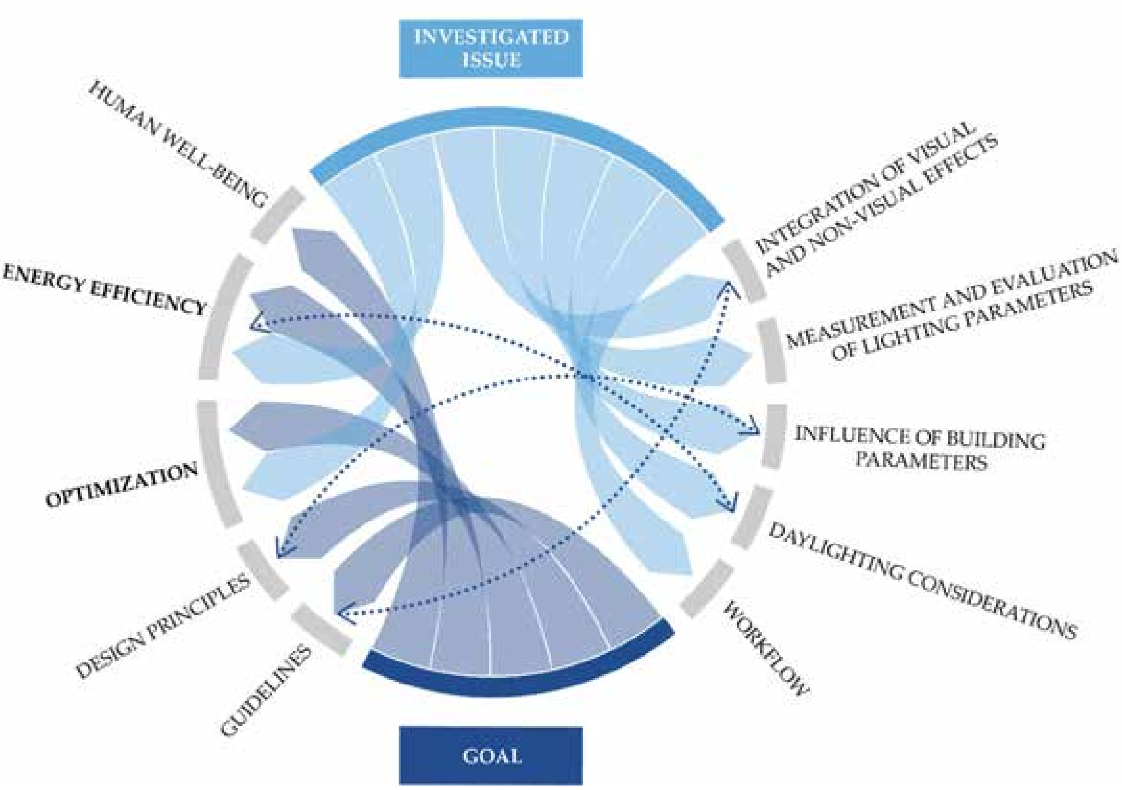
2.3.1.1. Environmental analysis

Environmental analysis focuses on the physical characteristics and metrics of lighting in different environments, taking into account environmental factors such as season, weather, time of day, orientation, glazing types, wall colors and room characteristics in the lighting design analysis.

Research goal and subject of investigation

In general, the studies aim to provide guidelines for integrative lighting design in real-world settings such as offices, classrooms, and other indoor environments; improving the understanding of lighting design principles, optimizing lighting systems for both visual and non-visual needs, promoting energy efficiency and human well-being in indoor environments.

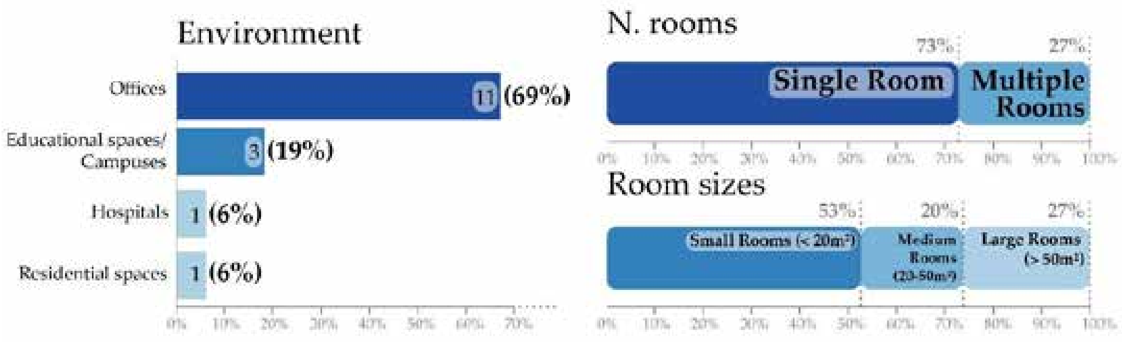
In the following diagram a list of topics extrapolated from the research objectives and investigated issues is shown:



Graph 2.4. Chord diagram of the relationships between goal and investigated issues of environmental analysis researches.

Environmental characteristics

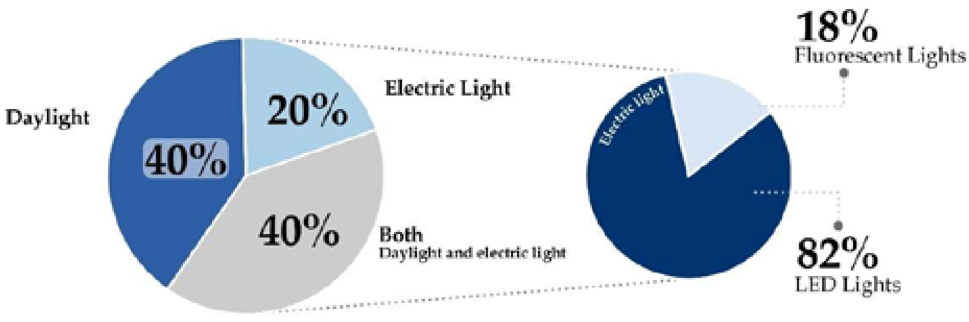
Regarding the built environment and its features, working spaces are the most analysed, with a 69% of offices, of the remaining 19% are educational spaces such as classrooms and university or school campuses, while few studies look at hospitals and residential spaces. The number of rooms analysed in these studies varies; most focus on single rooms (73%), while the rest examine multiple rooms (27%). Of those, a dimensional classification is made where small rooms (<20m²) account for 53% of the rooms analysed, medium rooms (20-50m²) for 20% and large rooms (>50m²) for 27%. The studies are mainly located in Europe (77%), followed by America (15%) and Asia (8%).



Graph 2.5-2.6-2.7. Bar charts on the experimental environments and their characteristics.

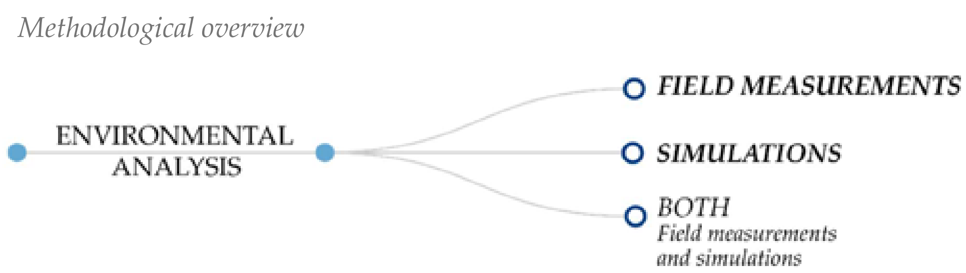
Graph 2.8. Distribution of studies (in percentage) by selected location, on map.

The types of light sources used in these studies vary: 40% were designed to use only daylight (40%), another 40% used both daylight and electric light, and only 20% used only electric light. Electric light sources used include LED lights (82%) and fluorescent lights (18%).



Graph 2.9. Pie chart on light sources and typologies.

Although there are only a few studies that focus solely on analysing electric light, there is a reason to explain this matter: the studies aimed to test a specific lighting setting (Bellia et al., 2023; Safranek et al., 2020) avoiding complications in the simulation/comprehension of the results obtained.



Graph 2.10. Linear dendrogram of the environmental analyses classification.

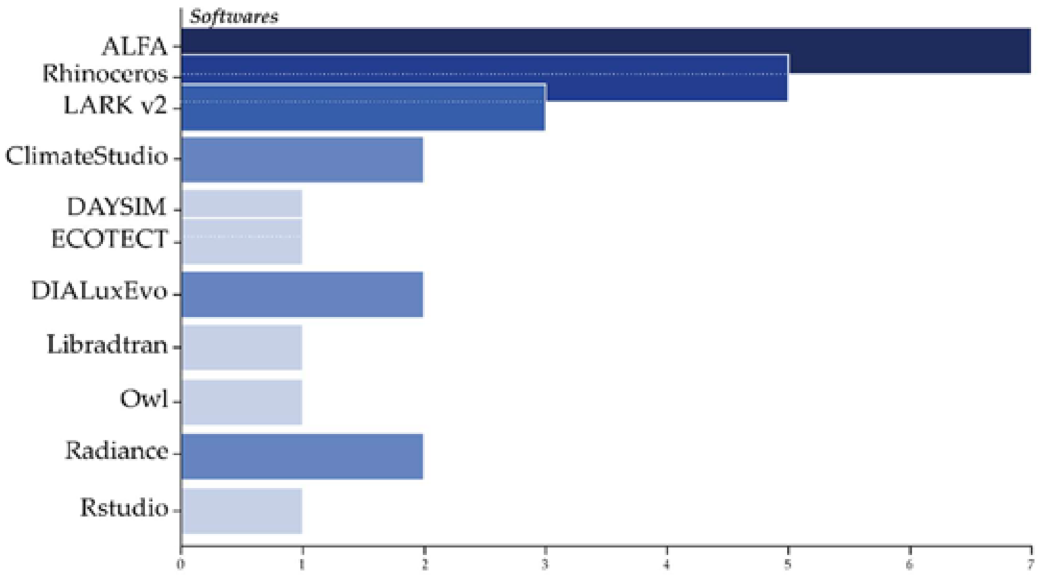
Environmental analyses methods focus mainly on the technical and spatial aspects of the lit environment, with the aim of optimising building parameters to maximise energy efficiency and daylight utilisation, while complying with regulations and improving visual comfort and circadian health. This methodology includes advanced simulations, real-time monitoring and the application of lighting standards for both visual and non-visual effects (e.g. EN1264-1, WELL Building Standard). In particular, of the 15 studies that used environmental analysis as a research method, 2 used **field measurements** (13%), 9 used **simulations** using specific software (60%) and 4 (27%) used a **combination** of the two.

1. Field measurements

Experimental studies involving **field measurements** provide empirical data on the effects of lighting interventions. Laboratory studies (one out of 15 analysis) provide controlled environments to isolate specific variables, while field studies evaluate the practical application of integrated lighting in real settings. A Spectrophotometer is used in almost every research where a field measurement is carried out, this tool allows measurement of the full colour spectrum and produces spectral colour data and photometric quantities. The variables measured in real settings are photopic illuminance, m-EDI (Melanopic Equivalent Daylight Illuminance), and seldomly Correlated Colour Temperature (CCT).

2. Simulations

As mentioned above, 60% of studies use **advanced simulation tools** to analyse lighting conditions and their effects. In detail, these studies model both daylight and electric lighting scenarios to predict visual and non-visual outcomes, helping optimize lighting systems and design recommendations, since they examine how daylight dynamics, including time of day, season, orientation, and sky type, affect melanopic EDI levels and horizontal illuminance standards. As an example, "*Twenty-seven different lighting scenarios are developed by varying luminaire fluxes to meet specific eye illuminance requirements*" (Bellia et al., 2023).



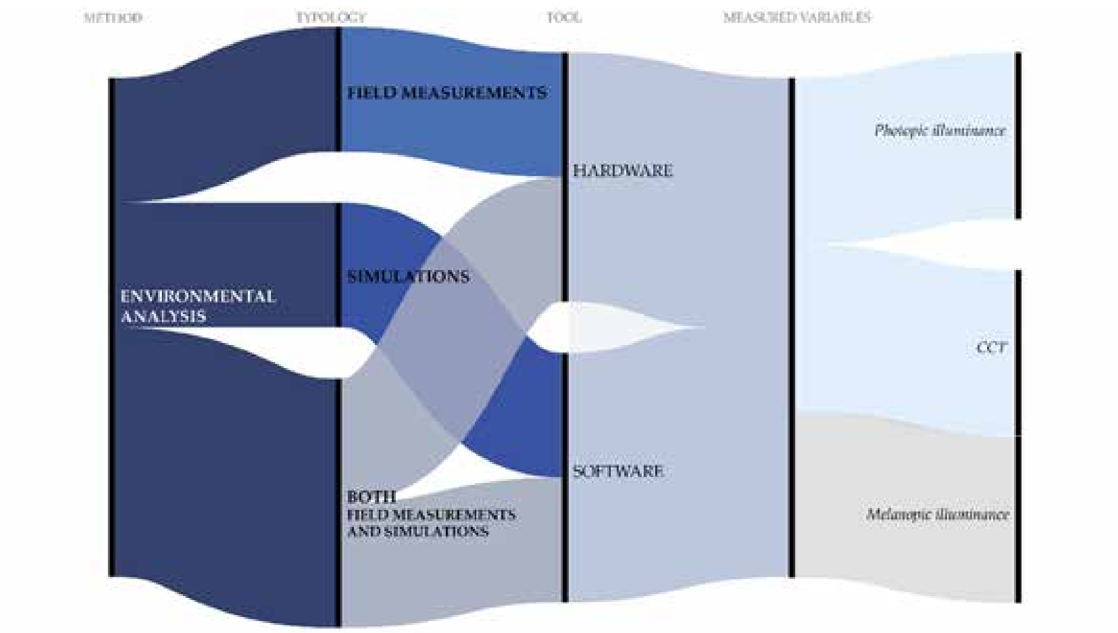
Graph 2.11. Bar diagram of the software used in the simulation experiments.

The software used, in order of frequency, are ALFA and Rhinoceros, almost always used in combination, LARK v2, ClimateStudio, Radiance and DIALuxEvo, which appear more than once in the papers consulted, and finally DAYSIM, ECOTEC, Libradtran, Owl, Rstudio. While Rhinoceros is a modelling tool, ALFA, LARK v2, ClimateStudio and Radiance are for daylight simulations; Dialux is mostly used alone for both modelling and electric lighting simulations. In one case the software ECOTEC is used as the modelling interface and DAYSIM as the tool for daylight calculations.

Illuminance, m-EDI and CCT are the most usual measured and simulated variables.

3. Both field measurements and simulations

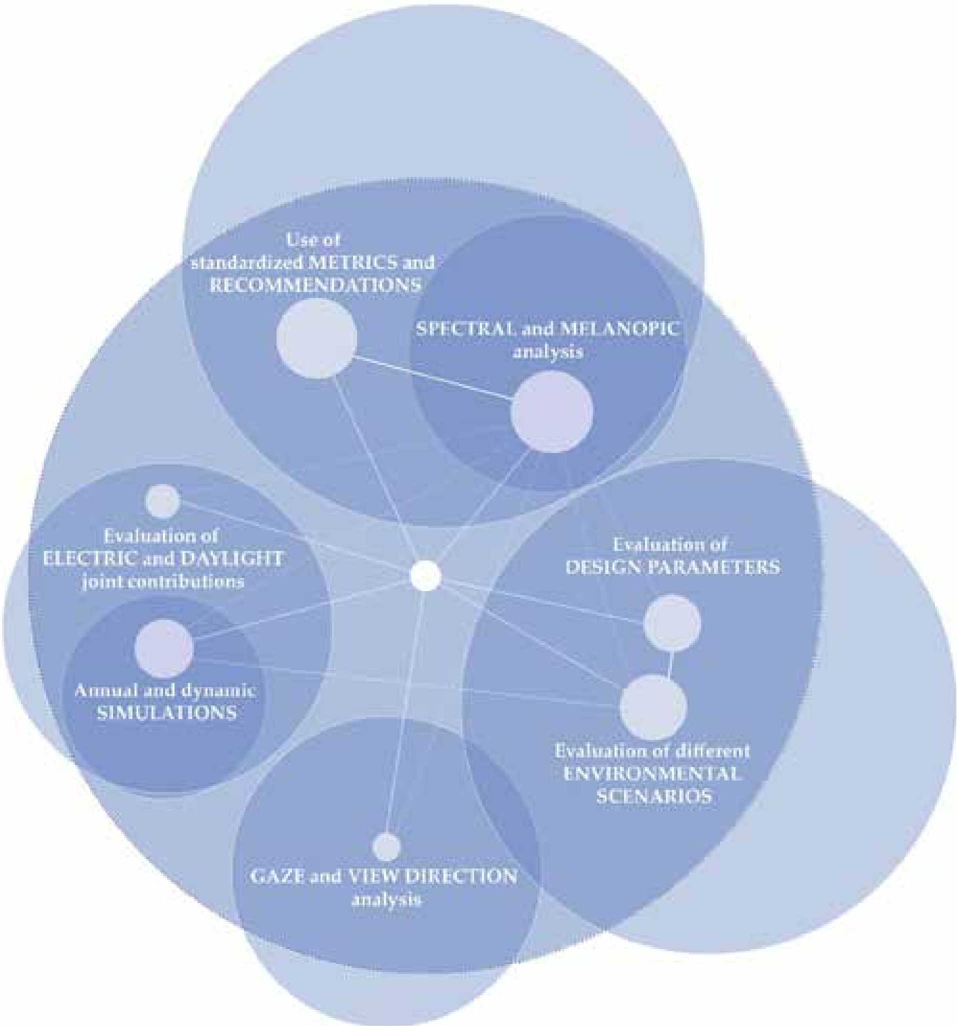
A **hybrid approach** is common, where simulations are used to predict lighting conditions, and field measurements are taken to validate these predictions, a dual methodology able to ensure reliability.



Graph 2.12. Alluvial Diagram showing correlations between the methodological categorizations.

Within this methodological categorization, different approaches are then developed based on the different goals of the researches. Studies often analyse a wide range of scenarios (e.g. different orientations, seasons, time of day) to understand the variability and performance of lighting solutions under different conditions, framework which includes annual daylight simulations. A **parametric approach**, on the other hand, explores the effect of design parameters on visual and non-visual metrics by varying them within different simulations (e.g. room geometry, material reflectance).

In general, nearly all methods expand traditional three-channel lighting analysis to multi-channel (e.g., 9-channel) approaches to capture spectral datas relevant to human health, particularly melanopic lux. Many studies use established **metrics and standards** such as the Melanopic Equivalent Daylight Illuminance (m-EDI) or Equivalent Melanopic Lux (EML), CIE S026 melanopic metrics and WELL standards as the starting point of the analysis to ensure comparability in the field. Some methods incorporate the analysis of different gaze directions and view positions to assess the variability in lighting exposure that occupants might experience, reflecting real-world usage more accurately. Other evaluate **electric and daylight joint contributions** in order to provide guidelines for lighting design; dynamic lighting systems and adaptive control strategies are examples of advanced techniques applied in these studies.



Graph 2.13. Infographic on the different approaches carried out within environmental analyses.

Daylight is often mentioned in connection with **energy consumption** (Zeng et al., 2021), a research presenting a workflow combining non-visual and visual requirements was able to show how the addition of non-visual requirements leads to a 57% increase in energy consumption, *"furthermore, daylight and light with a higher CCT are beneficial for non-visual energy-saving. The additional non-visual requirements will not increase the lighting energy consumption under favorable daylight conditions"* (Zeng et al., 2021). Anyway, the majority of the studies did not address the topic of **shading devices**, seen as an additional layer of complexity and therefore considered a limitation (Potočnik & Košir, 2021; Zeng et al., 2021). Nevertheless, one study analysed two shading systems in relation to melanopic values: a traditional roller blind and an electrochromic (EC) glass which would automatically tint with direct sunlight (Boubekri et al., 2020). Yet another research paper investigated the impact of using shading devices as a mean to control horizontal photopic illuminance, and evaluated it based on its circadian potential (Potočnik & Košir, 2019).

The following image illustrates an example of a comparative approach employed to evaluate compliance with visual and non-visual requirements:

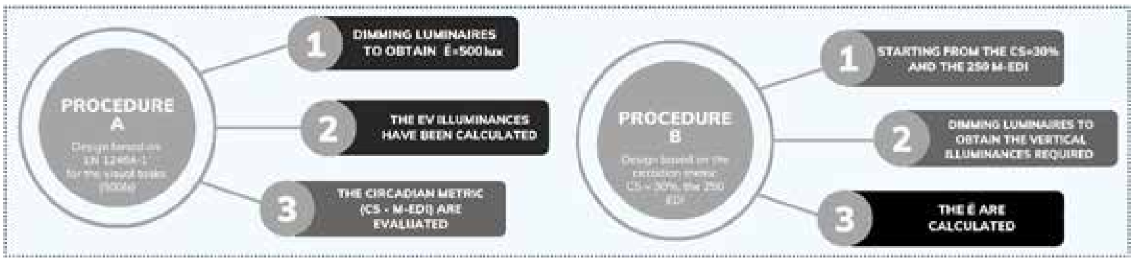
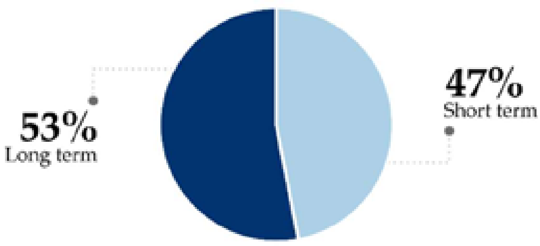


Figure 2.1. "Workflow (Procedure A design based on EN 12464-1 – procedure B design based on the circadian metric)" (Bellia et al., 2023).

Study duration

Thanks to the nature of the environmental analysis and the potential of simulation tools, most studies were long-term analyses (63%), with annual simulations using "weather files of a typical meteorological year" in the chosen location. The remaining (37%) were short term analyses, mainly in case of field measurements only researches.



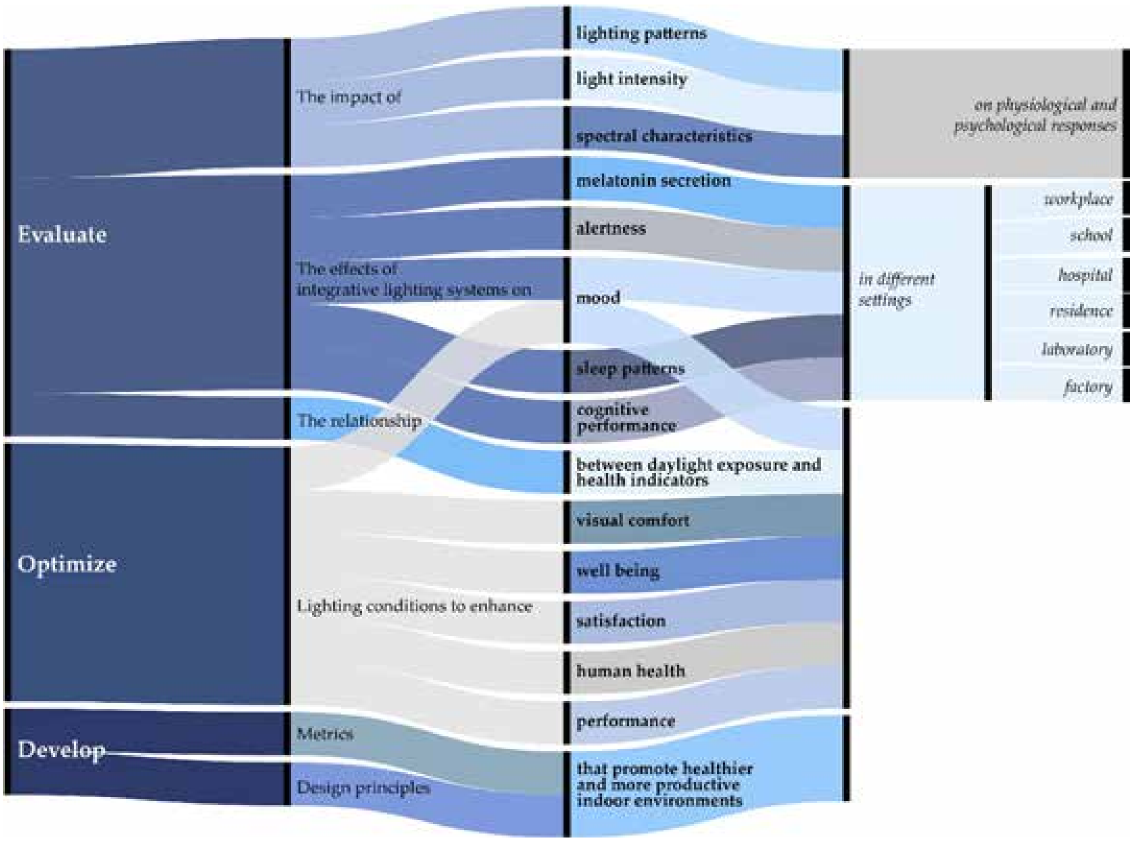
Graph 2.14. Pie chart regarding the typology "Study duration".

2.3.1.2. Subject survey

A subject survey is based on collecting and interpreting data about users and their needs to determine the impact of lighting on physiological, psychological and behavioural responses.

Research goal and subject of investigation

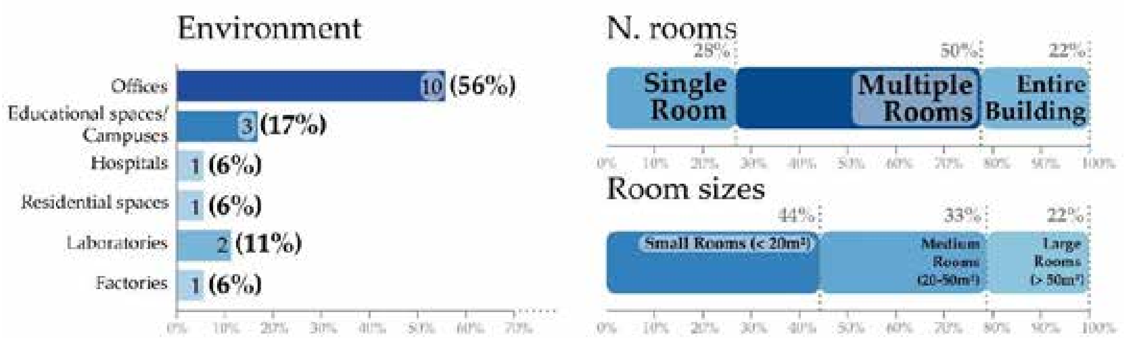
The research goals collectively explore the role of lighting on human circadian rhythms, sleep quality, and overall well-being. Specifically, they aim to evaluate the impact of different lighting characteristics on physiological and psychological responses. Key areas of focus include evaluating the effects of integrative lighting systems on melatonin secretion, alertness, mood, and cognitive performance across different settings, such as workplaces, schools, and hospitals. The studies also investigate the relationship between daylight exposure and health indicators. Moreover, by examining both static and dynamic lighting conditions, these goals aim to develop metrics and design principles that promote healthier and more productive indoor environments.



Graph 2.15. Alluvial Diagram of a pool of topics emerging from the research goals and topics.

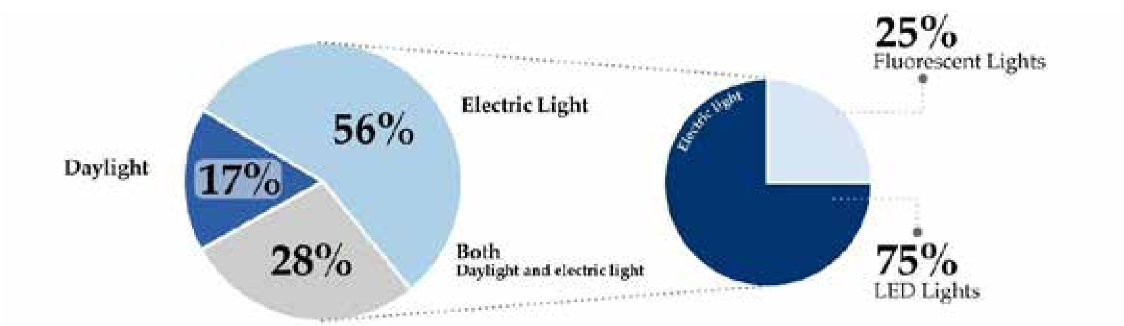
Environmental characteristics

These studies cover a range of real environments including offices (56%), educational spaces such as classrooms, whole schools or campuses (17%), but also hospitals (6%), residential spaces (6%) and factories (6%). However, two studies (11%) were conducted in laboratories. Most studies are conducted in multiple rooms (50%), with 28% using single rooms and the remaining 22% covering the entire buildings. In terms of size, 45% of rooms were small (<20m2), 33% were medium (20-50m2) and 22% were large (>50m2).



Graph 2.16-2.17-2.18. Bar charts on the experimental environments and their characteristics.

For the nature of the study itself and its limitations, when classifying the light sources used, there is a clear predominance of electric light studies (56%), with 28% using both electric and daylight, and only 17% of studies focusing on daylight alone. Of the electric light employed 75% are LED light sand 25% are fluorescent lights.



Graph 2.19. Pie chart on light sources and typologies.

Reasons why **daylight** is excluded by most cases can be summarized as following: (1) on purpose in order to understand the effects of daylight deprivation (Li et al., 2022), in case of shift workers for example (Bessman et al., 2023; Putte et al., 2022), or (2) to evaluate an electric lighting configuration (Schledermann et al., 2023; Wang et al., 2022) while avoiding complications in interpreting the results.

Participant involvement: selection criteria and instructions for individuals

In studies involving the participation of individuals, strict selection criteria on the population have been applied. Firstly, considering the high individual variability of the human circadian system, in order not to compromise the reliability of the results: tests have been carried out to determine the different **chronotypes** of the people involved (Prayag et al., 2019; Schledermann et al., 2023; Wang et al., 2022), using questionnaires such as the *Munich Chronotype Questionnaire*, where people with extreme chronotype were usually excluded; in many studies, a distinction has been made between the **sexes** due to the fact that men and women present different characteristics in terms of circadian and hormonal aspects; for this reason, some studies present the decision to exclude an entire gender so as not to compromise the reliability of the results (Wang et al., 2022); while others considered both genders even though gender effects are not addressed in the results, which is often expressed as a limitation that should, however, be pursued in future research (Fostervold & Eilertsen, 2022; Putte et al., 2022). In yet another case, both sexes are studied, but in regard to women, the menstrual phase in which they fall and the use of contraceptives are taken into account, still related to hormonal aspects (Grant et al., 2023). The majority of studies with participants also made a precise **age**-related selection, with participants often belonging to a small age range varying between two and three years at most (Fostervold & Eilertsen, 2022), caused by the different sensitivity of both vision and circadian system of different age groups. Other studies did not take this aspect into account and had much wider age ranges (Boubekri et al., 2020). Only one research (Huang et al., 2023) addressed age and gender impacts on results, however, no significant correlation was found with human and lighting metrics.

Other selection criteria consisted in **eye disease and psychological problems screenings** (Chen et al., 2019; Grant et al., 2023; He et al., 2023; Huang et al., 2023; Prayag et al., 2019). Also having travelled across more than one **time zone** in one/two month prior to the study was exclusionary (Boubekri et al., 2020; He et al., 2023; Huang et al., 2023; Prayag et al., 2019; Stebelová et al., 2024).

In order to have reliable results from a huge number of participants, every research assessed a series of **rules to standardize habits or behavioural aspects** that could affect the findings objectivity. First of all, defining a **constant bedtime** (Benedetti et al., 2022; Grant et al., 2023; Huang et al., 2023), for instance, in case of studies analysing sleep quality and duration; **avoid or limit alcohol and caffeine and not take medication** (Bellia et al., 2023; Benedetti et al., 2022; Bessman et al., 2023; Boubekri et al., 2020; Chen et al., 2019; Fostervold & Eilertsen, 2022; Grant et al., 2023; He et al., 2023; Prayag et al., 2019).

In some cases, limits were even placed on the diet, such as abstaining from eating bananas or chocolate (Fostervold & Eilertsen, 2022).

> *"Limitations of our study are certainly linked to the semi-naturalistic approach: there were no constraints on light exposures out of the office, for instance in the evening hours, or during the lunch break outside the building; there were no instructions for physical activity or meal timing, which may have contributed to individual variability of hormonal and light exposure data"* (Benedetti et al., 2022)

To avoid running into these kinds of limitations, some studies involving subjects set up **facilities** in which the participants would spend the entire study period without leaving, since "*This similar behaviour and light exposure largely reduced the experimental error*" (Xu et al., 2023). While others imposed a maximum walking distance of no more than 30 minutes from the lighting laboratory where the study was being conducted to the place participants were sleeping (Huang et al., 2023). Another effective measure taken in various study in order not to compromise the lighting impact on participants when outside the research environment was wearing **blue-block tinted glasses** (Bessman et al., 2023; Huang et al., 2023). Along the same lines, several studies selected their participants within **university campuses or high schools with dormitories**, thus ensuring that the participants lived in the same location, had a very similar lifestyle, with the same school and leisure hours, ate together at regular times and were subject to the same sleep-wake cycle (Fostervold & Eilertsen, 2022; Xu et al., 2023).

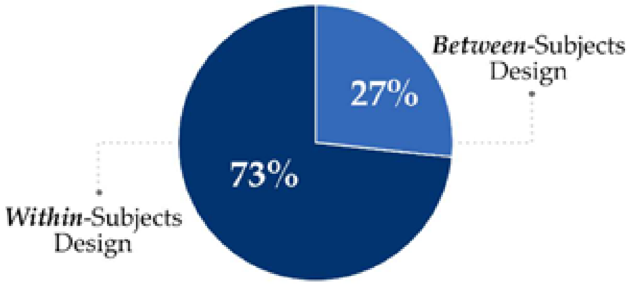
The subject of integrative lighting is associated with a wide range of issues related to wellbeing and human activities; when mentioning circadian cycles, roles such as **shift workers**, whose circadian health is strongly influenced by the occupation they practise, cannot but be mentioned. Reason why studies involving subjects and melanopically implemented devices often focus on this target group, searching for the best solutions to improve their circadian phases (Bessman et al., 2023; Putte et al., 2022; Schledermann et al., 2023).

> *"With the high prevalence and necessity of shiftwork in our society, interventions that mitigate its harmful effects on health and safety are warranted. A leading countermeasure is light, which acts via a range of physiological effects, including circadian resetting, alerting properties, and mood enhancement."* (Bessman et al., 2023)

> *"In shift work, appropriate lighting conditions are of additional relevance as disturbed hormonal regulations and physiological processes are typical consequences of shift work due to the mismatch between the light-dark pattern and the sleep-wake rhythm"* (Blask, 2009)

Subject surveys can be divided into two types of experimental design:

- **Within-subjects design**: Same groups of participants were exposed to different lighting conditions, so that each participant experienced all lighting conditions. 73% of the experiments used this design.
- **Between-subjects design**: 27% of the studies used a between-subjects design, where participants were randomly assigned to different lighting conditions for comparison, in other words, each group experienced only one lighting condition.

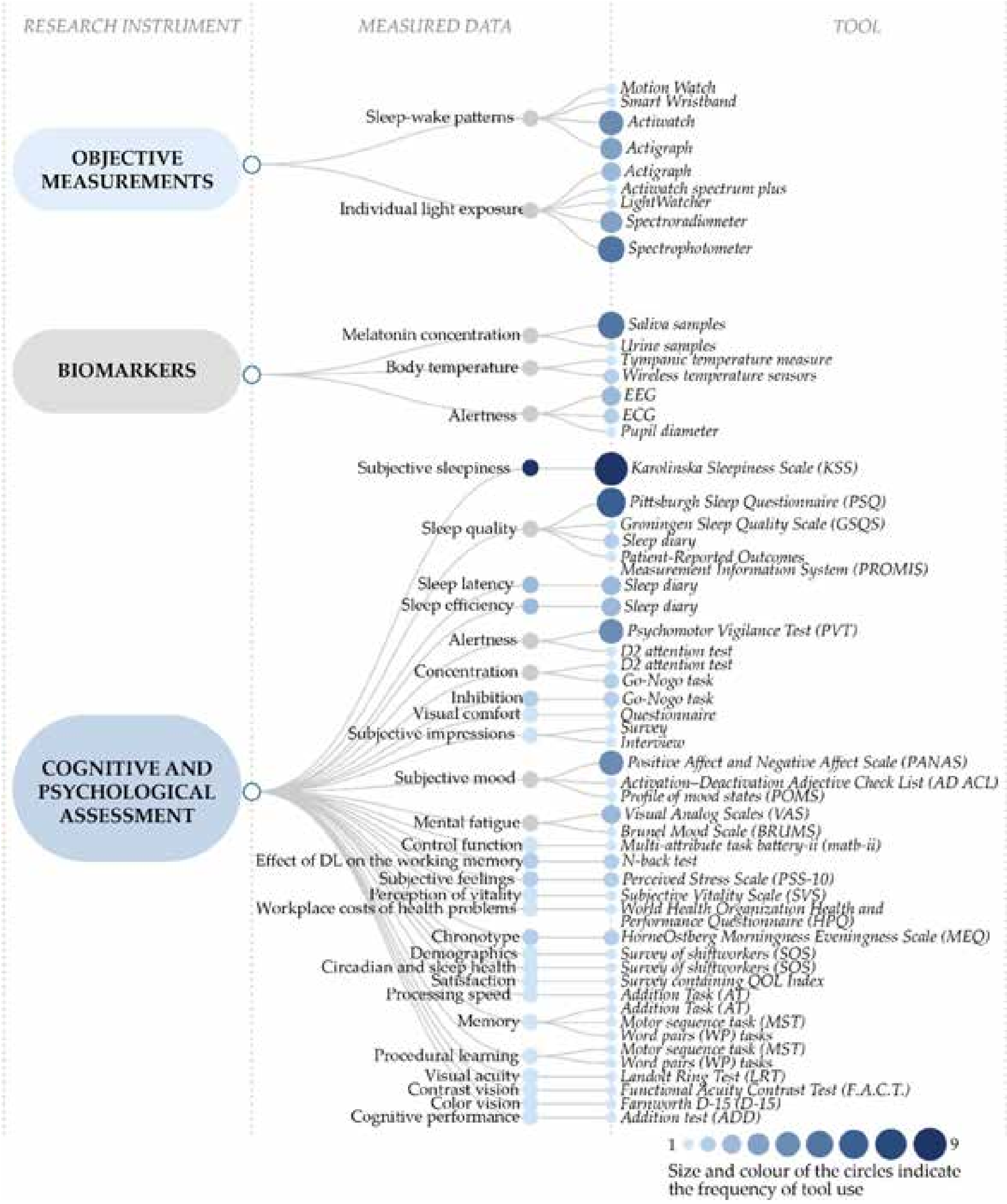


Graph 2.20. Pie chart of the Subject surveys' categorization.

The design is then structured around three primary measurement techniques: objective measurements, biomarkers, and cognitive and psychological assessments, each examining different variables through specific tools.

Objective measures acquire quantifiable data such as sleep-wake patterns and individual light exposure. Tools include different types of actiwatches and actigraphs for tracking sleep patterns, and various devices like spectroradiometers, spectrophotometers or sensors for measuring individual light exposure. On the other hand, biomarkers are used to assess physiological responses to lighting, such as melatonin concentration, body temperature, and alertness. Saliva and urine samples, tympanic and wireless temperature sensors, EEG, ECG, and pupil diameter measurements are among the tools used. Eventually, cognitive and psychological assessments evaluate subjective and behavioural responses to lighting; this category includes a wide range of measured variables, such as sleep quality, alertness, concentration, mood, mental fatigue, control function and memory. Tools and methods used include sleep diaries, questionnaires like the ones using the Karolinska Sleepiness Scale (KSS) and the Pittsburgh Sleep Questionnaire (PSQ), various cognitive tests like the Psychomotor Vigilance Test (PVT), D2 attention test and Go-Nogo task. Surveys and interviews are also employed to gather subjective impressions and feelings, or to implement information about participants.

There is, however, no lack of environmental measures, such as horizontal and vertical illuminance, along with spectral power distributions monitored in real time using devices like colorimeters and spectrophotometers, in order to compare objective and subjective outcomes.

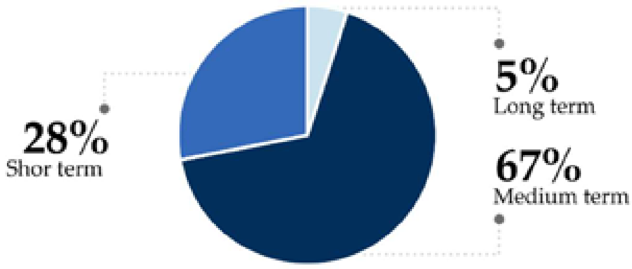


Graph 2.21. Linear dendrogram of the research instrument and respective measured data and tools for Subject surveys.

Study duration

The duration of the study includes both the time spent in the research environment and, when required, the washout period between different sessions of the same study.

The selected studies were divided into three main groups in terms of duration: as previously stated, short-term referring to a period of less than one week, medium-term referring to a period of between one week and six months and long-term referring to a period of more than six months and up to one year or more. In particular, research involving human subjects tended to be of **longer duration** because of the need for preparation time, for example to establish a regular schedule (bed and wake times) (Benedetti et al., 2022; Huang et al., 2023), but also because of the need for washout periods, for example when comparing different lighting scenarios in order to minimize any carryover effect (Benedetti et al., 2022; Bessman et al., 2023; Huang et al., 2023; Xu et al., 2023).



Graph 2.22. Pie chart regarding the typology "Study duration".

2.3.2 Comparative analysis

Differences and similarities

Environmental analyses and subject surveys have emerged as the fundamental approaches to integrative lighting research.

A comparative summary of the two series reveals a number of **common features**: starting from the goals, since both aim, overall, to optimise lighting environments for improved well-being and performance. In terms of approaches, empirical research methods such as simulations, measurements and controlled experiments are identifiable in both approaches. Consequently, common tools, including light sensors, measuring devices and software for lighting simulations, are employed, and the same metrics are assessed, such as Circadian Stimulus (CS) and Melanopic Equivalent Daylight Illuminance (m-EDI). Finally, a primary outcome focuses on improving cognitive function, mood, and sleep quality through better lighting design, while offering insights for circadian recommendations.

Conversely, **numerous differences** can be identified. Essentially, environmental analysis emphasises the physical aspects of the lighting environment, whereas subject surveys concentrates on the physiological and psychological impacts of lighting on humans. As a result, the former utilises dimensional and temporal parameters, while the latter mainly employs biological and subjective criteria. Summarizing the methodologies previously discussed: environmental analysis involves (1) the use of architectural and lighting design software to simulate and optimise lighting conditions, and (2) the analysis of environmental conditions, design parameters and shading effects on lighting quality; subject surveys relies on laboratory and field studies with human participants (1) to measure biological and psychological responses as well as (2) subjective impressions of satisfaction and well-being. Moreover, even the challenges in the two methodologies differ: for instance, environmental analysis must balance energy efficiency with lighting quality, or address the variability of daylight due to weather and seasonal changes. Conversely, subject surveys may encounter difficulties when addressing topics such as the individual variability in circadian responses or the integration between objective and subjective metrics.

Even though it can be challenging to quantify variables not conventionally measurable such as subjective variables and in general combine the two environmental and subject survey methodologies, an example approach can be found in the article "*Evaluating an integrative lighting design for elderly homes – a mixed methods approach*" (Bochnia et al., 2022), where, as the title announces, a mixed method approach is carried out showing the meeting points of the two opposite approaches.

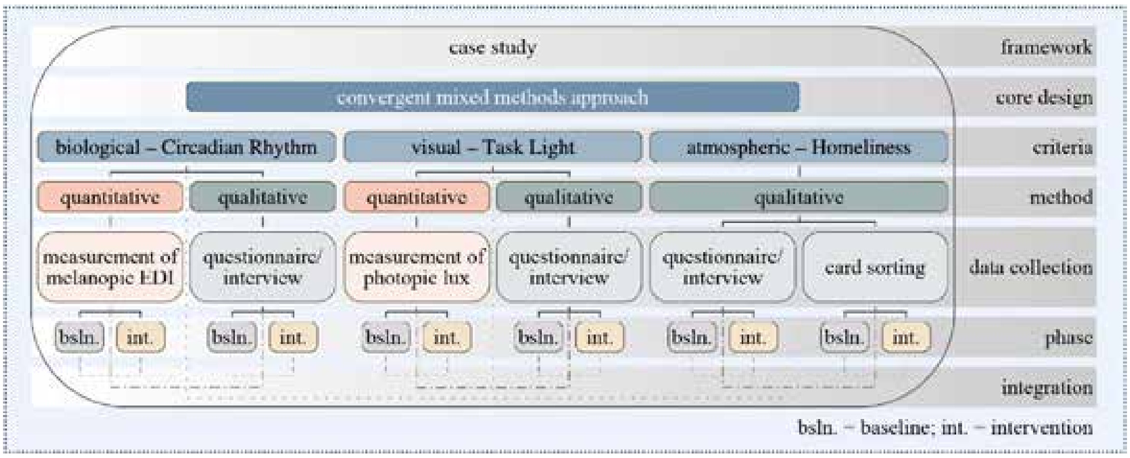


Figure 2.2. "Methodology chart based on Creswell & Plano 2018" (Bochnia et al., 2022).

A mixed method approach can "*potentially contribute to other research by presenting an approach that could be applied to other lighting design cases where more than one factor needs to be addressed and investigated in field studies*." (Bochnia et al., 2022).

Results and limitations:

In general, results from both environmental analyses and subject surveys show common features. Regarding the 34 different results achieved from the respective research papers: non-visual parameters and recommendations, architectural and lighting design strategies, circadian health and wellbeing and energy efficiency are the most cited topics.

Several papers discuss the role of lighting in promoting circadian rhythms and look at strategies involving higher melanopic illuminance in the morning and lower levels in the evening. The integration of daylight with electric lighting systems is another recurring theme; this approach often aims to maximise the availability of daylight during peak hours, while using energy-efficient electric lighting to maintain appropriate lighting levels. Another approach is to implement dynamic or tunable lighting systems that adjust colour temperature and intensity throughout the day to mimic natural daylight patterns. Moreover, combining daylight with advanced lighting control systems, such as luminaire-level lighting controls (LLLC) and task lighting (Rockcastle & Mahic, 2024), can result in significant energy savings compared to simple on/off systems. As well as using vertical rather than just horizontal lighting to meet eye-level lighting recommendations. Also, considering the impact of architectural features: window design, orientation, glazing properties, and surface finishes significantly influence the spectral qualities and overall effectiveness of lighting designs in providing adequate circadian light exposure. Factors such as the position of workstations in relation to windows and the use of shading systems can have a significant impact on the efficacy of lighting designs. Finally, improved sleep quality, alertness, and cognitive performance are frequently reported outcomes of optimised integrative lighting designs. However, the recognition of individual variability in response to light exposure suggests the need for personalised lighting solutions.

A series of papers offers insights on how to **improve circadian values/recommendations**. Some studies that analyse existing lighting conditions or compare different lighting conditions, such as static and dynamic lighting/circadian lighting, provide information on the circadian values of these systems and environments and, in the case of studies involving human subjects, make a comparison between these values and the non-visual effects that occur in participants, showing that different levels of melanopic amounts produce different effects on people's health and well-being, even when the recommended values are not reached or, on the contrary, are greatly exceeded.

Although popular metrics and current recommendations for non-visual effects are based solely on melanopic illuminance[1], this could not be sufficiently accurate in predicting the circadian effects of light, therefore some studies investigated other factors, such as the contribution of single visual photoreceptors which could be also involved in the circadian phototransduction process and thus improve the present guidelines; for instance, one research (Huang et al., 2023) investigated the influence of different levels of cyanopic illuminance on a study population while keeping photopic and melanopic illuminance constant, based on the results obtained cyanopic illuminance could be beneficially incorporated with melanopic illuminance to **improve circadian values**:

> *"These findings challenge the assumption that the current popular circadian metrics based solely on melanopic illuminance, such as m-EDI and EML, can accurately predict the circadian effects of different lighting conditions. Instead, our results suggest that the contribution of S-cone signals from the visual pathway, quantified by cyanopic illuminance, should also be considered when evaluating the circadian effects of lighting environment. […] A multi-photoreceptor approach considering both melanopic and cyanopic illuminance may be a more optimized solution."* (Huang et al., 2023)

The research "*Determining critical points to control electric lighting to meet circadian lighting requirements and minimize energy use*", by Abboushi B. and Safranek S. examines and proposes a new approach to the development of recommendations on circadian lighting from the point of view of **critical measurement points**; in fact, here, the recommended values are not debated, on the contrary, the discussion is about how to consider the position and melanopic contribution on each point of measure: "*The determination of critical points is closely related to several decisions such as selecting a circadian lighting metric, timing of exposure, and position and orientation of measurement points*" (Abboushi & Safranek, 2022). As known, the WELL building standard considers all workstations where an individual spends at least one hour or two cumulative hours per day (WELL 2021), the critical points here are the ones receiving the lowest daylight levels related to numbers of hours in a year, this approach is referred to as 'lowest daylight' (LD). The paper previously cited proposes two new approaches other than this one: the Daylight Autonomy using EML (DA_{EML}) approach, which represents the percent of the time at which each measurement point met the required threshold; and the Continuous Daylight Autonomy using EML (cDA_{EML}) approach, useful since it considers even the partial non-visual effects that a light value below the threshold still has.

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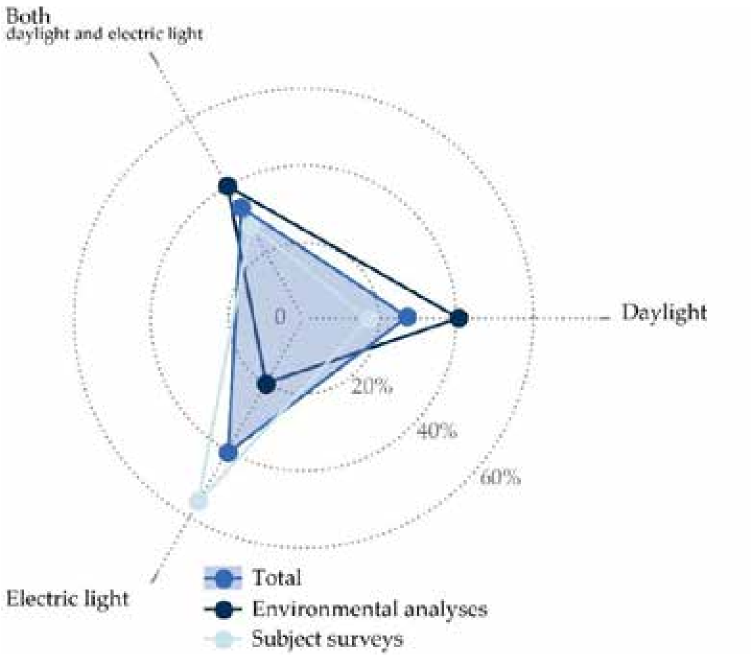
[1] "*Due to the dominant role of melanopsin-expressing ipRGCs in the circadian phototrasduction process, melanopic illuminance has been adopted as a convenient measure to quantify circadian illuminance for practical engineering applications.*" (Huang et al., 2023)

Results

Comparative analysis

Variability is a term that fits well with the subject of integrative lighting design; in this regard the research titled "*Investigation of the daylight spectrum in an indoor environment using CIE S 026 melanopic metrics*" (Englezou & Michael, 2023) presents the variability in daylight spectral characteristics focusing on seasonality, timing and gaze direction.



Graph 2.23. Radar chart showing relations between methodologies (environmental analysis and subject surveys) and light sources (daylight, electric light and both).

In the study "*Evaluation of visual and non-visual effects of daylighting in healthcare patient rooms using climate-based daylight metrics and melanopic metrics*" (Englezou & Michael, 2022), an attempt is made to improve on visual and non-visual effects by combining climate-based and melanopic metrics. Anyway, the outcome of the research is that there is no possibility of correlation between the different metrics. Besides these considerations, there are also studies whose results support the current recommendations in terms of circadian metrics (Favero et al., 2023). In general, a common issue that emerges from the various studies is that the recommended circadian values require more light and consequently, in many cases where daylight is inadequate, more energy, which is why many studies dealing with circadian metrics addressed the issue of energy consumption. Other suggestions to reach circadian values consist in the implementation of lighting systems such as use of task lamps (Grant et al., 2023) or higher illuminance and short-wavelength (blue) enriched light that show better physiological responses.

The integration of these results provides an overview of the future of integrative lighting design and possible directions for further investigations.

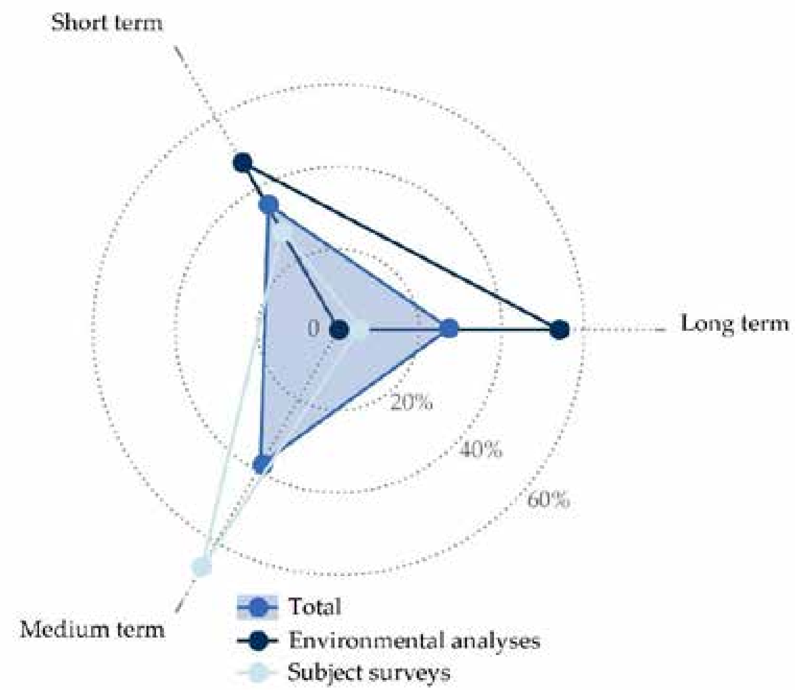
As for results, common topics can also be named for **limitations** addressed at the conclusion of every study:

Each study object is located or has been simulated in a specific **location**. In some studies, the location was an important, if not fundamental parameter taken into account in the analysis of the results; in one case, for example, the experiment took place in sub-Arctic regions as they wanted to analyse the light in the northern architecture scene (Espinoza-Sanhueza et al., 2024). Yet another study selected two different locations, Seoul in Korea and Champaign in Illinois (USA), in order to test the metrics proposed in the study in different contexts (Lee & Boubekri, 2022). In general, location is often seen as a limitation to the study as it cannot represent the general case but only a particular one.

Figure 2.3. Map signalling environmental analyses and subject surveys locations.

One of the main difficulties in research involving subjects is the risk of incurring **bias** or conditioning on the part of those involved, which is why in almost all cases, when subjects were subjected to questionnaires, they were not previously informed of the purpose of the research (Boubekri et al., 2020). "*While participants were not made aware of the purpose of the study, it was impossible to fully blind them to conditions as they were visually different. To avoid potential bias, we used objective assessment methods; sleep duration was measured by actigraphy and cognitive function through a simulation-based assessment. Some of the effect on these outcomes could result from a placebo effect, which nonetheless would be present wherever blinds or EC glass is used in practice*" (Boubekri et al., 2020). Another method to overcome this problem and not incur the placebo effect consisted in "*designing lights that were white-appearing, not significantly brighter than typical indoor lighting, and near-cone metamers*" (Bessman et al., 2023).

For different reasons and in different contexts, **time** was one of the main research factors presented as a limitation (Bochnia et al., 2022). When the research consisted of an environmental analysis based on simulations, this problem was overcome thanks to the availability of data on annual spectral sky conditions that allowed for annual simulations (Abboushi & Safranek, 2022; Englezou & Michael, 2022; Espinoza-Sanhueza et al., 2024; Giovannini et al., 2023; Rockcastle & Mahic, 2024; Zeng et al., 2021). On the other hand, this was not possible when the research involved human subjects, mainly due to individual occupations and schedules. This can be seen by correlating the number of long-term, medium-term and short-term studies with their type (environmental analysis or subject involvement): 11 research projects were identified as long-term studies, representing 32% of the total. Of these, 10 were environmental analysis projects and only one involved human subjects. The majority of the 15 environmental analyses were long-term (53%), while 47% were short-term studies. Conversely, 67% of the studies involving subjects were medium term, with the remaining 28% being short term. Only one study was long term.



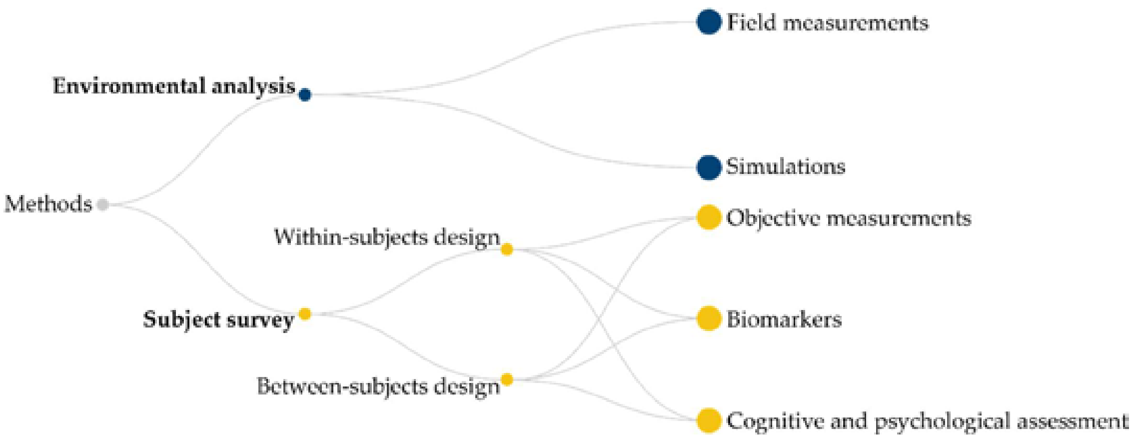
Graph 2.24. Radar chart showing relations and differences between study durations and methodologies.

A recurring limitation in researches involving participants is the **small sample size** (Chen et al., 2019; Favero et al., 2023), due to the fact that first of all, the majority of studies is on a voluntary basis and overall, managing a larger sample requires a high amount of space and time.

2.4. Conclusions

Numerous and intrinsically diverse variables influence the circadian system together with visual and non-visual effects of light, ranging from environmental factors and conditions to physiological and psychological processes. For this reason, it is necessary to develop a standardized methodological template working as a reference for research in the field of integrative lighting.

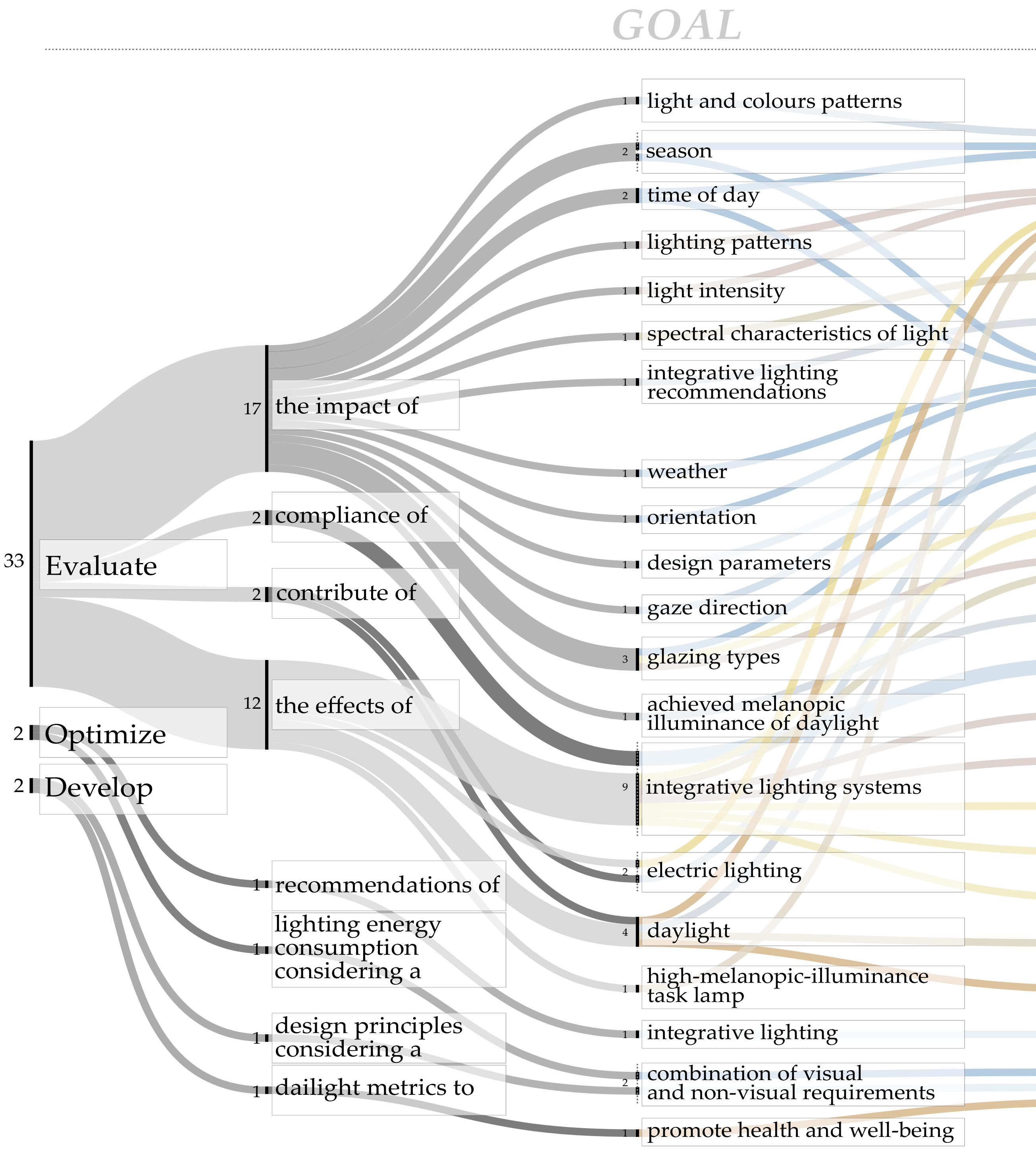
In order to do so, this literature review of 34 studies on integrative lighting has identified a range of methods employed to achieve significant results in the field, thereby proving the validity of such methods. Summarizing the work done in the previous sections, the first step consisted of sorting each method into a primary group division consisting of Environmental analysis and Subject survey. Each of these groups is further subdivided based on specific approaches and tools used. The first category is divided between Field measurements and Simulations; the second include both a classification based on the approach ("Between-subject" and "Within-subject analysis"), and a classification of the tools used, into the three categories of "Objective measurements", "Biomarkers", and "Cognitive and psychological assessment".

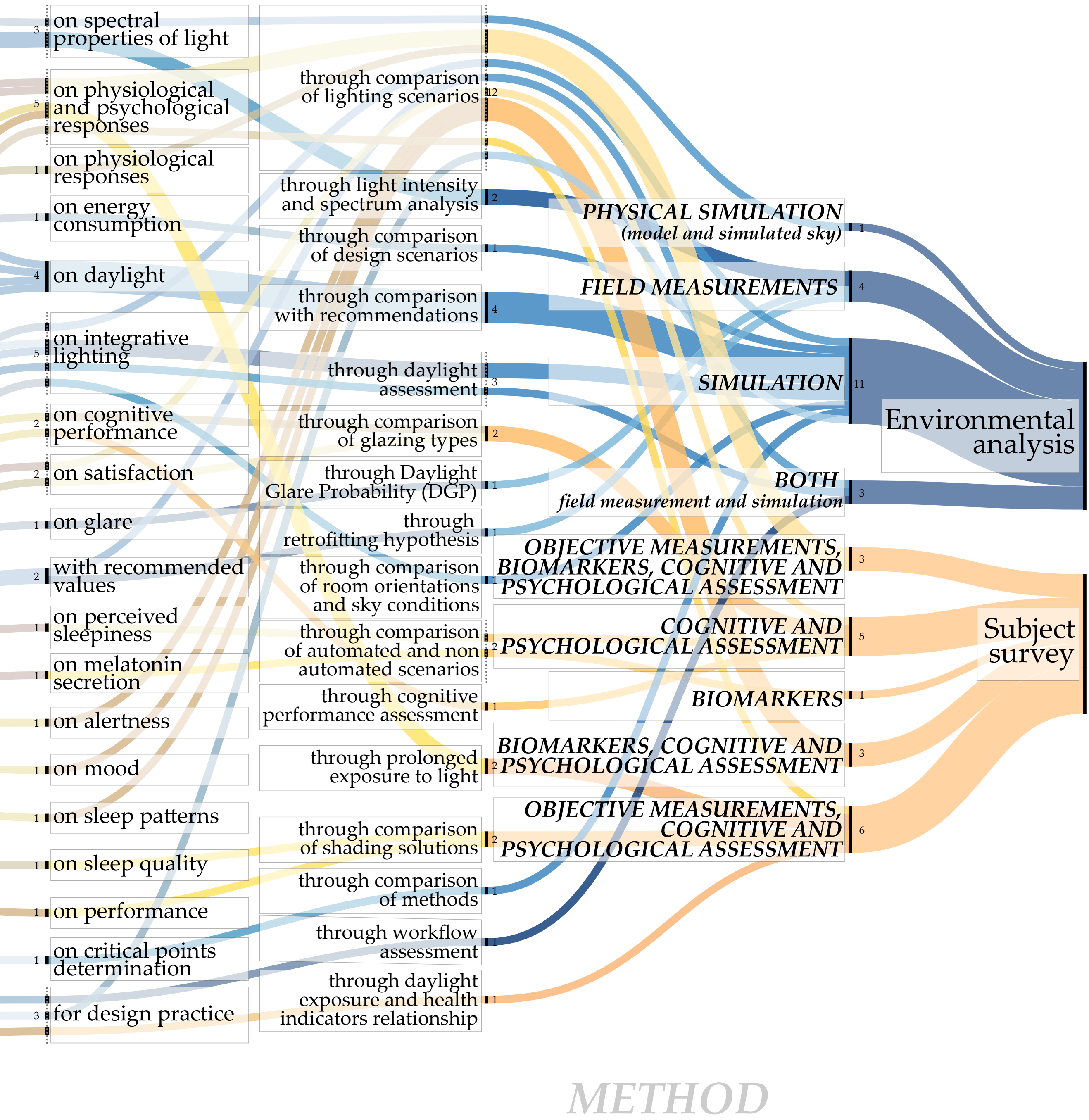


Graph 2.25. Linear dendrogram of research methods and tools classification.

At this stage of the process, a further classification was made of the research goals. The research objectives have been translated into a series of representative terms and grouped according to the methods used to achieve them. This categorisation facilitates the creation of a reference table for future research, a valuable tool enabling researchers to align their objectives with the most suitable methodologies.

Following is a clear mapping of the research objectives outlined as a function of the most effective methods to achieve them.


GOAL
33
Evaluate
2
Optimize
2
Develop
17
the impact of
2
compliance of
2
contribute of
12
the effects of
1
recommendations of
1
lighting energy consumption considering a
1
design principles considering a
1
dailight metrics to
light and colours patterns
season
time of day
lighting patterns
light intensity
spectral characteristics of light
integrative lighting recommendations
weather
orientation
design parameters
gaze direction
glazing types
achieved melanopic illuminance of daylight
integrative lighting systems
electric lighting
daylight
high-melanopic-illuminance task lamp
integrative lighting
combination of visual and non-visual requirements
promote health and well-being



▲Graph 2.26.Systematisation of methods as a function of research goals.

Conclusions

Bibliography	GOAL			
53	Evaluate	the impact of	light and colours patterns	on the spectral properties of light
57	Evaluate	the impact of	season	on the spectral properties of light
57	Evaluate	the impact of	time of day	on the spectral properties of light
23	Evaluate	the impact of	lighting patterns	on physiological and psychological responses
39	Evaluate	the impact of	light intensity	on physiological and psychological responses
17; 42; 63; 68; 144	Evaluate	the impact of	spectral characteristics of light	on physiological responses
125	Evaluate	the impact of	integrative lighting recommendations	on energy consumption
84	Evaluate	the impact of	season	on daylight
84	Evaluate	the impact of	weather	on daylight
84	Evaluate	the impact of	time of day	on daylight
84	Evaluate	the impact of	orientation	on daylight
110; 123; 140	Evaluate	the impact of	design parameters	on integrative lighting
110; 123	Evaluate	the impact of	gaze direction	on integrative lighting
140	Evaluate	the impact of	glazing types	on integrative lighting
138	Evaluate	the impact of	glazing types	on cognitive performance
138	Evaluate	the impact of	glazing types	on satisfaction
142	Evaluate	the impact of	achieved melanopic illuminance of daylight	on glare
143	Evaluate	compliance of	integrative lighting systems	with recommended values
59	Evaluate	compliance of	integrative lighting systems	with recommended values
59; 143, 145	Evaluate	contribute of	electric lighting	on integrative lighting
59; 143; 145	Evaluate	contribute of	daylight	on integrative lighting
18	Evaluate	the effects of	integrative lighting systems	on satisfaction
37, 60	Evaluate	the effects of	integrative lighting systems	on melatonin secretion
60	Evaluate	the effects of	integrative lighting systems	on perceived sleepiness
33	Evaluate	the effects of	integrative lighting systems	on alertness
33	Evaluate	the effects of	integrative lighting systems	on mood
10	Evaluate	the effects of	integrative lighting systems	on sleep patterns
10; 33	Evaluate	the effects of	integrative lighting systems	on cognitive performance
115	Evaluate	the effects of	electric lighting	on physiological and psychological responses
115; 139	Evaluate	the effects of	daylight	on physiological and psychological responses
134	Evaluate	the effects of	daylight	on sleep quality
134	Evaluate	the effects of	daylight	on performance
75	Evaluate	the effects of	high-melanopic-illuminance task lamp	on physiological and psychological responses
47	Optimize	recommendations of	integrative lighting	on critical points determination approaches
124	Optimize	lighting energy consumption considering a	combination of visual and non-visual requirements	for design practice
89	Develop	dailight metrics to	promote health and well-being	for design practice
69	Develop	design principles considering a	combination of visual and non-visual requirements	for design practice

METHOD		
through comparison of lighting scenarios	PHYSICAL SIMULATION (reduced scale model and simulated sky)	Environmental analysis
through light intensity and spectrum analysis	FIELD MEASUREMENTS	Environmental analysis
through light intensity and spectrum analysis	FIELD MEASUREMENTS	Environmental analysis
through comparison of lighting scenarios	OBJECTIVE MEASUREMENTS, BIOMARKERS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of lighting scenarios	OBJECTIVE MEASUREMENTS, BIOMARKERS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of lighting scenarios	OBJECTIVE MEASUREMENTS, BIOMARKERS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of design scenarios	SIMULATION	Environmental analysis
through comparison with recommendations	SIMULATION	Environmental analysis
through comparison with recommendations	SIMULATION	Environmental analysis
through comparison with recommendations	SIMULATION	Environmental analysis
through comparison with recommendations	SIMULATION	Environmental analysis
through daylight assessment	SIMULATION	Environmental analysis
through daylight assessment	SIMULATION	Environmental analysis
through daylight assessment	BOTH field measurement and simulation	Environmental analysis
through comparison of glazing types	COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of glazing types	COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through Daylight Glare Probability (DGP)	FIELD MEASUREMENTS	Environmental analysis
through comparison of lighting scenarios	BOTH field measurement and simulation	Environmental analysis
through	FIELD MEASUREMENTS	Environmental analysis
through comparison of lighting scenarios	SIMULATION	Environmental analysis
through comparison of room orientations and sky conditions	SIMULATION	Environmental analysis
through comparison of lighting scenarios	COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of automated and not automated scenarios	BIOMARKERS	Subject survey
through comparison of automated and not automated scenarios	COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of lighting scenarios	BIOMARKERS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of lighting scenarios	BIOMARKERS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of lighting scenarios	BIOMARKERS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through cognitive performance assessment	COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through prolonged exposure to light	OBJECTIVE MEASUREMENTS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through prolonged exposure to light	OBJECTIVE MEASUREMENTS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of shading solutions	OBJECTIVE MEASUREMENTS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of shading solutions	OBJECTIVE MEASUREMENTS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of lighting scenarios	OBJECTIVE MEASUREMENTS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
through comparison of methods	SIMULATION	Environmental analysis
through workflow assessment	BOTH field measurement and simulation	Environmental analysis
through relationship between daylight exposure and health indicators	OBJECTIVE MEASUREMENTS AND COGNITIVE AND PSYCHOLOGICAL ASSESSMENT	Subject survey
different lighting scenarios	SIMULATION	Environmental analysis

◀ Table 2.3. Table of data entered in previous graph.

The graphic illustrates the process to be followed once a research objective has been established in order to select a suitable method. The table provides a schematic summary of these processes, enhancing their readability. The table comprises a series of rows, each of which corresponds to one or more selected papers; these are indicated by their respective codes in the first column, which refer to the numbers in the attached bibliography. The total number of analysed objectives exceeds the number of analysed papers, as some papers contain multiple objectives investigated using different methods.

In summary, from this table it can be drown out how environmental analyses with field measurements are suitable for research focusing on spectral properties of light and daylight analysis, for example. Research goals in this category include evaluating the impact of light and colour patterns, season, time of day, but also daylight on achieved melanopic illuminance, moreover the analysis of glare is addressed. Additionally, such method is able to assess the compliance of integrative lighting systems with recommended values and contribute to developing daylight metrics to promote health and well-being. On the other hand, environmental analysis with simulation addresses goals related to energy consumption and efficiency, the contribution of daylight and electric lighting, as well as the optimisation of design principles. The research goals, moreover, include evaluating the impact of integrative lighting recommendations on energy consumption, assessing the influence of season, weather, time of day, orientation, and design parameters on daylight values, and evaluating the contribution of electric lighting. Furthermore, the environmental simulation method aims to optimize integrative lighting recommendations and lighting energy consumption taking into account a combination of visual and non-visual requirements, and develop design principles that integrate such requirements, as simulated luminance and irradiance data are able to assess the relative impact of design options on the non-visual system.

Indeed, for considerations concerning the harmonisation of visual and non-visual normative values and recommendations, the recommended approach seems to be environmental analysis with dual methodology: field measurements and simulations; example of this statement can be found at (Giovannini et al., 2023).

Although, on-subject studies are useful for investigating a range of factors, including psychological and physiological responses, cognitive performance, and satisfaction, as well as the effects on sleep patterns, alertness, mood, and melatonin secretion. The research goals here specifically include evaluating the impact of lighting patterns, light intensity, and spectral characteristics on physiological and psychological responses, as well as the impact of glazing types on cognitive performance and satisfaction, for example. This method also assesses the effects of integrative lighting systems on melatonin secretion, perceived sleepiness, alertness, mood, sleep patterns, and cognitive performance, along with the effects of electric lighting on physiological and psychological responses. Moreover, it evaluates the effects of daylight on sleep quality and performance. Subject investigation through biomarkers analysis has been seen to focus on the physiological impacts of integrative lighting and its alignment with circadian rhythms. The research goals, in this case, include evaluating the impact of lighting patterns, light intensity, and spectral characteristics on physiological responses but this time through biomarkers, a branch of objective measurements of physiological changes induced by lighting conditions. Such approach is equally suitable to analyse the effects of integrative lighting systems on melatonin secretion, sleep patterns, alertness, and mood. In general, this research approach is beneficial when insights are needed into subjective experiences and perceived impacts of lighting on individuals, but also to assess biological processes occurring within them, entrained by such lighting inputs.

In conclusion, this chapter presents a synthesis of the critical insights gained from the literature review conducted, mainly about research methodologies and general workflows applied, offering an extremely diverse overview on the discipline of integrative lighting. The literature review was structured around well-defined questions and a desire to provide useful input for future research; and did so by providing a clear methodological framework. Undoubtedly, this work faced limitations, one of them being the limited number of selected papers. In any case, it can be seen as a stimulus for further research.

List of illustrations, Chapter 2

Bibliography of literature review pool, Chapter 2

The following list contains the numbered references of the collected papers, each of which has been assigned a code from N.1 to N.147, in order to help with the selection process. The order reflects the sourcing process, papers found first appear first, with a subdivision by source database: the initial 30 papers were retrieved from ScienceDirect, followed by papers N.31 through N.98 sourced from Scopus, the subsequent 22 papers (N.99 through N.120) were identified via ResearchGate, and the final set of papers (N.121 through N.147) were obtained from various reference lists.

Texts highlighted in blue correspond to papers selected for the review.

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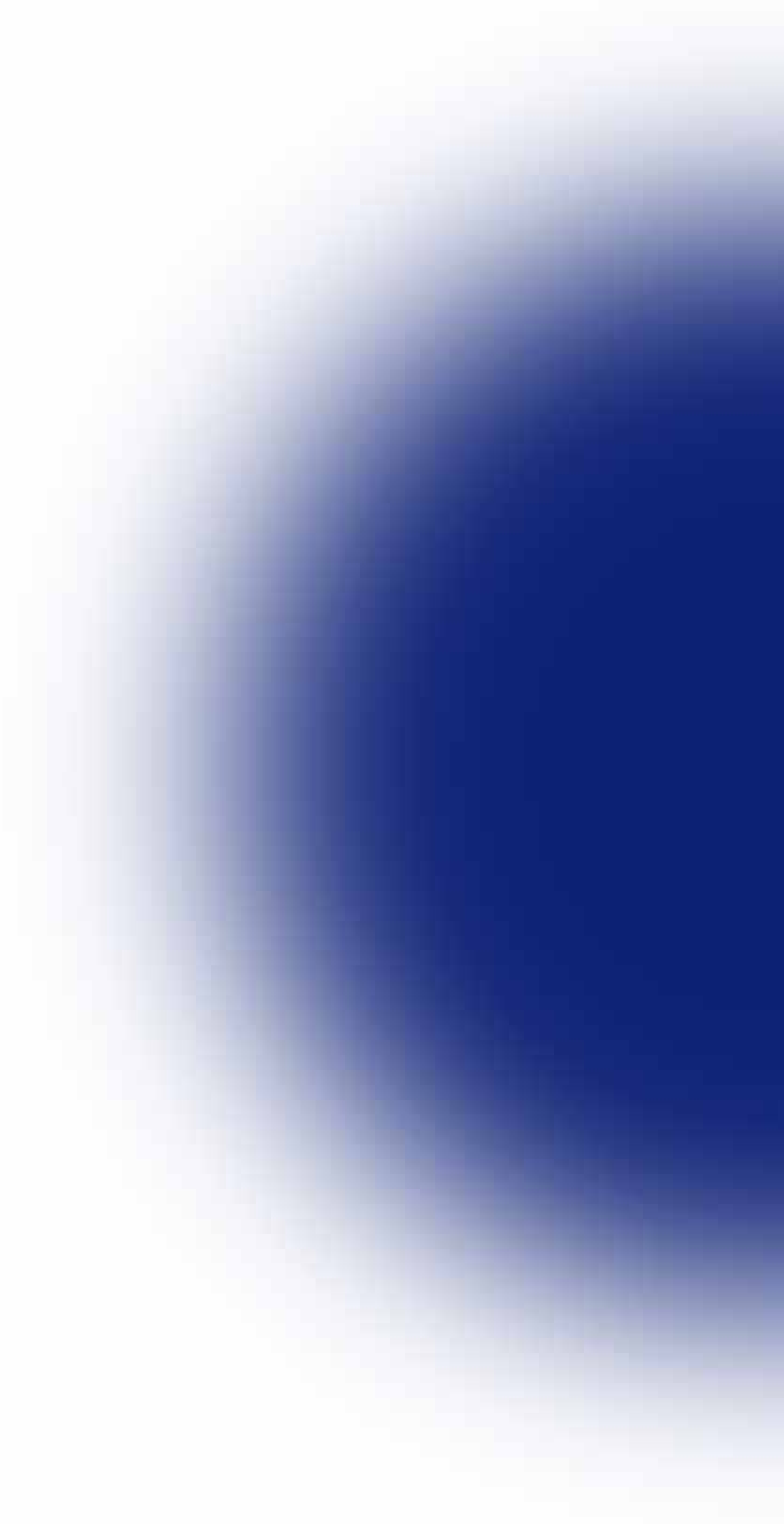

3. Case study:

Environmental analysis, field measurements and annual daylight simulations[1]

[1] The case study analysis was conducted by the research group comprising Professor Anna Pellegrino, Professor Valerio R.M. Lo Verso, PhD student Luigi Giovannini, PhD student Lodovica Valletti, and PhD student Jenifer Godoy Daltrozo from the DENERG department at the Polytechnic University of Turin. Specifically, PhD student L. Giovannini conducted in-depth software simulations, scripts development and data analysis, while PhD students L. Valletti and J.G. Daltrozo contributed to field data collection. Costant support at all stages of the research, data analysis and results of the study were provided by Professor V.M.R. Lo Verso. Furthermore, Gabriele Picablotto and Rossella Taraglio from LAMSA (Laboratory of Environmental Systems Analysis and Modeling) of the Polytechnic University provided assistance in data export from the field instrumentation and support in internship activities.

Detailed index

3.1 Introduction

The discipline of integrative lighting is a practice that can be investigated from multiple perspectives. As seen in the previous chapter, based on research goal, configuration of the analysed environment, availability of resources and time it is possible to identify the best method among those available. For this thesis, it was planned to produce a real-life case study developing some of the observed research methods, so that theoretical observations could be combined with practical findings.

At present, and as noted in the literature review, significant interest is directed at office space[2] regulations as they currently lack specific references or values congruent with the role, occupant behaviour and time of occupancy of such locations[3], all interesting topics needing to be investigated. Offices, after all, are spaces in which an occupant spends on average 8 hours a day, one third of the available daily time and, apart from exceptional cases of shift workers, half of the time in which there is availability of daylight contributing to circadian entrainment. To further illustrate, research on the topic state that "*Office workers spend the majority of their work time within buildings, where lighting quantity and quality might not be adequate enough to elicit a sufficiently strong signal for entrainment of internal clocks with the external 24-h day. […] Improving indoor lighting conditions at the workplace has the potential to support proper circadian entrainment of hormonal rhythms, sleep, and well-being*" (Benedetti et al., 2022).

> *As we lack field-studies that evaluate the impact of these design recommendations on measured non-visual light exposure in offices, it's difficult to say whether the current WELL recommendations are appropriate […] current recommendations do not consider the role of occupant behaviour on eye-level light exposure. (Rockcastle & Mahic, 2024)*

The case study therefore focused on workplaces, specifically those at the Polytechnic of Turin. Firstly, the offices of the Polytechnic's main campus were selected as the location for the investigation due to their accessibility for the team involved in the research. Upon observation, it was remarked that the lighting system of such offices was outdated and that the distribution of offices in plan allowed for the examination of different exposures, additionally, each office had identical openings, which were all equipped with shading systems. In consideration of these baseline characteristics, combined with the topic of office spaces investigations, the research dealt specifically with two goals: the first centred on the assessment of whether or not the available lighting conditions achieved the WELL and CIE recommendations, and the second examining the contributions of electric light and daylight on integrative lighting.

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[2] From the literature review, a total of 21 research studies over a pool of 34 were held in office spaces, corresponding of a 62% of papers.

[3] (Rockcastle & Mahic, 2024)

Starting from these objectives, it was then reasoned on the delineation of the most appropriate method to achieve them. From the experience gained through the literature review, it was opted for an environmental analysis, associating the first goal with conducting field measurements, while the second involved the simulation of natural light. On the contrary, research comprising subject involvement was not suitable to achieve the defined goals, also the availability of resources and environmental aspects did not allow for such an approach; for instance, wanting to assess photopic and melanopic illuminance values on a person, for example, using sensors, it would have been necessary to ensure environmental conditions that guaranteed variability in daylight conditions, which was not feasible given the time of year in which the study was conducted.

3.2 Methodology

As mentioned, the methodology chosen to achieve the set objectives was an environmental analysis conducted through the use of both field measurements and software simulations. First, a survey of the campus had to be made in order to select a set of offices with representative characteristics, at which point field measurement of photopic and melanopic illuminance values according to specific visual directions took place. The environments were, in addition, detected geometrically and their material characteristics recorded for the subsequent three-dimensional modelling required for the simulation of daylight on a dedicated software. the combination of electric and daylight measurements contributed to the integrative assessment of light.

3.2.1 Site inspection and selection process

In May 2023, a series of site inspections were conducted in the south wing of the Polytechnic University of Turin main campus, located between Via Giuseppe Peano and Corso Luigi Einaudi. The objective of these inspections was to document the physical characteristics and lighting conditions of the offices within this section of the campus.

Figure 3.1. South wing of the Polytechnic University of Turin main campus, view from Via Giuseppe Peano. Ph: Jose Luis Reyes Mesias.

Ph: Jose Luis Reyes Mesias

The inspections focused on 22 accessible offices within this wing, on the third floor, and consisted of different activities carried out, including:

1. Photographic documentation:
   - Photographs were taken of each office to capture their current state and provide a visual record.
2. Sketching floor plans:
   - Approximate sketches were made to delineate the layout and dimensions of each office, number of workstations and window orientation.
3. Annotating colours and materials
   - For each office, the predominant colours of the walls, furniture and ceiling were noted, as well as the type of flooring and materials that had the greatest impact on the configuration.
4. Observing lighting characteristics:
   - An assessment of the lighting fixtures (types and quantification) was conducted.
   - The presence of malfunctioning of light fixtures was verified and noted.
5. Examining openings:
   - Windows in each office were assessed for their size and placement (the depth of each room, i.e. the distance between the window and the parallel wall, was measured).
   - The type of shading devices (e.g., blinds, curtains) was documented.
   - Notes were taken on whether these shading devices were operational.

On the side, when the presence of workers in the offices allowed it, questions about the pleasantness and likeliness of the lighting systems were asked.

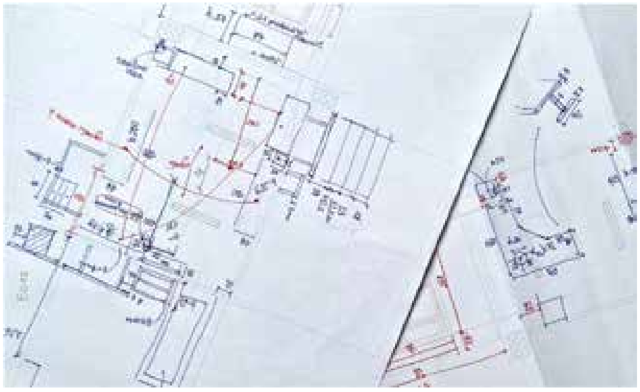
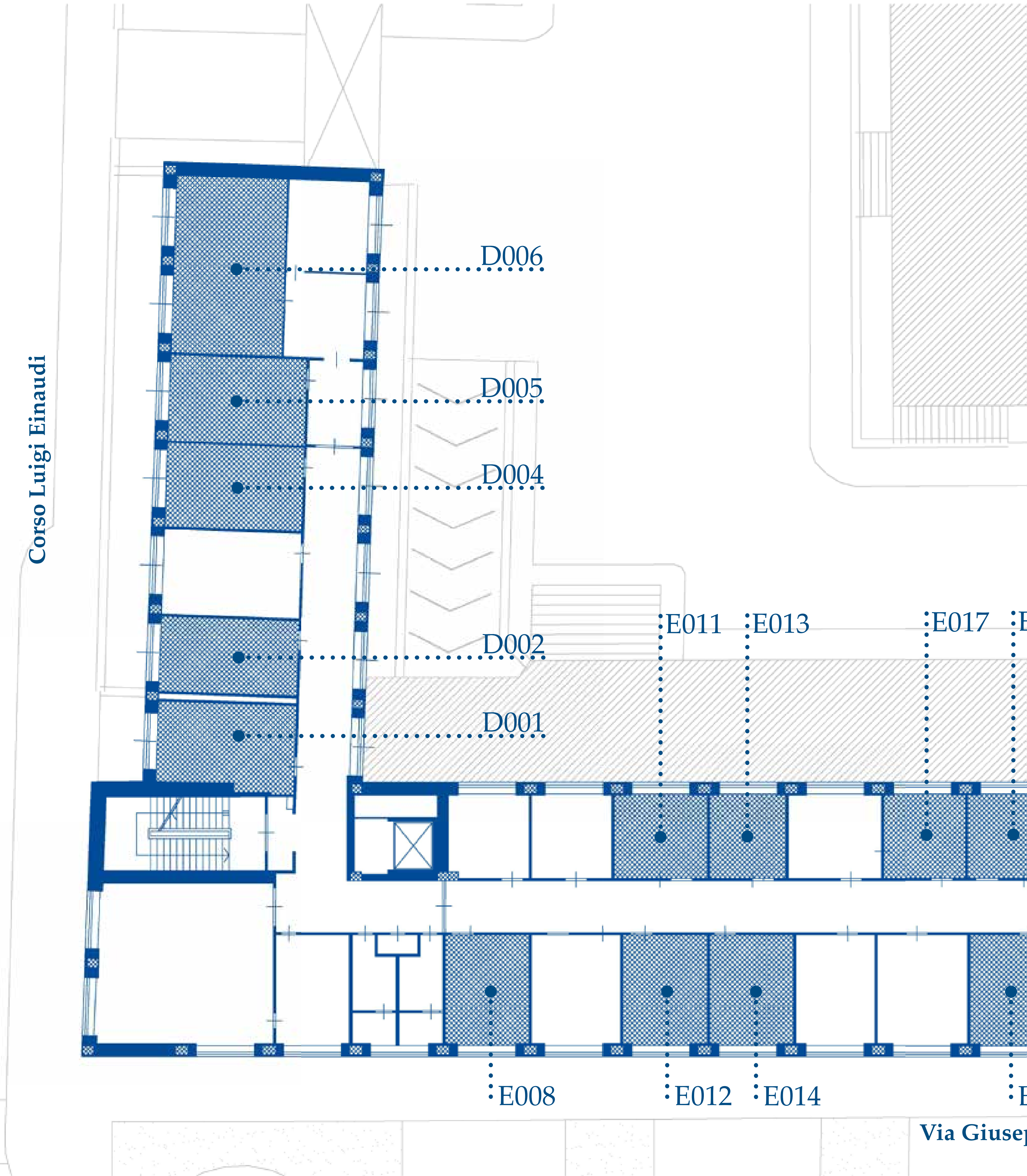


Figure 3.2. Sketches of offices floor plans from on-site inspection of the south wing of the Polytechnic University of Turin.

An overview of the characteristics of each office observed are presented on the following pages.

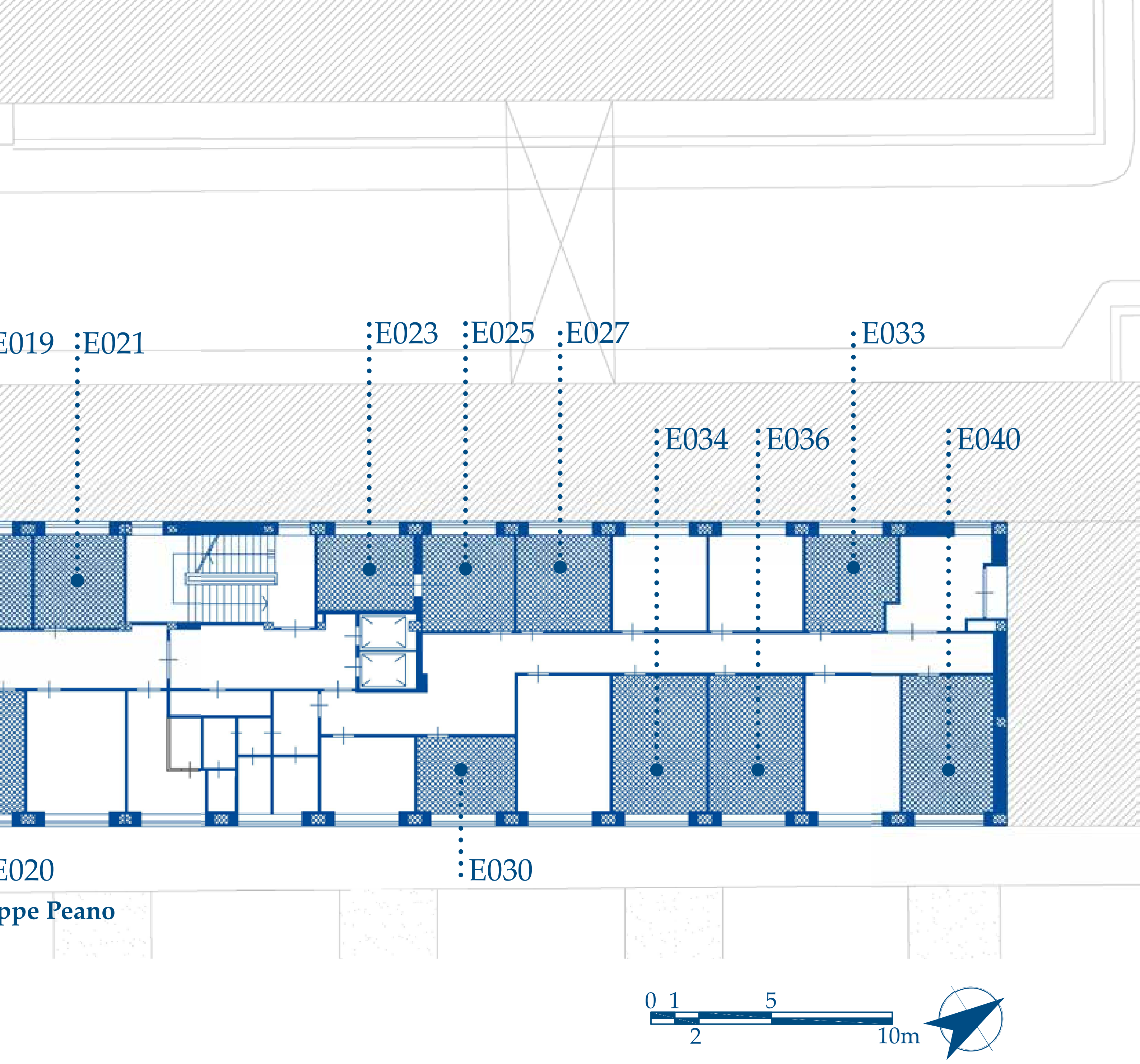


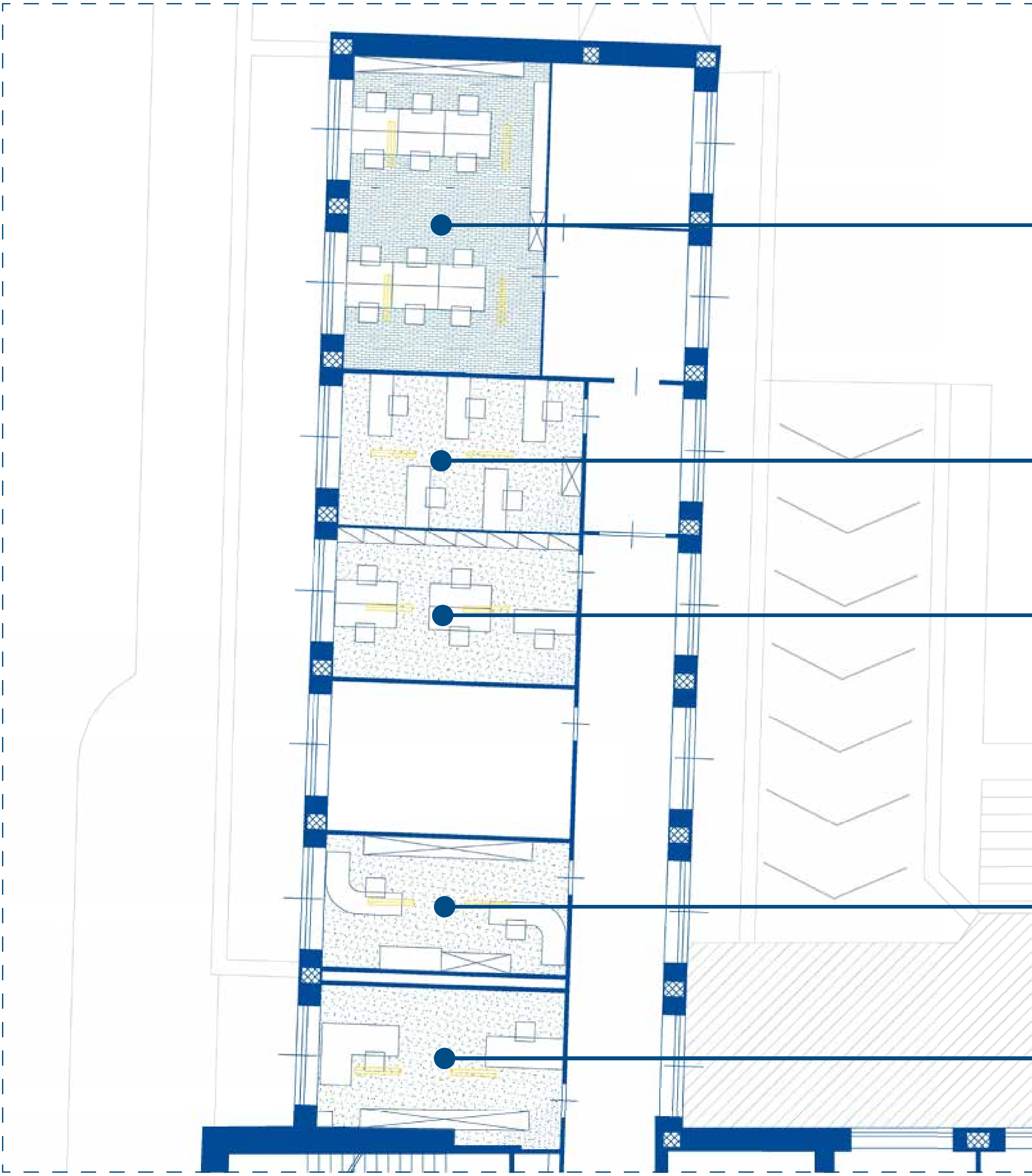
Corso Luigi Einaudi
D006
D005
D004
D002
D001
E011
E013
E017
E008
E012
E014
Via Giusep

South wing

Polytechnic of Turin

Via Giuseppe Peano - Corso Luigi Einaudi



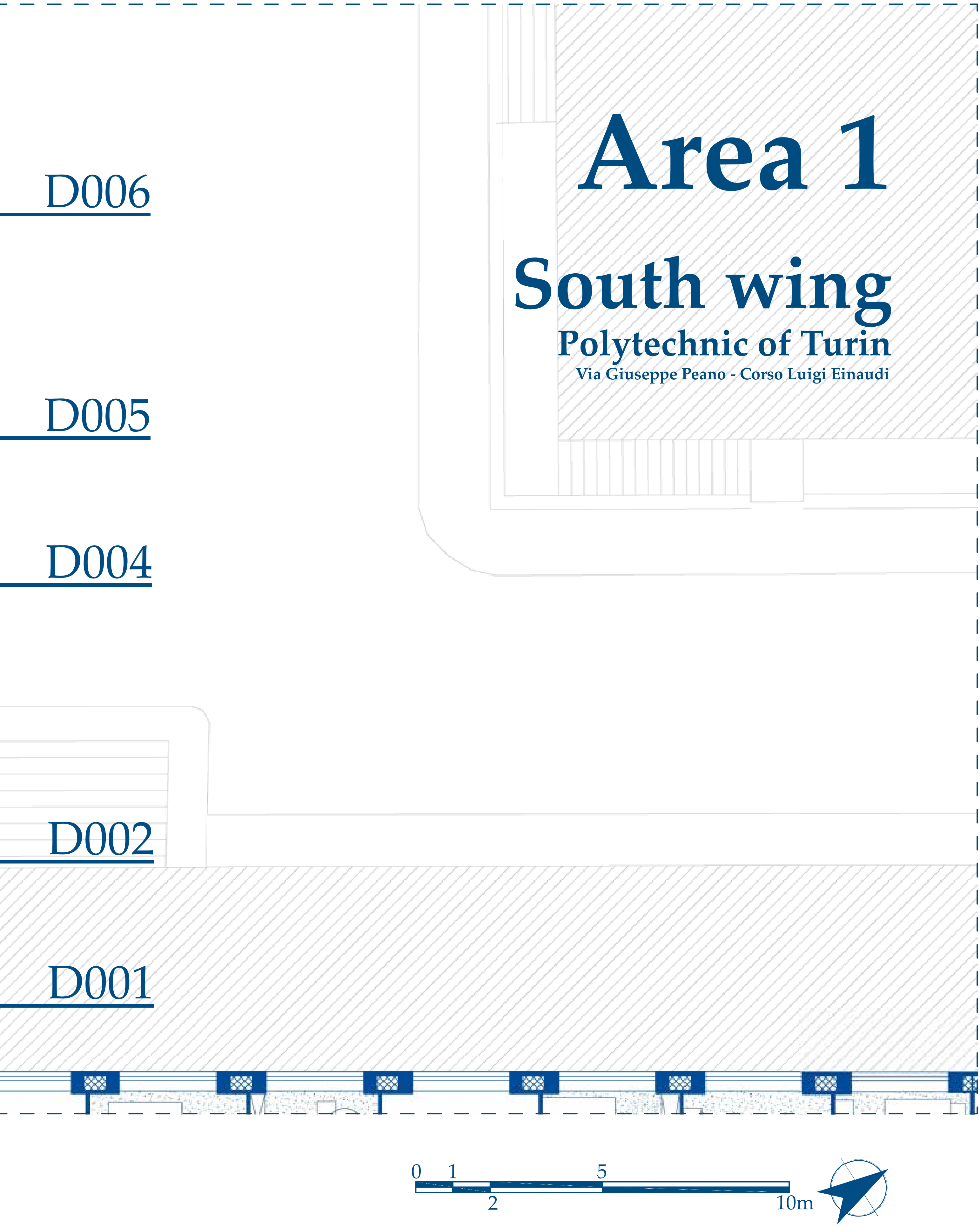


Area 1

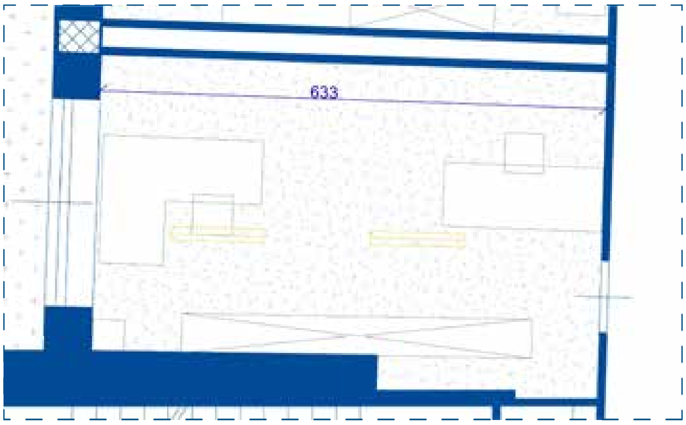
South wing

Polytechnic of Turin

Via Giuseppe Peano - Corso Luigi Einaudi



03



Shading typology

External motorised blinds

Note

- Malfunctioning lighting system

Room code
D001

Room area
24.4 m^2

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.70m

Depth
6.33m

Surface colors and materials

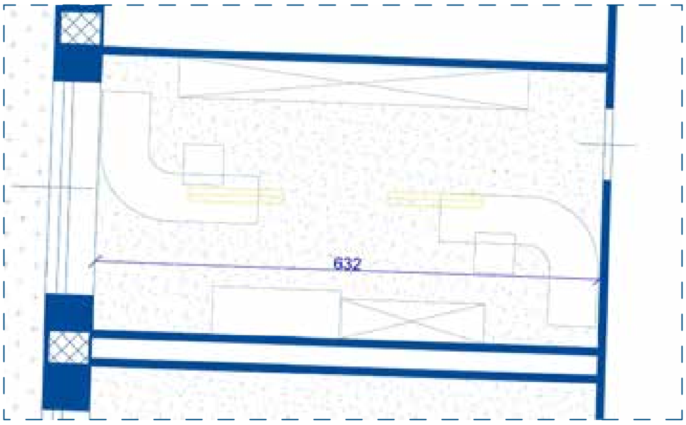
Walls

Ceiling

Floor

Furnitures

Photos



Shading typology

External motorised blinds

Room code
D002

Room area
21.8 m^2

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.70m

Depth
6.32m

Surface colors and materials

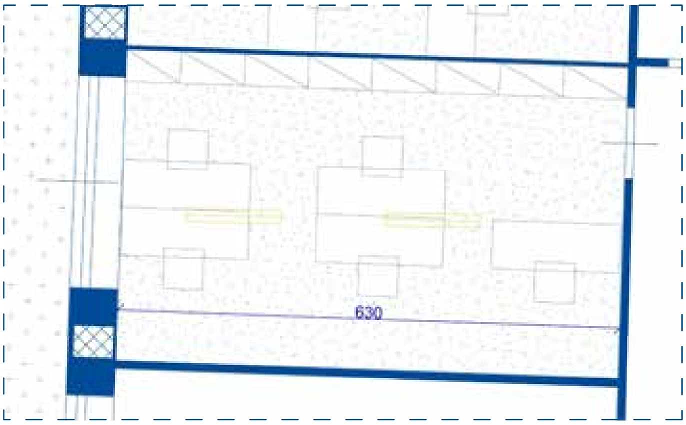
Walls

Ceiling

Floor

Furnitures

Photos



Room code
D004

Room area
24.4 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.70m

Depth
6.30m

Surface colors and materials

Walls · Ceiling · Floor · Furnitures

Shading typology

External motorised blinds

Photos


Room code
D005

Room area
24.8 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.70m

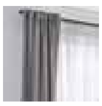
Depth
6.28m

Surface colors and materials

Walls · Ceiling · Floor · Furnitures

Shading typology

External motorised blinds
Internal curtains

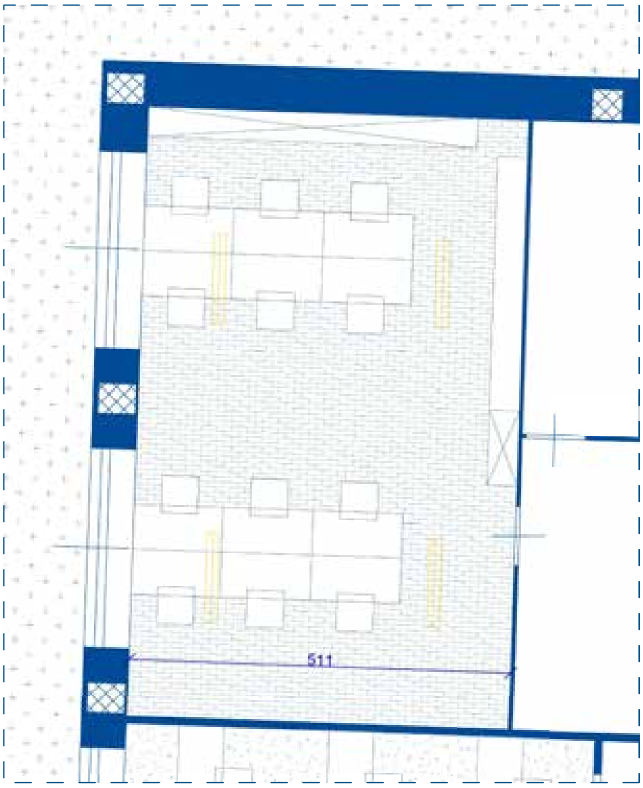



Note

- Malfunctioning lighting system

Photos


03



Room code

D006

Room area

41.5 m^2

Light fixtures

Typology	Number
Industrial, Fluorescent light source	4, double

Height

h: 3.70m

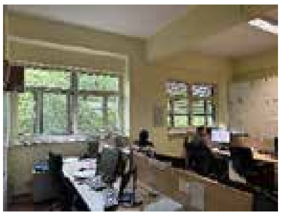
Depth

5.11m

Surface colors and materials

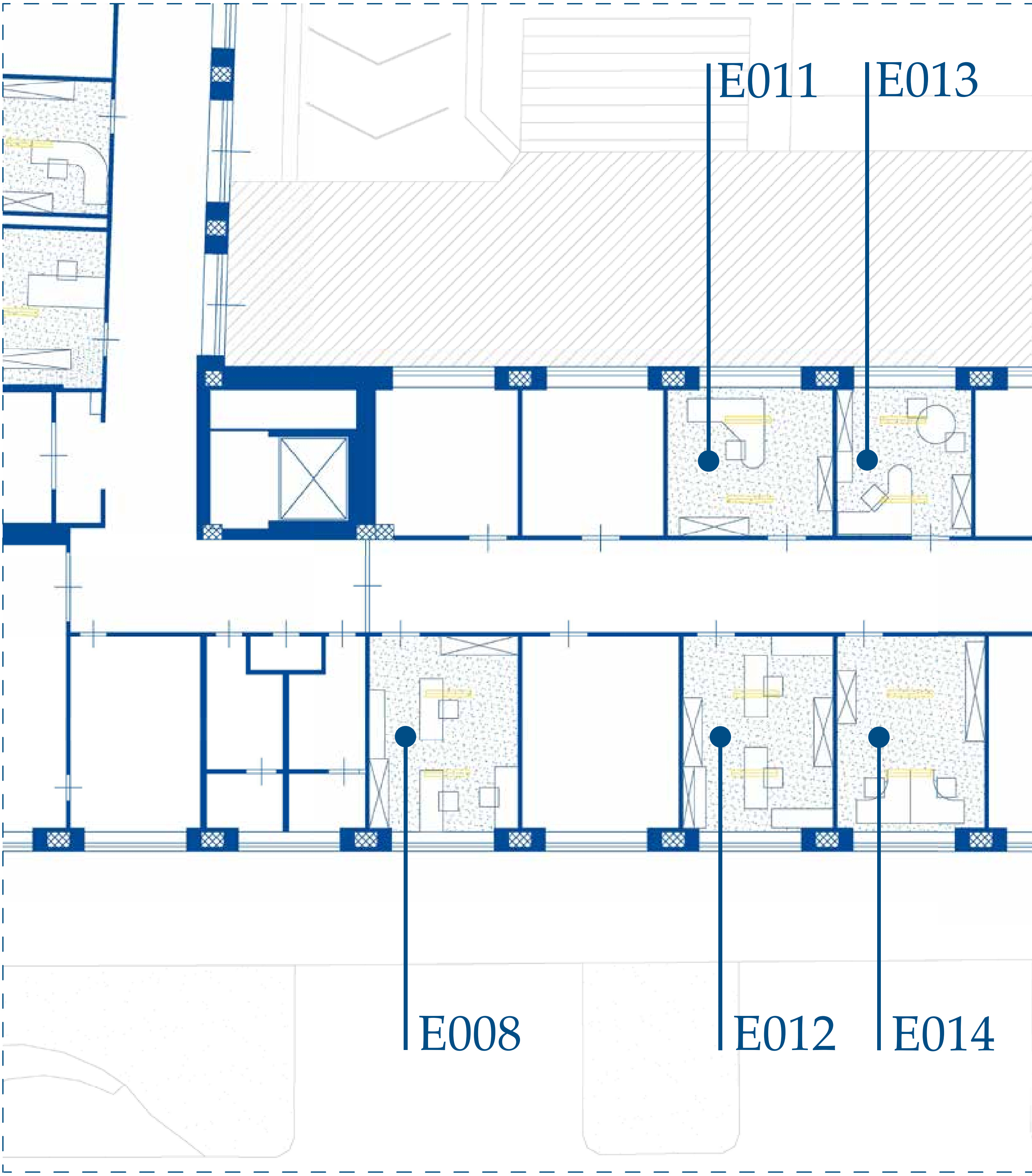
Walls	Ceiling	Floor	Furnitures

Photos



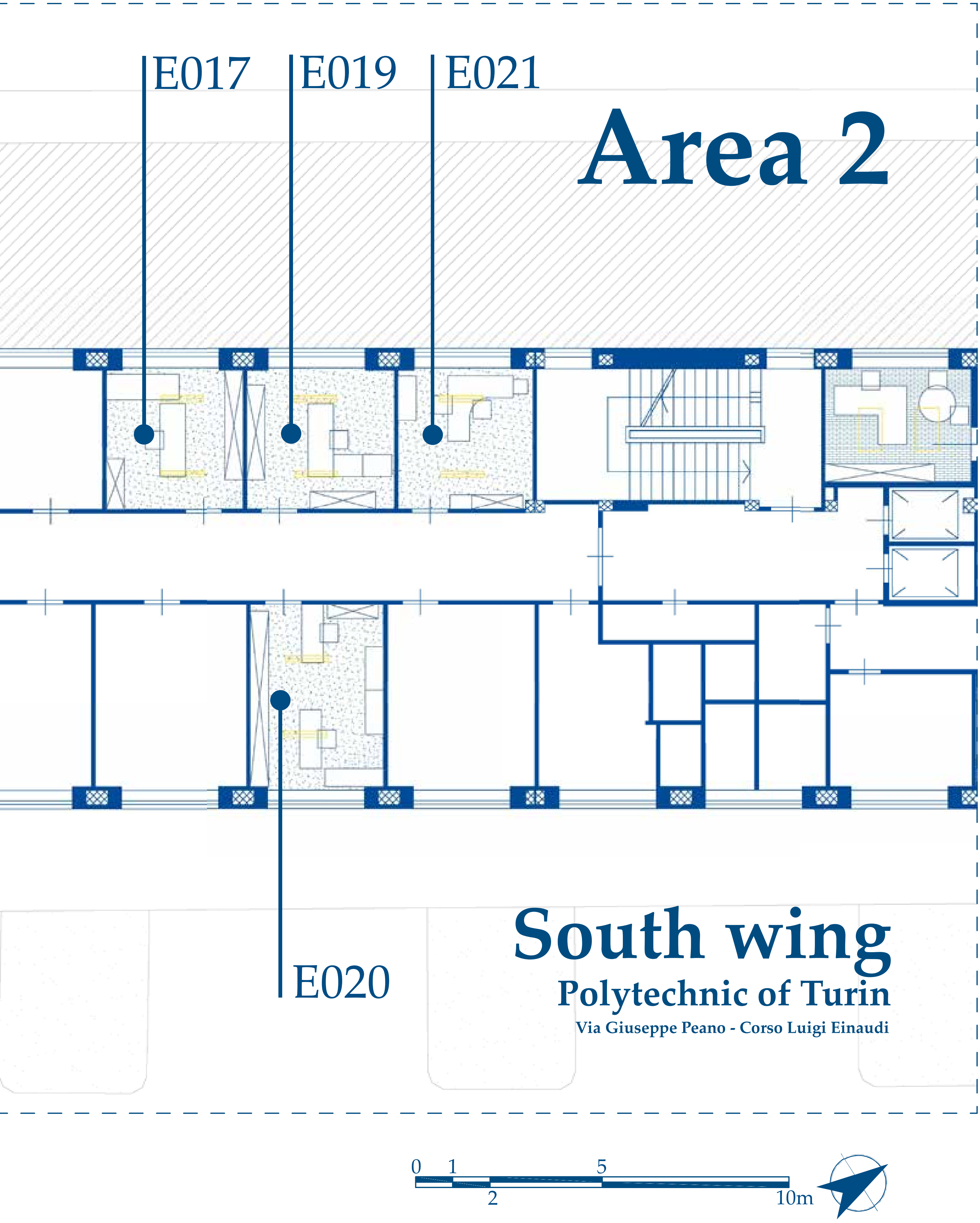
Shading typology

External motorised blinds



E011
E013
E008
E012
E014

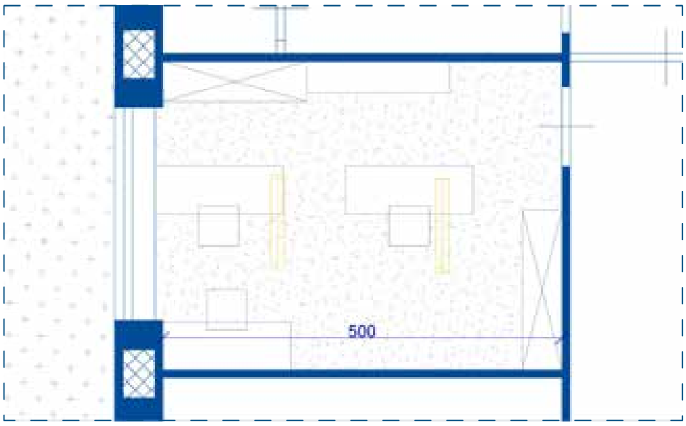
Area 2



South wing

Polytechnic of Turin

Via Giuseppe Peano - Corso Luigi Einaudi



Room code
E008

Room area
19.6 m²

Light fixtures
Typology: Industrial, Fluorescent light source

Number: 2, double

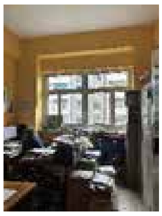
Height
h: 3.70m

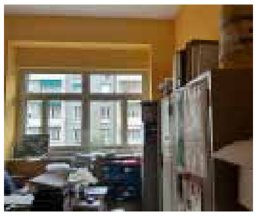
Depth
5.00m

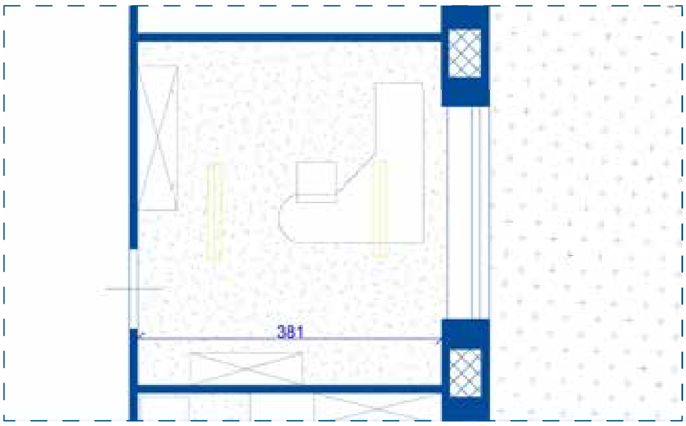
Surface colors and materials
Walls | Ceiling | Floor | Furnitures

Shading typology
External motorised blinds

Photos







Room code
E011

Room area
16.6 m²

Light fixtures
Typology: Industrial, Fluorescent light source

Number: 2, double

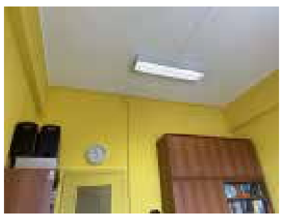
Height
h: 3.75m

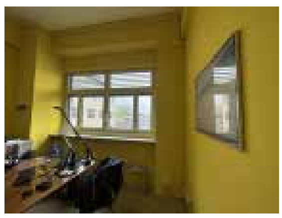
Depth
3.81m

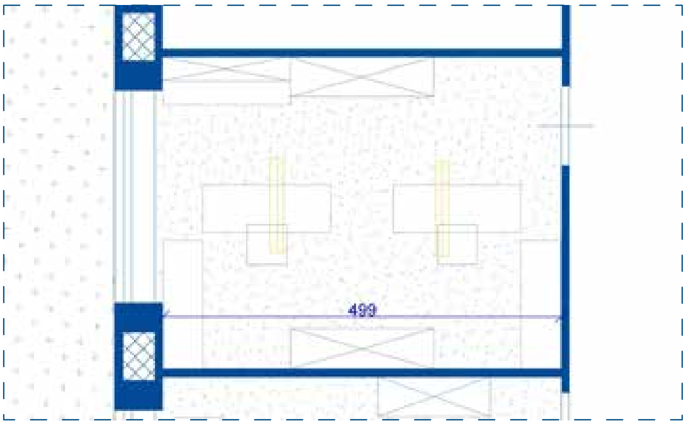
Surface colors and materials
Walls | Ceiling | Floor | Furnitures

Shading typology
External motorised blinds

Photos







Room code
E012


Room area
19.8 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.75m

Depth
4.99m

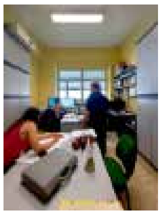
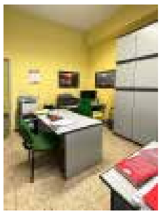
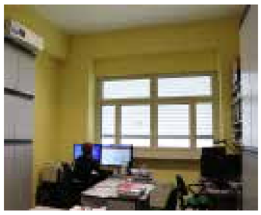
Surface colors and materials

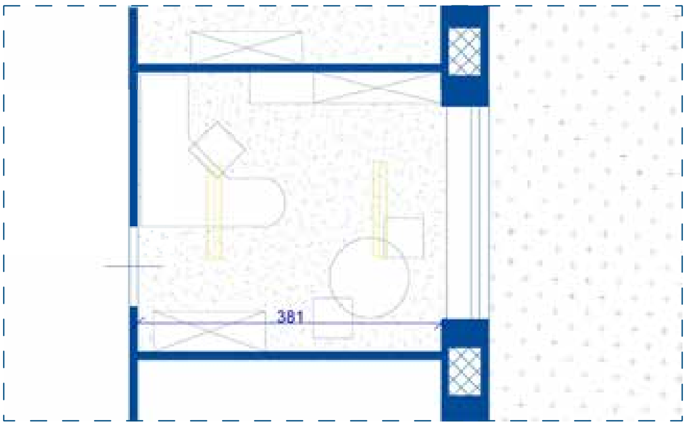
Walls | Ceiling | Floor | Furnitures

Shading typology

External motorised blinds

Photos



Room code
E013


Room area
13.5 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.75m

Depth
3.81m

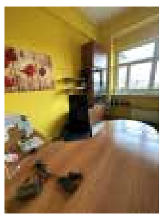
Surface colors and materials

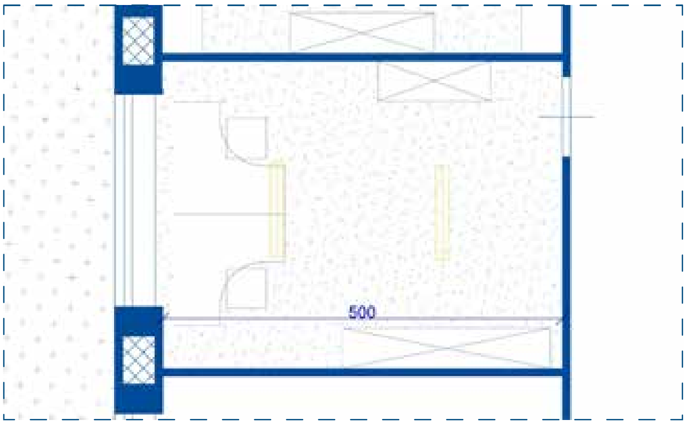
Walls | Ceiling | Floor | Furnitures

Shading typology

External motorised blinds

Photos



Room code
E014

Room area
19.5 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.75m

Depth
5.00m

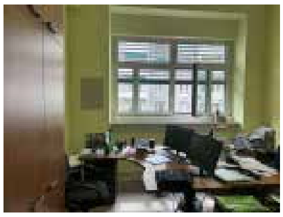
Surface colors and materials

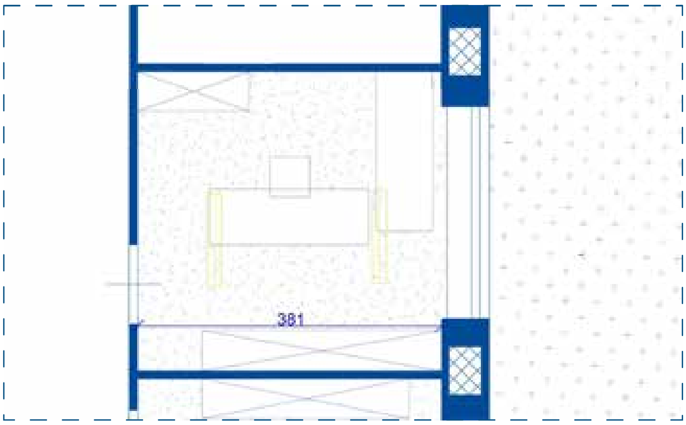
Walls | Ceiling | Floor | Furnitures

Shading typology

External motorised blinds

Photos





Room code
E017

Room area
14.5 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.75m

Depth
3.81m

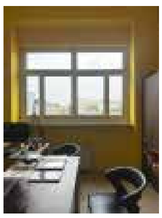
Surface colors and materials

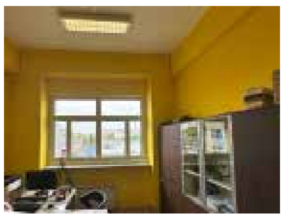
Walls | Ceiling | Floor | Furnitures

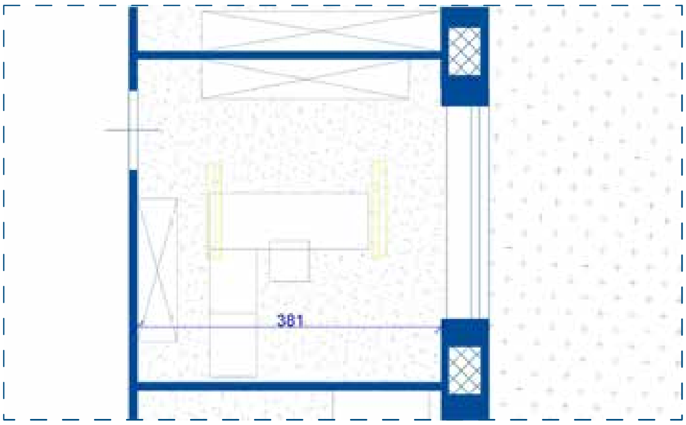
Shading typology

External motorised blinds

Photos







Room code
E019

Room area
15.6 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double + 1 central

Height
h: 3.75m

Depth
3.81m

Surface colors and materials

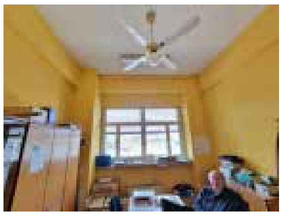
Walls

Ceiling

Floor

Furnitures

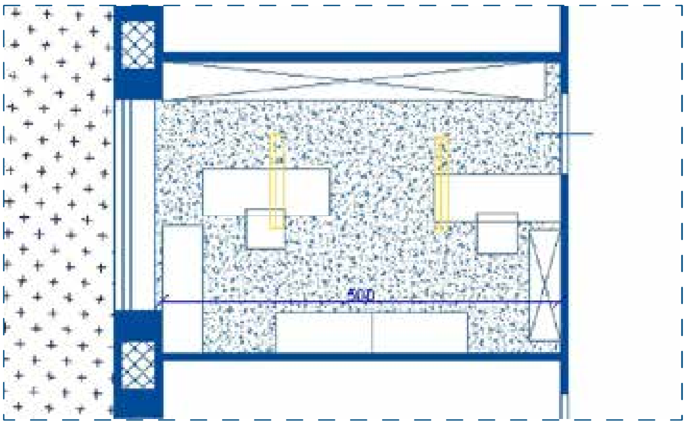
Photos



Shading typology

External motorised blinds

Note
- Luminaire with fan in the middle of the ceiling



Room code
E020

Room area
18.5 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.75m

Depth
5.00m

Surface colors and materials

Walls

Ceiling

Floor

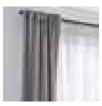
Furnitures

Photos

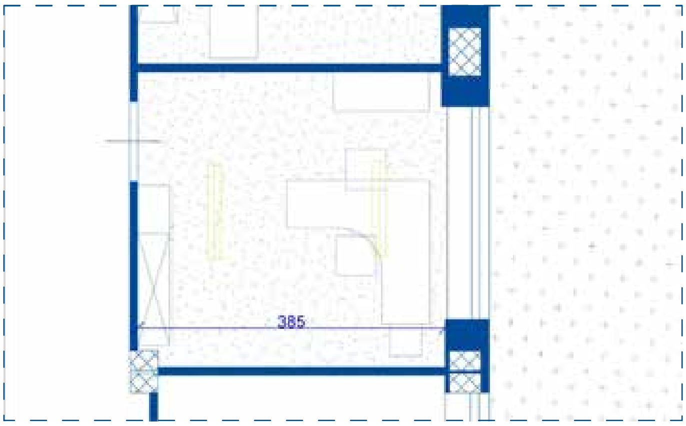
Shading typology

External motorised blinds

Internal curtains



03



Shading typology

External motorised blinds

Room code
E021

Room area
14.2 m²

Light fixtures

Typology	Number
Industrial, Fluorescent light source	2, double

Height
h: 3.75m

Depth
5.00m

Surface colors and materials

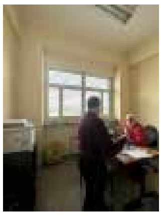
Walls

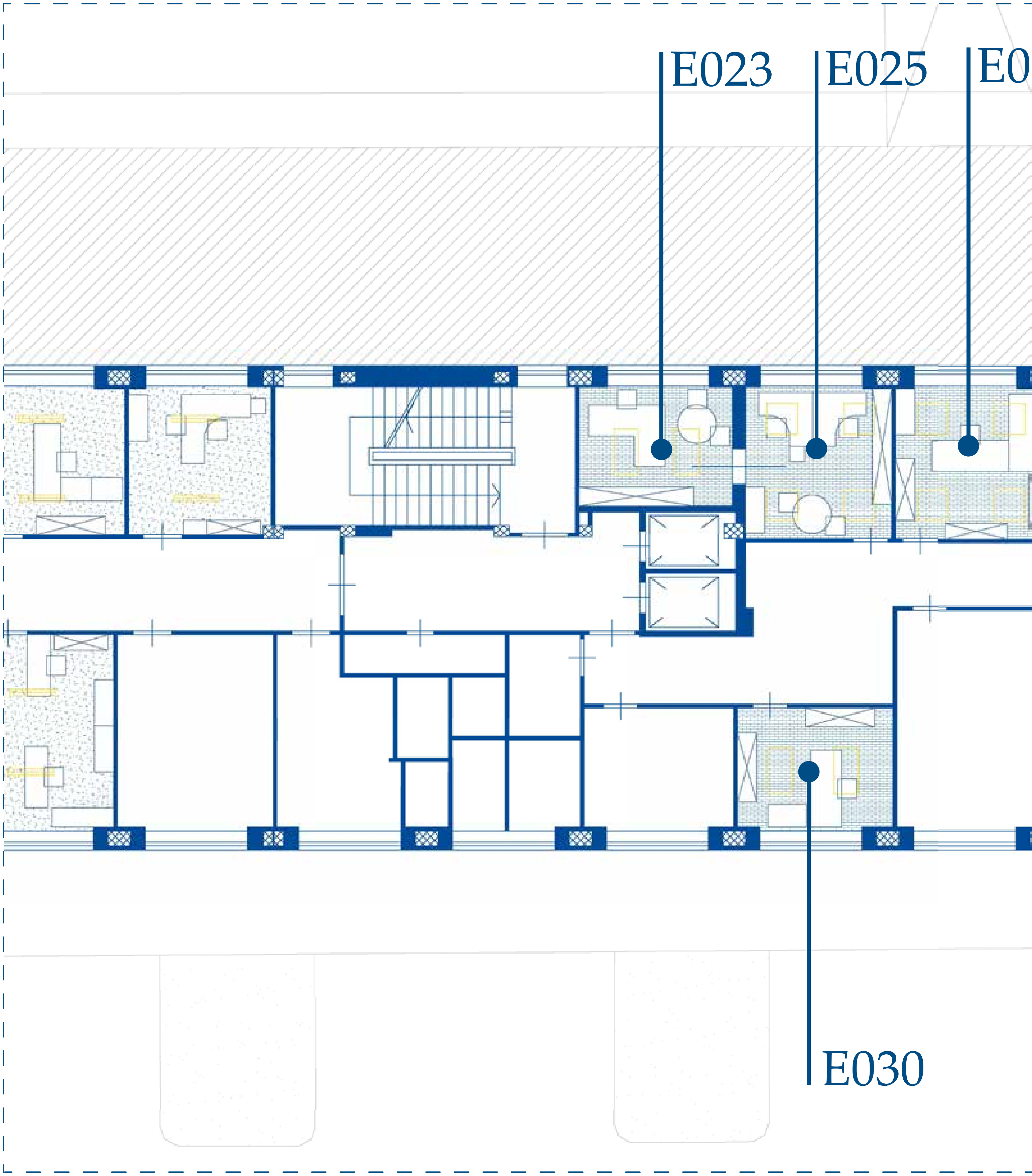
Ceiling

Floor

Furnitures

Photos



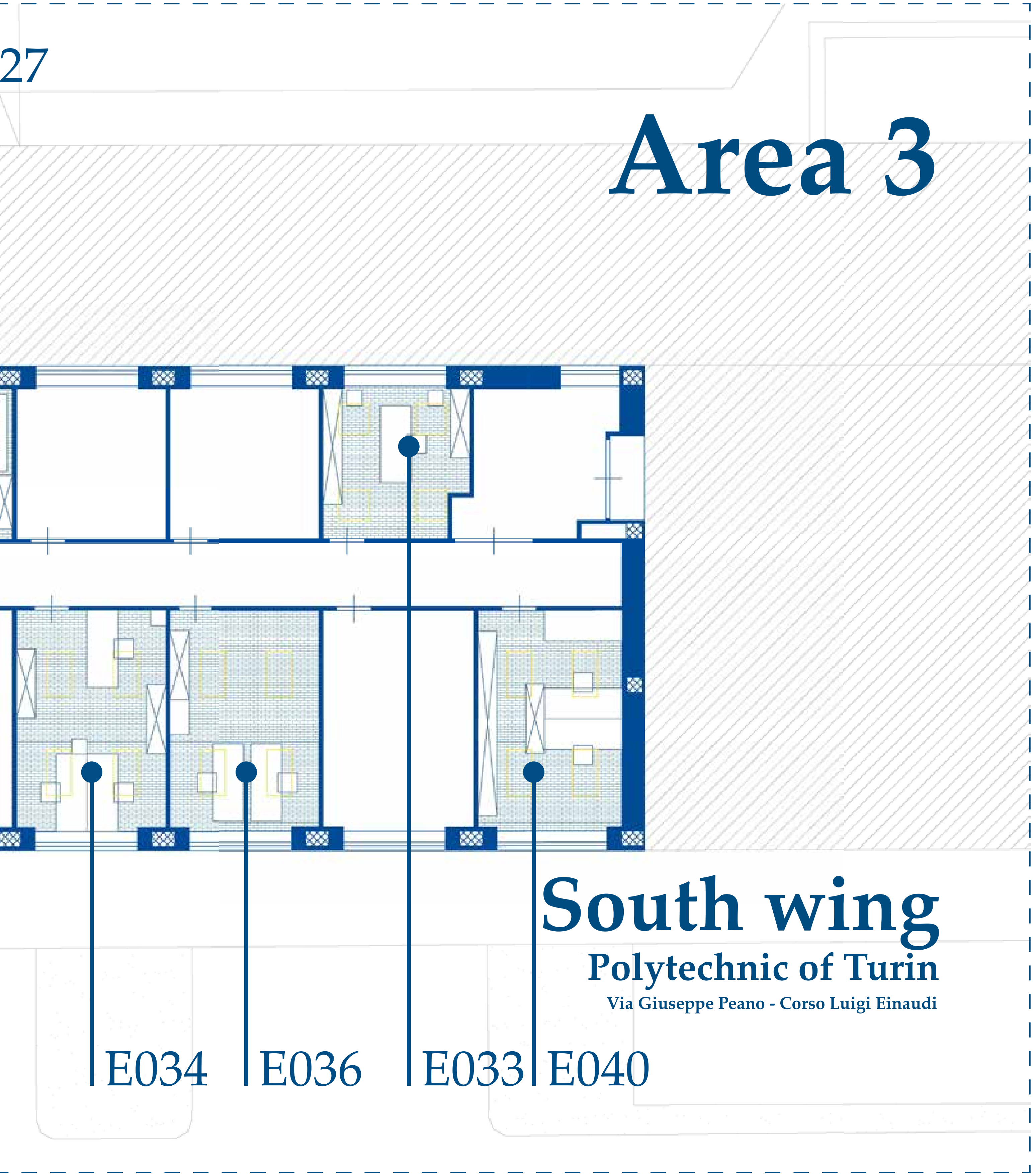

E023
E025
E0
E030

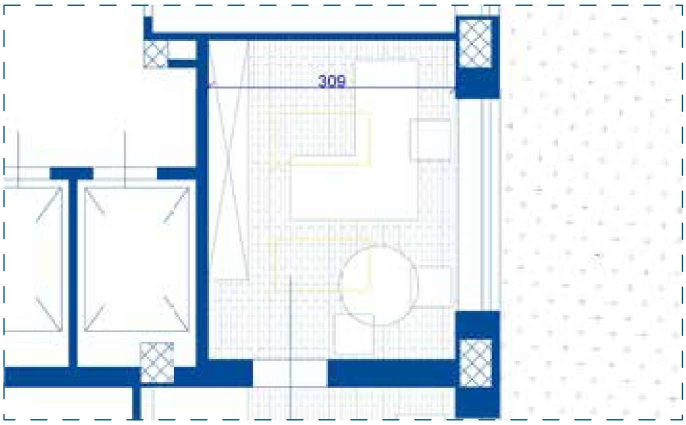
Area 3

South wing

Polytechnic of Turin

Via Giuseppe Peano - Corso Luigi Einaudi





Shading typology

External motorised blinds

Room code
E023

Room area
12.4 m²

Light fixtures

Typology	Number
LED	2

Height	Depth
h: 3.70m	3.09m

Surface colors and materials

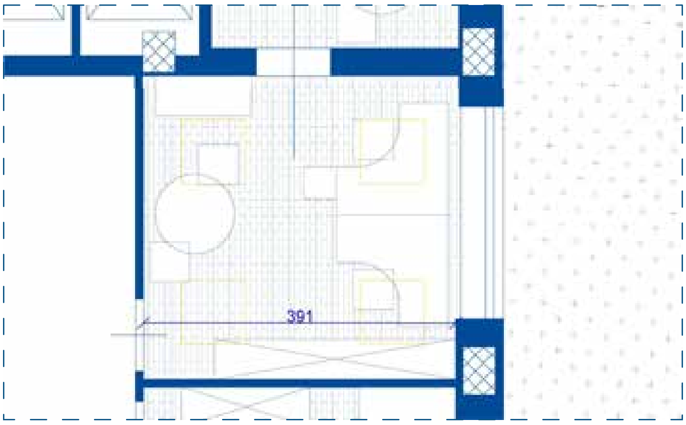
Walls

Ceiling

Floor

Furnitures

Photos



Shading typology

External motorised blinds

Room code
E025

Room area
15.1 m²

Light fixtures

Typology	Number
LED	4

Height	Depth
h: 3.70m	3.91m

Surface colors and materials

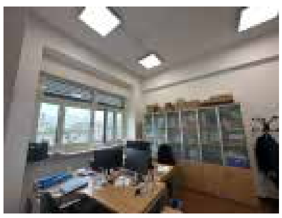
Walls

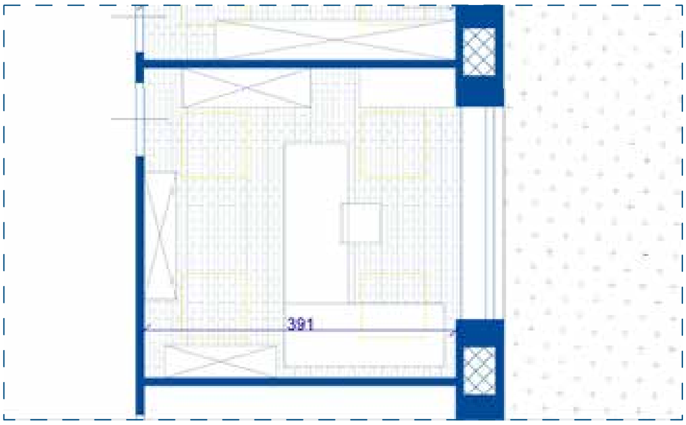
Ceiling

Floor

Furnitures

Photos





Shading typology

External motorised blinds

Room code
E027

Room area
15.3 m^2

Light fixtures

Typology	Number
LED	4

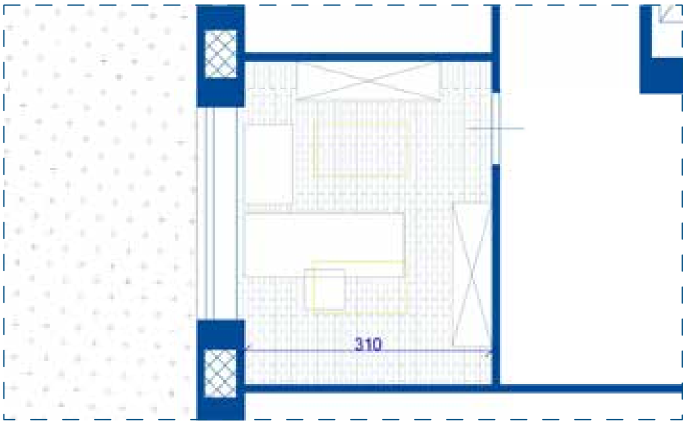
Height	Depth
h: 3.70m	3.91m

Surface colors and materials

Walls Ceiling Floor Furnitures

Phot





Shading typology

External motorised blinds

Room code
E030

Room area
12.8 m^2

Light fixtures

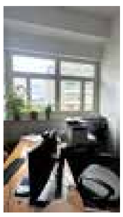
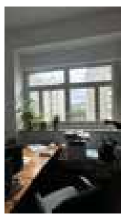
Typology	Number
LED	2

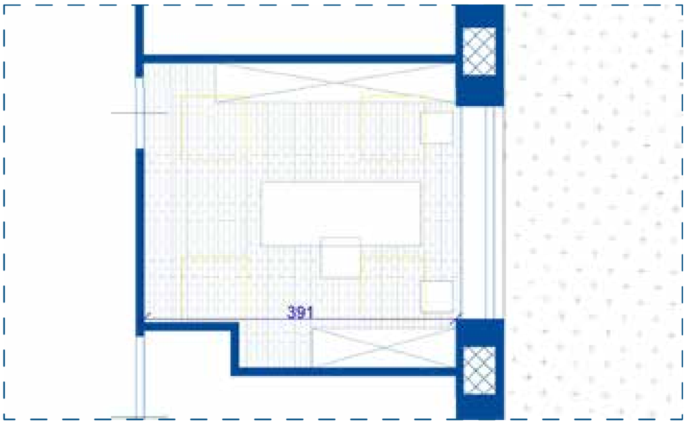
Height	Depth
h: 3.70m	3.10m

Surface colors and materials

Walls Ceiling Floor Furnitures

Photos

Shading typology

External motorised blinds

Room code
E033

Room area
14.4 m²

Light fixtures

Typology	Number
LED	4

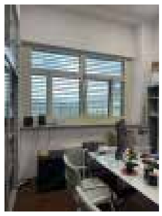
Height
h: 3.70m

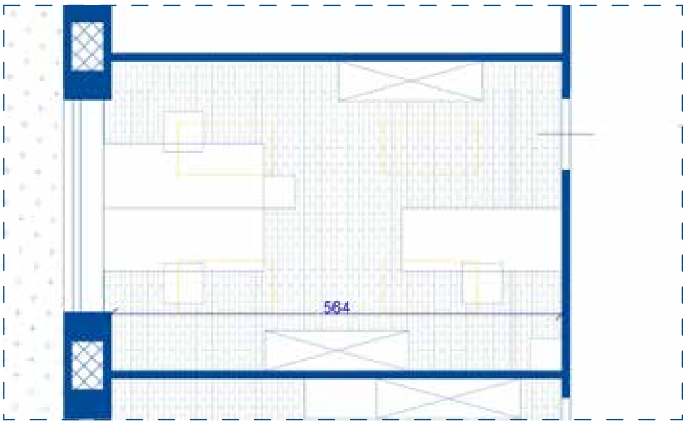
Depth
3.91m

Surface colors and materials

Walls | Ceiling | Floor | Furnitures

Photos





Shading typology

External motorised blinds

Room code
E034

Room area
22.1 m²

Light fixtures

Typology	Number
LED	4

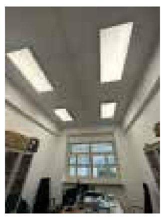
Height
h: 3.70m

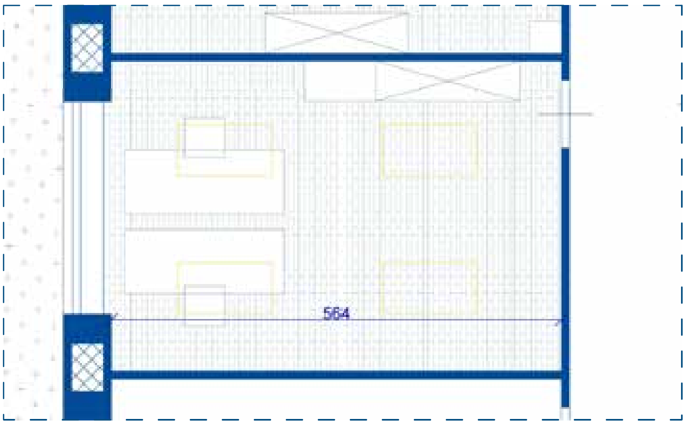
Depth
5.64m

Surface colors and materials

Walls | Ceiling | Floor | Furnitures

Photos





Shading typology

External motorised blinds

Room code
E036

Room area
22.1 m^2

Light fixtures

Typology	Number
LED	4

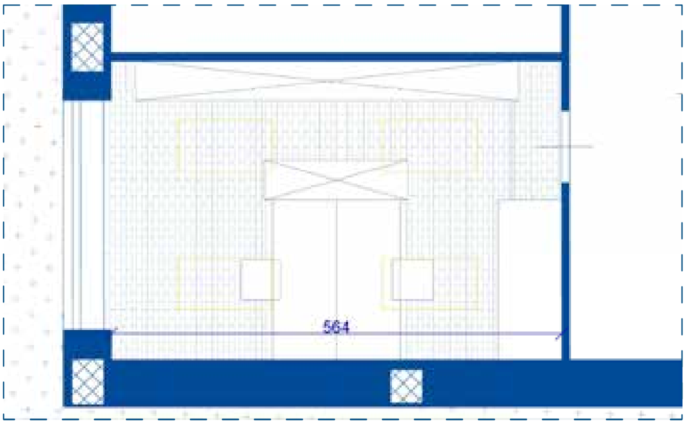
Height
h: 3.70m

Depth
5.64m

Surface colors and materials

Walls | Ceiling | Floor | Furnitures

Photos

Shading typology

External motorised blinds

Room code
E040

Room area
21.4 m^2

Light fixtures

Typology	Number
LED	4

Height
h: 3.70m

Depth
5.64m

Surface colors and materials

Walls | Ceiling | Floor | Furnitures

Phot



As for findings, the offices inspected varied in size and layout. The average office size was 19.2 square meters, with the largest being 41.5 square meters and the smallest being 12.4 square meters. The average depth, which is the distance between the window and the parallel wall, was 4.74 meters, in a range of measurements from the deepest being 6.33 meters and the shallowest measuring 3.1 meters. In terms of orientation, the building and office layout offered a degree of variety; of the total number of offices, nine faced Northwest, eight opened Southeast, and five faced Southwest. As for ambience, thirteen offices featured walls and furnishings in cool tones (59%), while nine offices had warm tones (41%). Common features include standard office furniture arrangements with desks, chairs, and storage units, in materic terms seven offices had metal furniture (32%), while fifteen had wooden furniture (68%), information recorded since the colour and material of furnishings can affect the appearance of a room and the light reflections within it. In terms of workstations, ten offices had two workstations (45%), seven offices were single-occupant (32%), two offices had three workstations (9%), two offices had five workstations (9%), and one office had twelve workstations (5%). Regarding lighting fixtures, fourteen offices were equipped with fluorescent lighting (64%), while eight offices had LED fixtures (36%). Fourteen offices had two lighting fixtures, seven offices had four fixtures, and one office had three fixtures. All offices had an identical window in dimensions, providing natural light. For shading systems, twenty offices were equipped with motorized external blinds, while two offices had both blinds and internal curtains, allowing occupants to control light levels and reduce glare.

Data collected on site inspection									
Dimensions			Orientation			Ambience			
	Area	Depth				Tones		Furniture materials	
Average	19.2 mq	4.74 m	S-SW	5	23%	Cool	13	Metal	7
Min	12.4 mq	3.09 m	E-ES	8	36%	(% cool)	59%	(% metal)	32%
Max	41.5 mq	6.33 m	W-WN	9	41%	Warm	9	Wood	15
Mode	24.4 mq	5 m				(% warm)	41%	(% wood)	68%
Workstations			Light fixtures					Shading systems	
Number			Light source		Number			Typology	
Single (1)	7	32%	Fluorescent	14	2 fixtures	14	64%	Blinds	20
Double (2)	10	45%	(% fluo)	64%	3 fixtures	1	5%	(% blinds)	91%
Triple (3)	2	9%	LED	8	4 fixtures	7	32%	Blinds+Curtains	2
Quintuple (5)	2	9%	(% LED)	36%				(% both)	9%
Duodecuple (12)	1	5%							

Table 3.1. Data collected on site inspection. Information about dimension, orientation, ambience, workstations, lights and shadings.

After gathering data from the 22 offices, four offices were selected to be representative of the sample. Specifically, medium-sized offices with variations in depth and the number of workstations were selected. All three observed orientations were included in the selection. Moreover, to represent both types of lighting sources investigated (fluorescent and LED), three offices with fluorescent lighting and one with LED lighting were chosen. Offices with malfunctions or too unique characteristics were excluded from the selection.

Selected offices

Distributed throughout the third floor of the south wing of the Polytechnic of Turin, four offices were chosen for their highly representative characteristics on the sample in terms of size, orientation and environmental features. As background information, each office of this wing is coded using a letter and a number, in the shorter side of the south wing, offices are designated with the letter "D" followed by numbers in ascending order from 1 to 8. In the longer side, offices are marked with the letter "E" and numbered from 8 to 40.

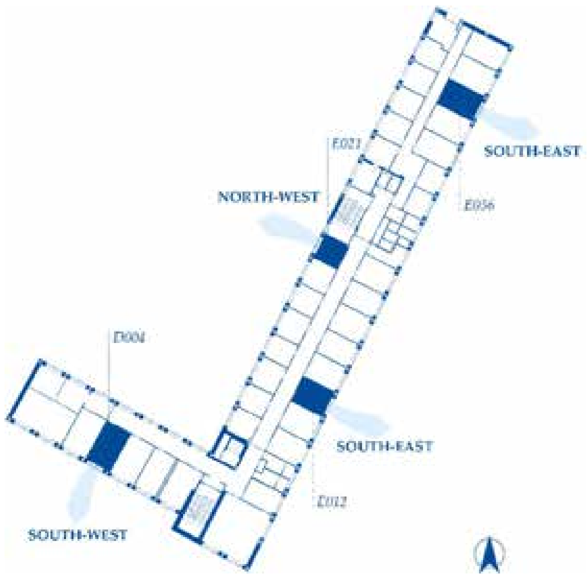


Figure 3.4. Overview of selected offices as case study and relative orientations.

- **Office D004:** Located in the shorter side of the south wing, Office D004 is the largest among the four selected, although its size is close to the average of the inspected offices. It covers an area of 24.4 square meters with a depth of 6.30 meters. The office houses five workstations, two of which are paired, positioned at distances of 1 meter, 3.4 meters, and 5.5 meters from the window. The office faces southeast and features two pairs of fluorescent lighting fixtures with a colour temperature of approximately 3900K. The walls are painted in extremely neutral tones of white, the floors are gray, and the furnishings are made of light metal. A notable feature of this office is a bookshelf that runs along the entire west wall.
- **Office E012:** In the longer side of the south wing, Office E012 spans an area of 19.8 square meters with a depth of approximately 5 meters. It contains two workstations positioned 1.9 meters and 3.9 meters from the window. The lighting system is similar to Office D004, with two pairs of fluorescent fixtures emitting a colour temperature of around 3700K. The walls are painted a vibrant yellow, while the floor, ceiling, and furnishings are in neutral colours.

- **Office E021:** Office E021 is the smallest of the four selected offices, with an area of 14.2 square meters and a depth of 5 meters. It accommodates a single occupant with the workstation located 1.5 meters from the window. This office also has two pairs of fluorescent lighting fixtures, but with a higher CCT of 4062K and a lower Colour Rendering Index (CRI) of 60, compared to the CRI of around 80 in the other offices. The walls are painted in a very neutral off-white colour, while the furnishings are very dark, almost black.
- **Office E036:** Selected for being representative of LED-lit offices, Office E036 covers 22.1 square meters with a depth of 5.64 meters. It has three workstations, with the farthest one being 4.4 meters from the window. This office features four LED lighting fixtures, whose photometric curve is illustrated in Figure 3.5. The LED sources have a colour temperature of 4000K and a CRI of 80.

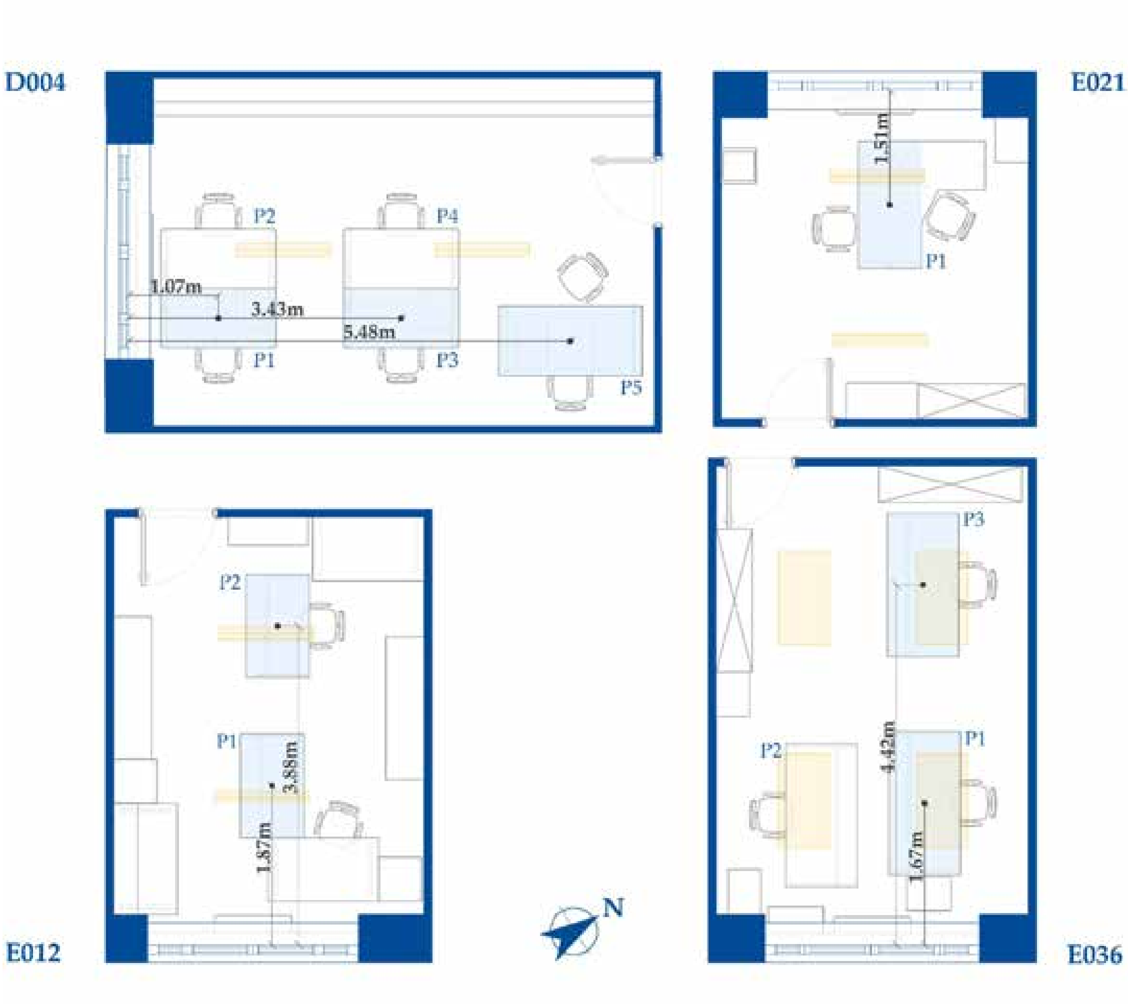
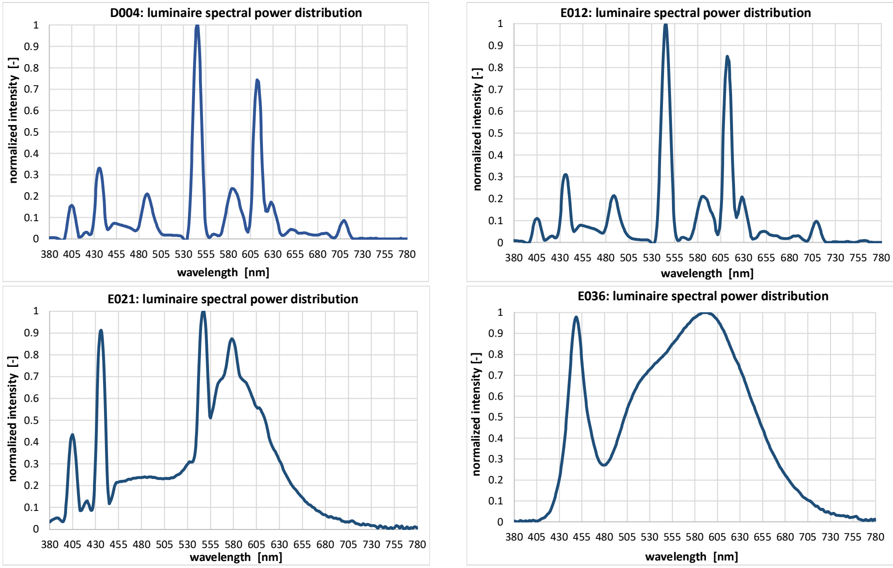


Figure 3.5. Floor plans of the four offices selected as case study.



	D004
CCT	3878K
CRI	84

	E012
CCT	3733K
CRI	82

	E021
CCT	4062K
CRI	60

	E036
CCT	4014K
CRI	81

Table 3.2. Spectral power distribution and characteristics of the luminaires in the four offices analysed.

All four offices feature a double-hung window of equal size (2.7 m by 1.8 m = 4.86 sqm) and are equipped with external motorized blinds. Given the same window size but different floor areas, the Window-to-Floor Ratio (WFR) varies across the offices: D004 has a WFR of 0.18, E012 has a WFR of 0.25, E021 has a WFR of 0.34, and E036 has a WFR of 0.22; overall, all rooms have an "air-lighting" ratio ("*rapporto aeroilluminante*") greater than 0.125, which is the 1/8th required by Italian regulations[4].

Code	Dimensions	Orientation	WFR	VCS (%)	N. Workstations	Light sources
D004	24.4 sqm (3.9*6.3 m)	Sout-West	0.18	29.6	5 (4 W; 1 W+V)	Fluorescent
E012	19.8 sqm (3.9*5.0 m)	South-East	0.25	23.7	2 (2 W+V)	Fluorescent
E021	14.2 sqm (2.8*5.0 m)	North-West	0.34	37.5	1 (1 W+V)	Fluorescent
E036	22.1 sqm (3.9*5.6 m)	South-East	0.22	30.3	3 (3 W+V)	LED

Table 3.3. Features of the four offices selected as case study (W: worker; V: visitor).

The VSC (Vertical Sky Component) is an extremely useful parameter to get information about obstructions, access to daylight and for sky classification[5-6].

[4] While the Italian standard, included in art.5 of DM05/07/1975, explicitly defines a WFR value of 1/8; there is no universal value for this ratio. In general, European and other international standards tend to focus on performance metrics such as daylight factor, daylight autonomy, and overall daylight provision, standards that aim to ensure that buildings are designed to provide sufficient natural light, enhancing the well-being and productivity of occupants (e.g: European Standard EN 17037:2018 "Daylight in Buildings", LEED certification and WELL Building Standard). However, there is another ratio, the Window-to-Wall Ratio (WWR), defined by the global society ASHRAE and classified as 90.1-2007, which indicates the percentage of a building's glazing; its ideal value is set at 24% of the wall. (Khoukhi et al., 2020) (ANSI/ASHRAE/IESNA Standard 90.1-2007) (EN 17037:2018).
[5] (Li et al., 2015)
[6] (Granados Lopez et al., 2020)

These recorded differences and thus representativeness of the overall sample, allowed for a comprehensive analysis of typical office environments within the campus, the subsequent phase will involve conducting extensive light measurements of this selected sample.

3.2.2 Data collection methods

In the analysis of the case study, two methodological approaches were employed: field measurements and simulations. Each focusing on one aspect of office lighting: electric light and daylight. The combination of these two approaches is the pivotal point of integrative lighting assessment.

3.2.2.1 Field measurements for electric lighting

Due to time constraints and other limitations caused by the variability of sunlight, field measurements were limited to electric light. Longer on-site inspection allowed for a characterization of the spaces from the point of view of architectural features, as detailed measurements were taken, of light, both of the source and of photopic and melanopic illuminances and, lastly, of material characterization.

The process started by deciding where to place the measurement points and how many workstations to measure. Generally, it was agreed to consider two opposite directions for each desk positioned perpendicularly to the window (with the worker's front view direction parallel to the window). Each view direction was further subdivided into alternative directions: -45°, +45°, and -45° downward. This setup represented the presence of a worker ("W" or "A") and a visitor ("V" or "A' "). Each office had, then, to be considered individually; in office D004, four out of five desks were positioned opposite each other. Hence, the user sitting in the opposing position (B) also represented the opposite position or visitor of A (i.e., A'). For the fifth workstation, which was separate from the others, both worker and visitor measurements were taken, totaling six work positions in office D004. In office E012, the primary workstation faced the window. Although the analysis primarily considered view directions parallel and opposite to the window, an additional perpendicular measurement was also taken during the fieldwork. However, for the final data analysis, only the perpendicular directions were retained, resulting in four measurement points, with the fifth point (facing the window) discarded. A similar approach was applied in office E021, a single-occupant office with an L-shaped desk. Initially, measurements were taken at points perpendicular to the window. An additional point, corresponding to a secondary screen position parallel to the window, was also measured but only the perpendicular points were considered in the final analysis. Finally, in office E036, the presence of three separate desks, all perpendicular to the window, allowed for the recording of six measurement points: three "worker" and three "visitor" points.

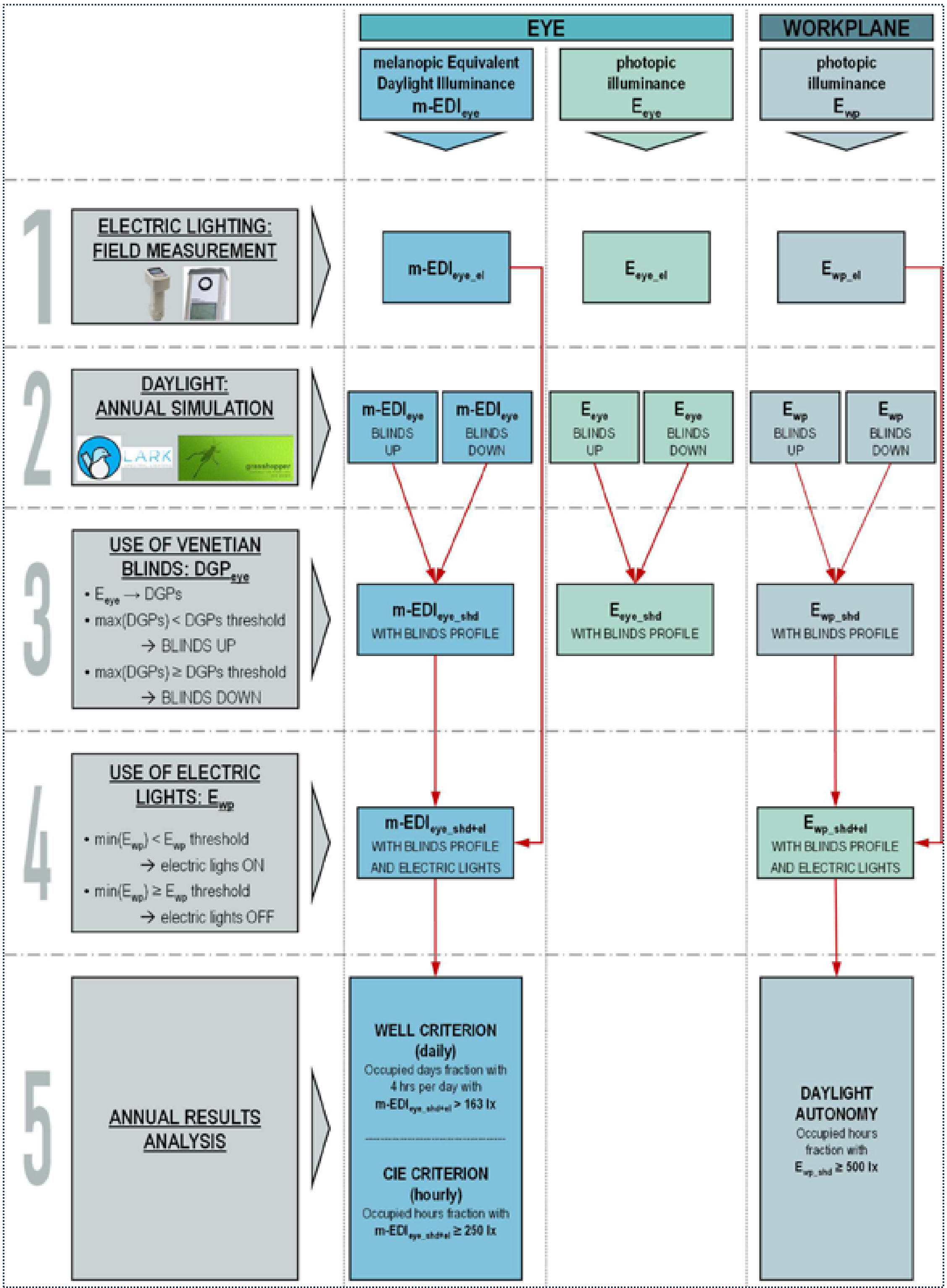


Figure 3.6. "Workflow of the method used in the study, based on a combination of measurements for electric lighting and LARK v2 annual simulations for daylighting" in (Giovannini et al., 2023).

The practical execution of these measurements involved the following steps: after setting up the room by completely darkening the openings to eliminate any natural light, the first step was to characterize the light sources by acquiring their spectral power distribution using the Gigahertz BTS256-EF spectrophotometer (measurement range: 360–830 nm; measurement sensitivity: 10 nm; error: ±2.2%), to do so the spectrophotometer was placed as close to the light source as possible. Subsequent measurements were taken at the workstations, divided into two types: pupillary illuminance measurements (according to the occupant's view directions, particularly for the melanopic aspect) and photopic illuminance measurements on the work plane to characterize the performance of the electric lighting. For these measurements, a template was positioned at the centre of the desk, featuring a grid of six or four points (based on the dimension and positioning of the desk) for horizontal measurements and showing another point consisting in the location to set the instrument for vertical measurements.

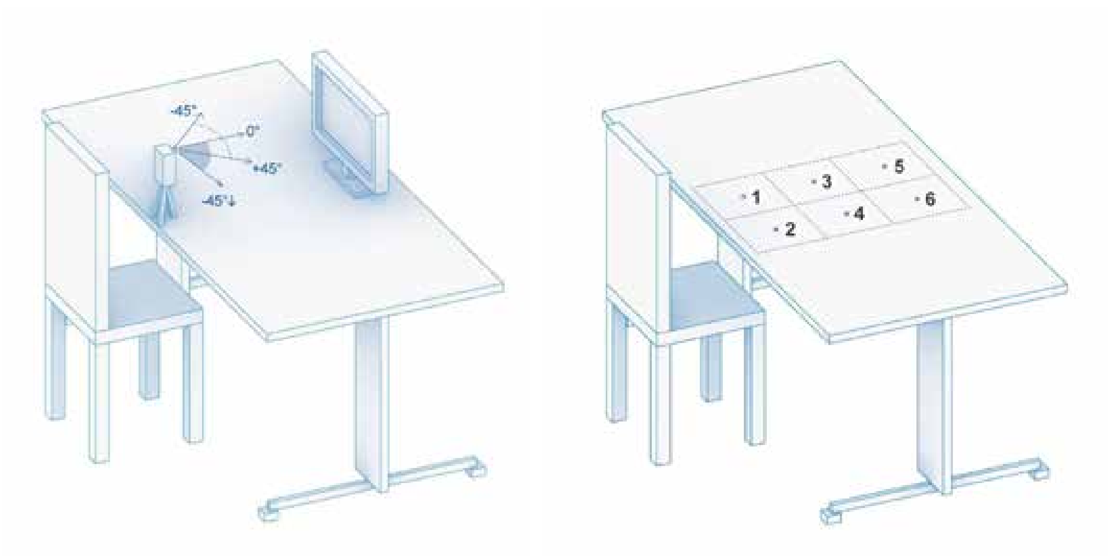
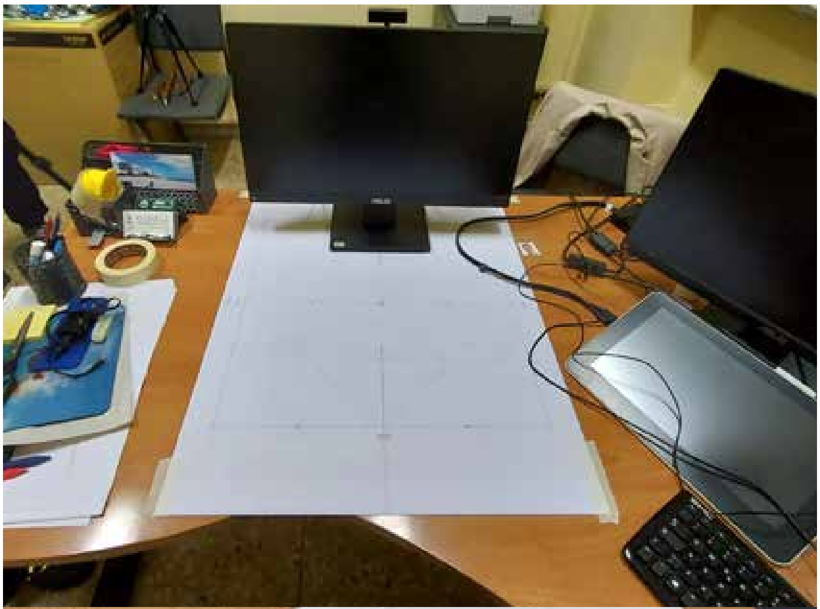
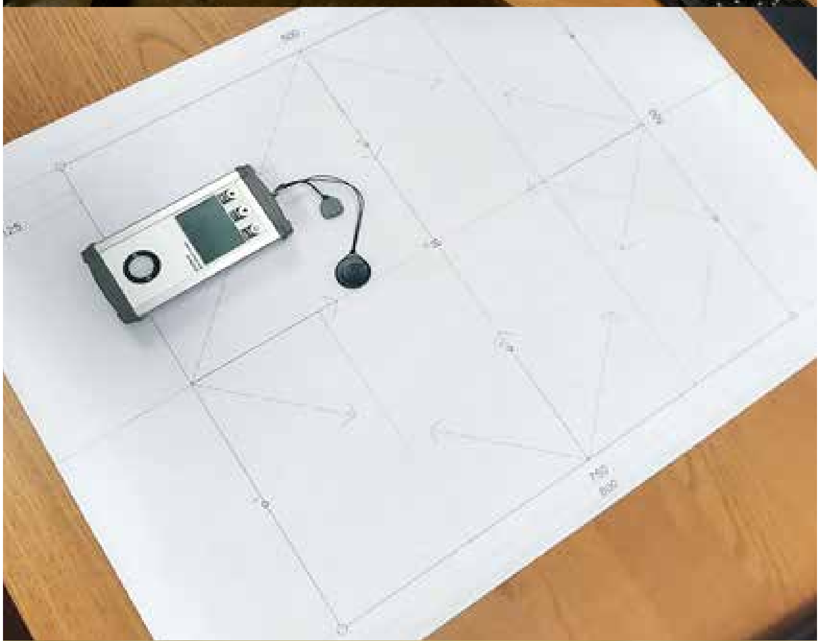


Figure 3.7. View directions and grid of horizontal points measured.

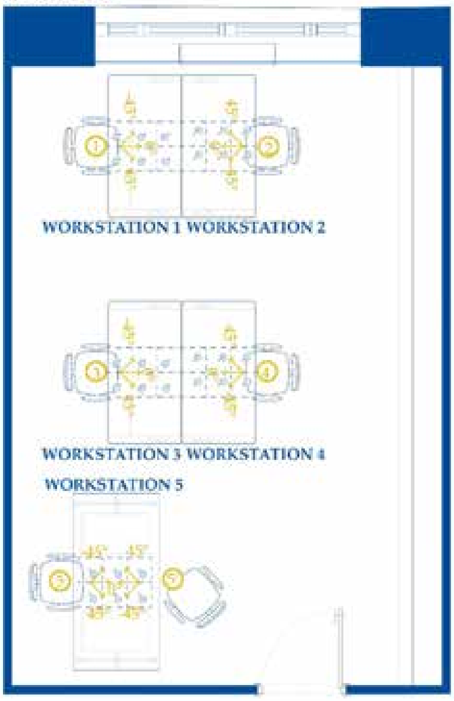
Pupillary measurements were taken with the Gigahertz BTS256-EF spectrophotometer mounted on a tripod at a height of 1.2 meters from the floor, simulating the seated height of an occupant. Four measurements were taken corresponding to four view angles: facing forward (0°) and rotating the instrument according to two azimuthal rotations of +45° and -45°, with a fourth view direction taken by tilting the instrument toward the desk to simulate the position an occupant assumes to write or read a paper on the desk (-45° vertical view direction). In this way, a range of the most common view directions was considered. Both photopic and melanopic illuminances were recorded for these points and positions (m-ED_{eye_el} and E_{eye_el}). On the horizontal plane, only photopic illuminance (E_{wp_el}) was measured at six grid points, each 25 cm apart.

03

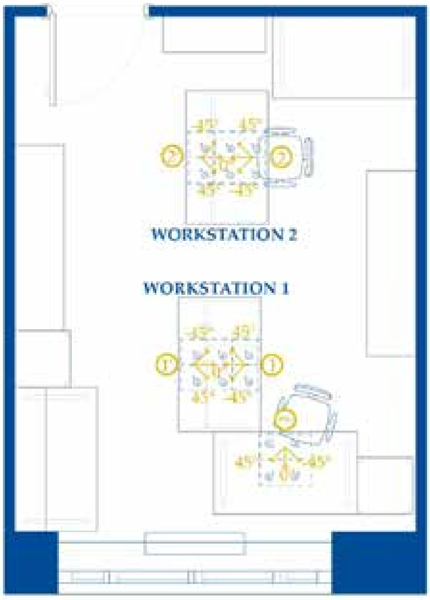




Office D004



Office D004					
Workstation 1	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	1	45°	20.0	1	205.2
		0°	43.1	2	231.8
		-45°	21.3	3	203.7
		-45° ↓	30.7	4	230.1
Workstation 2	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	2	45°	24.6	1	215.7
		0°	43.5	2	190.1
		-45°	83.0	3	215.6
		-45° ↓	39.2	4	190.3
Workstation 3	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	3	45°	80.7	1	354.8
		0°	81.9	2	355.1
		45°	45.2	3	352.6
		-45° ↓	45.6	4	353.4
Workstation 4	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	4	45°	73.4	1	348.5
		0°	71.3	2	348.1
		-45°	78.0	3	348.4
		-45° ↓	53.0	4	347.1
Workstation 5	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	5	45°	36.9	1	258.4
		0°	63.1	2	231.3
		-45°	30.5	3	263.7
		-45° ↓	35.1	4	234.3
	5'	45°	36.6	5	268.2
		0°	35.6	6	234.1
		-45°	35.5		
		-45° ↓	43.6		

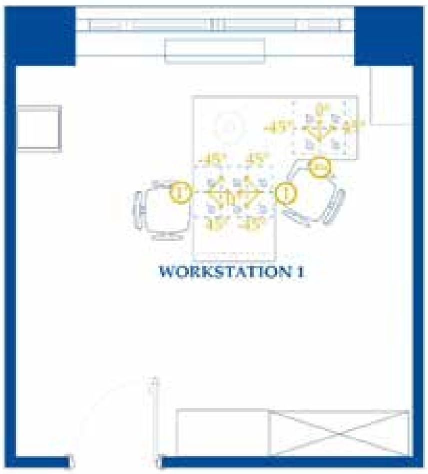


Office E012

Office E012					
Workstation 1	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	1	45°	89.6	1	421.9
		0°	59.1	2	454.0
		-45°	38.8	3	426.5
	1'	45°	42.4	4	460.0
		0°	62.9	5	420.8
		-45°	90.6	6	454.0
Workstation 1bis	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	1bis	45°	29.7	1	295.4
		0°	25.6	2	314.8
		-45°	24.8	3	278.0
				4	292.1
Workstation 2	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	2	45°	45.6	1	438.8
		0°	64.1	2	403.9
		-45°	90.1	3	450.3
	2'	45°	93.4	4	414.7
		0°	51.7	5	449.4
		-45°	37.6	6	413.9

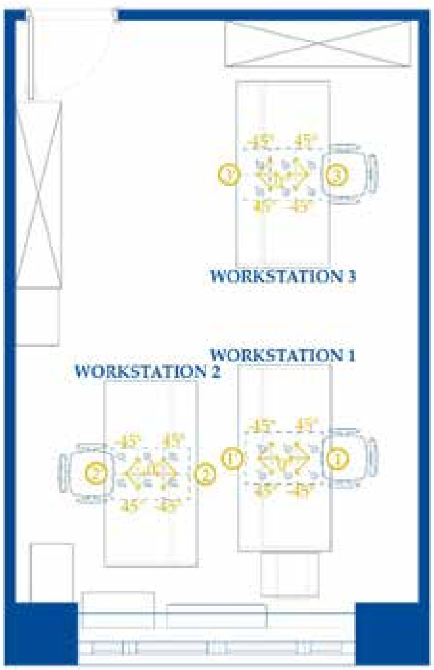
Methodology *Data collection methods*

A sample of measurement was manually annotated and numbered (Table 3.4) for comparison purposes, to prevent errors during data processing; while the entire data set, including melanopic measurements, was recorded using digital devices.



Office E021

Office E021					
Workstation 1	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	1	45°	25.1	1	231.1
		0°	35.4	2	210.5
		-45°	47.3	3	238.6
	1'	45°	39.3	4	216.7
		0°	26.2	5	239.2
		-45°	22.3	6	218.0
Workstation 1bis	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	1bis	45°	20.4	1	170.9
		0°	16.7	2	160.0
		-45°	26.0	3	165.3
				4	153.8



Office E036

Office E036					
Workstation 1	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	1	45°	241.6	1	691.1
		0°	194.6	2	727.1
		-45°	147.2	3	703.9
	1'	45°	148.8	4	743.8
		0°	186.6	5	714.6
		-45°	206.5	6	754.0
Workstation 2	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	2	45°	135.1	1	709.6
		0°	192.7	2	673.1
		-45°	208.8	3	726.4
	2'	45°	205.1	4	636.0
		0°	163.1	5	734.4
		45°	130.6	6	693.0
Workstation 3	Vertical illuminance (lx)			Horizontal illuminance (lx)	
	3	45°	151.5	1	765.4
		0°	200.2	2	737.2
		-45°	212.4	3	789.6
	3'	45°	221.1	4	755.9
		0°	200.6	5	797.3
		-45°	156.8	6	764.3

Table 3.4. Plan view showing measured points locations and sample of measurements.

For each office, all surfaces were characterized using a contact spectro-photometer Minolta M-600; this step was necessary to assign real characteristics to the environments modelled via software. Additionally, light trasmittance measurements of the window glass were taken by calculating the ratio of lux measured through the glass and lux measured with the window open. These measurements were performed using a spectrophotometer and repeated with a luminance meter for comparison.

Figure 3.8. Measuring process to calculate light transmittance.

Light measuring tools: a focus

- *Spectrophotometer*

A spectrophotometer is able to give information about the intensity of light at different wavelengths. *"It operates by passing a beam of light through a sample"*[7] and measuring the amount of light absorbed or transmitted at each wavelength. The resulting spectrum provides detailed information about the optical properties of the sample.

Figure 3.9. "BTS256-EF for complex measurements in lighting technology, including flicker measurement". In gigahertz-optik.com.

[7] "*The complete guide to spectrophotometers*", in MRC laboratory-instruments (mrclab.com).

In the context of the case study lighting analysis, the spectrophotometer used was the Gigahertz BTS256-EF; this device shows high precision and sensitivity, with a measurement range of 360–830 nm and a sensitivity of 10 nm. The error margin is ±2.2%, which ensures reliable and accurate spectral data. The instrument is equipped with a spectral sensor that allows for the acquisition of the spectral power distribution (SPD) of light sources. SPD is crucial for understanding the colour characteristics and quality of lighting, as it shows how much power is emitted at each wavelength of light.

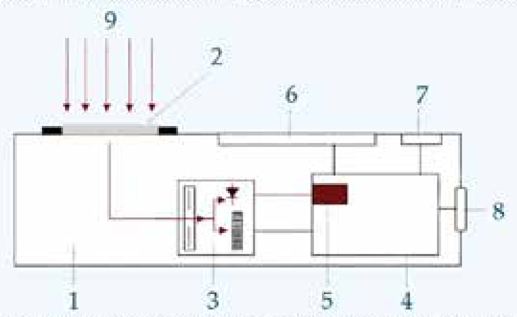


Figure 3.10. "Principle illustration of the BTS256-EF. 1) BTS256-EF; 2) Precision cosine diffuser; 3) BiTec sensor with Si photodiode, CMOS diode array spectrometer and shutter; 4) Photometric Si-photodiode with fast amplifier; 5) Microprocessor; 6) Display; 7) Control Buttons; 8) USB 2.0 interface; 9) Light incident". In gigahertz-optik.com.

- *Contact spectrophotometer*

A contact spectrophotometer is designed to measure the spectral reflectance of surfaces. Unlike traditional spectrophotometers, which measure light in a non-contact manner, contact spectrophotometers are placed directly on the surface to be measured. This method provides accurate reflectance data by minimizing the interference of ambient light and ensuring consistent contact with the surface. The Minolta M-600 used for this field measurements, features a broad spectral range and high accuracy, making it ideal for characterizing the reflectance properties and color of pigments of various materials in the office environment.

Figure 3.11. Contact spectrophotometer Minolta M-600. Photos from konicaminolta.us.

- *Luminance meter*

A luminance meter measures photometric brightness, or, in simple terms, the brightness of a surface as perceived by the human eye, value expressed in candelas per square meter (cd/m²). Unlike a lux meter (an additional device for measuring the properties of light, specifically its intensity), which measures the amount of light falling on a surface, a luminance meter measures the light emitted or reflected from a surface.

For field measurements in general, this tool is useful to assess the brightness of various surfaces, including computer screens, walls, and workstations. This information is important for evaluating visual comfort and the potential for glare, which can affect productivity and well-being.

Figure 3.12. Field measurement with a Luminance Meter Konica Minolta LS-100.

In summary, one of the fundamental aspects of a field measurement approach is the availability of measuring tools. As previously discussed in the initial chapter and further discussed in these pages, specific properties of light necessitate the utilisation of distinct tools for their measurement. For this case study a spectrophotometer Gigahertz BTS256-EF was employed to collect data on photopic and melanopic illuminance, light transmittance of windows, and spectral characterisation of light sources. Materials and colours were assessed through a Minolta M-600 contact spectrophotometer. Finally, a luminance meter (Konica Minolta LS-100) was employed to obtain comparative data on window transmittance. By employing such range of sophisticated tools, the study was able to provide a comprehensive understanding of the lighting conditions in the office spaces.

3.1.1.1 Annual simulations for daylight

Three-dimensional model using Rhinoceros

Figure 3.13. Rhinoceros software logo. From rhino3d.com.

The simulation phase involved a preparatory step of 3D modelling of the environments using the software Rhinoceros. Rhinoceros, also referred to as Rhino 3D, is a three-dimensional modelling software characterised by the capability to create complex solids, from geometric entities called NURBS (Non-Uniform Rational B-Splines) and engage in algorithmic modelling, particularly through the Grasshopper plug-in for computational design, which generates outputs such as lighting analysis and simulation, as well as acoustics, structural verification, and numerous other features.

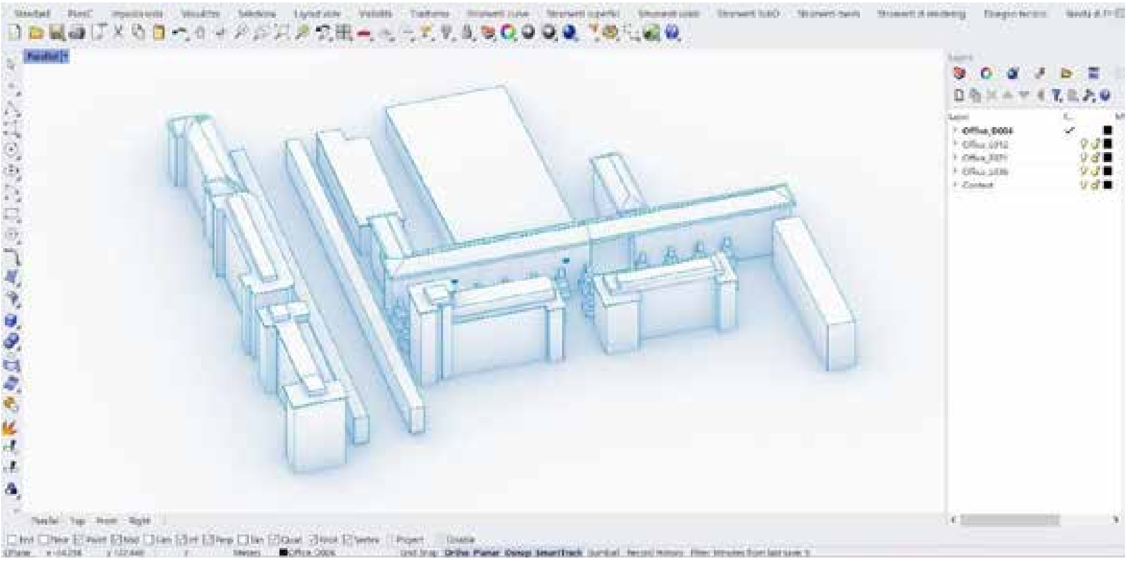
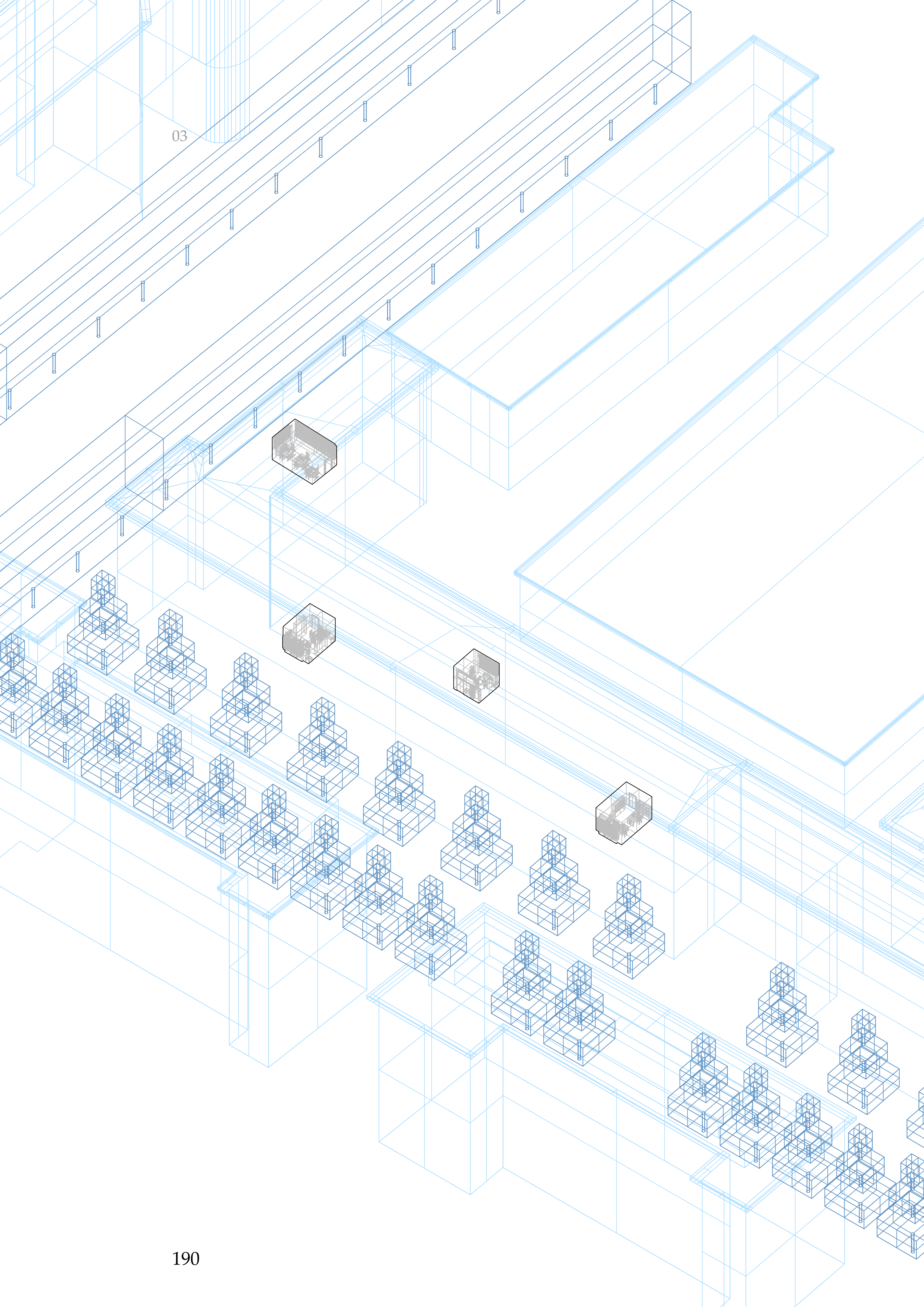


Figure 3.14. Rhinoceros interface and built model with context.

For the three-dimensional modelling of a building, the first step is to import a plan file in order to extrude its elements. Using the Turin Polytechnic's maps and the plans of the area obtained from the Geoportale[8], the entire southern sleeve building was modelled, as well as the context buildings and high-trunk trees that could represent obstructions.

[8] (geoportale.comune.torino.it)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Following thorough site inspections, the office environments were accurately measured in order to be modelled in the software within the context model. The architecture, openings (doors and windows, blinds), light fixtures and all furniture (desks, chairs, shelves, and cabinets) were modelled for each office. However, the model required a limited level of detail, as a huge amount of surfaces would increase the simulation running time. Therefore, a schematic representation of the furniture was created, simplified to basic geometries. Within the model of each office, measurement points were placed on the desk (horizontal and vertical, for the vertical points individual lines indicated the measurement directions), with the point command, such points were needed as simulation input. After modelling, the offices were oriented according to a cartesian coordinate system to match the real orientation, and the entire building, including the surrounding context (especially adjacent buildings and trees that could obstruct light), was also modelled.

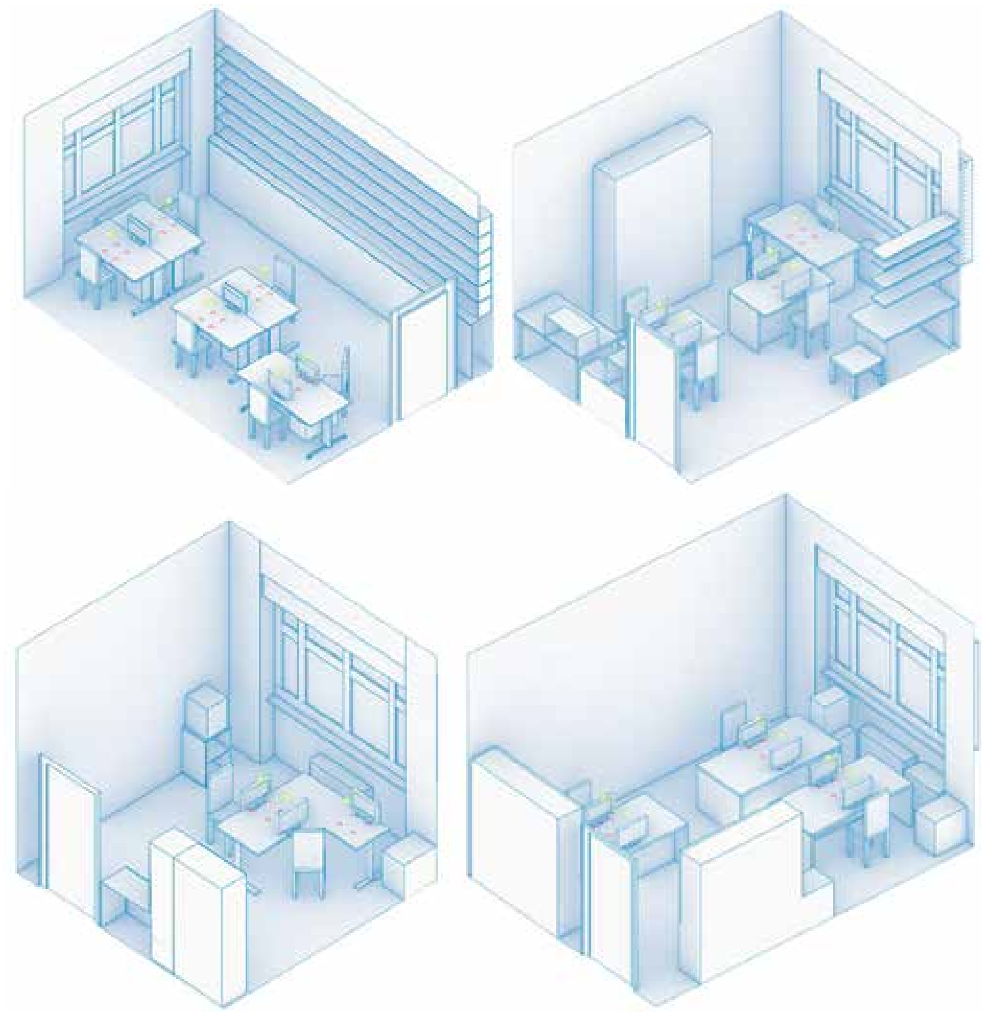


Figure 3.15. 3D model of the offices selected for the case study, in the order: D004, E012; E021; E036.

An important step, at this point, was the subdivision and classification of the modelled elements into correctly coded layers, with each material corresponding to a layer.

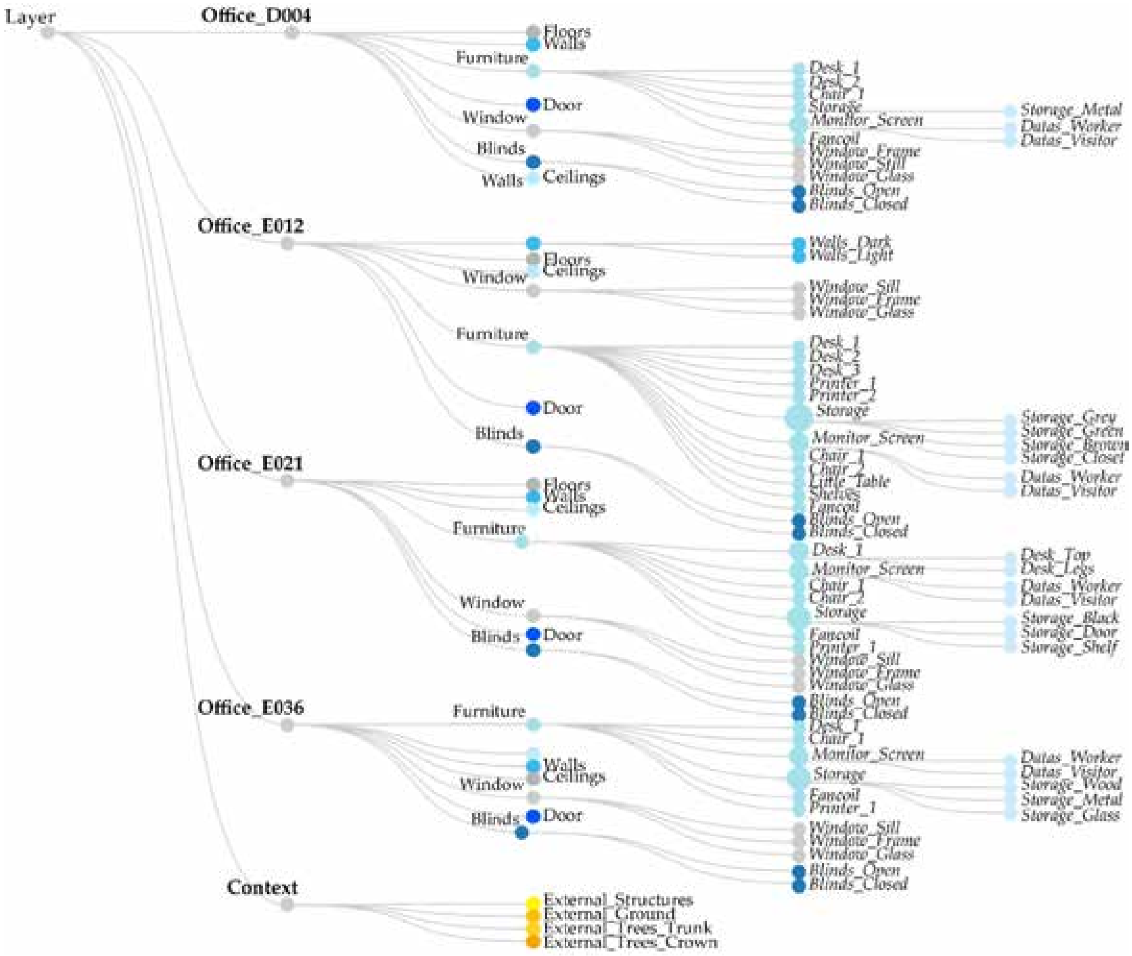


Figure 3.16. Layer hierarchy on the Rhinoceros 3D model.

This process was done to later associate each material with its measured value of light reflectance and colour. The process of recording these measurements and subsequently refining them to be suitable for software analysis is as follows: in the real environment, during the field measurement campaign, a single measurement was recorded for each material with uniform characteristics in terms of colour. Conversely, for materials that do not have uniform surfaces, such as wood with veins of different colours, multiple measurements were taken on the same surface and then averaged after being downloaded from the instrument and imported into a spreadsheet for further analysis. Each colour measurement was expressed in the spreadsheet as a value for every 10nm range in the visible wavelength; the spectral transmittance of the glazing was modelled in the program Optics 6, given the values previously calculated, since it was not possible to measure it through the contact spectrophotometer.

Annual simulations with LARK v2[9]

Given the 3D model and the material characterization information, light simulations were performed using the LARK v2 software. LARK v2 (Lark Spectral Lighting) is a tool within the Radiance group for the Grasshopper/Rhinoceros environment, capable of running both daylight and electric light spectral simulations *"in 9 channels, computing photopic luminance and illuminance values and circadian/non-visual metrics (e.g., alpha-opic values)"*[10]. This tool is therefore valuable in architectural practice for non-visual analysis of circadian metrics.

As the first step of the workflow, annual daylight simulations in the offices were conducted, assuming a work shift from 8 a.m. to 7 p.m. (defined as the "occupancy profile") and utilizing the weather file of Turin. The inputs for these simulations were: (1) the horizontal grid on each desk, the same used for field measurements, which provided output measurements of photopic illuminance; and (2) the four view directions in the vertical plane to obtain values of photopic and melanopic illuminances.

$$DGPs = 6.22 \times 10^{-5} E_v + 0.184$$

- E_v: vertical Eye illuminance [lux]

Equation 3.1. Equation of simplified daylight glare probability or DGPs proposed by Wienold. It should be noted that the DGPs model is an accurate metric when there is no direct sunlight.

The necessity of using shading devices was then analysed. Initially, the values of vertical photopic illuminance obtained in the previous step were used to calculate the DGPs (Daylight Glare Probability). When these values were lower than 0.4 (indicating a disturbing glare condition), the model with blinds up was considered. Conversely, if the value exceeded the indicated threshold, the blinds were "lowered" in the model. Specifically, two distinct layers modelled for each office represented the conditions of "blinds-open" and "blinds-closed".

Thus, two annual simulations were obtained, respectively with blinds up and blinds down, which were then merged into a single simulation based on the shading activation profile. The output of this phase provided three illuminance profiles (i.e. two vertical illuminance profiles m-EDI$_{eye_shd}$ and E$_{eye_shd}$, and an horizontal illuminance profile E$_{wp_shd}$).

[9] (Giovannini et al., 2023)
[10] "*Lark v2.0*", in GitHub, Inc. (2024), github.com/larkspectral/Lark_Spectral_Lighting.

The third phase of the simulation work involved calculating the average horizontal illuminance values for each desk at each time step, considering the blinds activation profile. This allowed for determining whether it was necessary to integrate natural light with electric light for each time step. Specifically, since the electric light sources in the offices were not dimmable, when the horizontal illuminance value was below the 500 lx required by the standard (EN 12464-2021, CEN 2021), the electric light was considered to be on, and vice versa. This resulted in three new illuminance profiles that accounted for both the blinds activation profile and the need for electric light integration ($\text{m-EDI}_{eye\_shd+el}$, E_{eye_shd+el}, E_{wp_shd+el}).

3.1.1.1 Combination of sources: Integrative lighting approach

Finally, a combination of the previously obtained results was assessed, "*accounting for electric lighting, daylighting, and the integration of both, from an integrative lighting perspective*"[11]. The entire simulation workflow was managed by a Phyton script.

On the one hand, the annual calculations yielded the percentage of Daylight Autonomy (DA), i.e. the percentage of hours when the office is occupied in which photopic horizontal illuminance levels exceed 500 lux (E_{wp_shd+el}>500lx). On the other hand, the circadian aspect, supported by the values of vertical photopic illuminance and melanopic illuminance, was analysed with reference to the current WELL and CIE recommendations, in particular the WELL criterion, according to which the percentage of occupied time whose m-EDI is less than 163 melanopic lux ($\text{m-EDI}_{eye\_shd+el} \geq$ 163lx) must be at least 4 hours per day and one of those must necessarily be before noon; and the CIE criterion requiring the calculation of the percentage of occupied hours in which the melanopic illuminance value exceeds 250lx.

3.3 Results

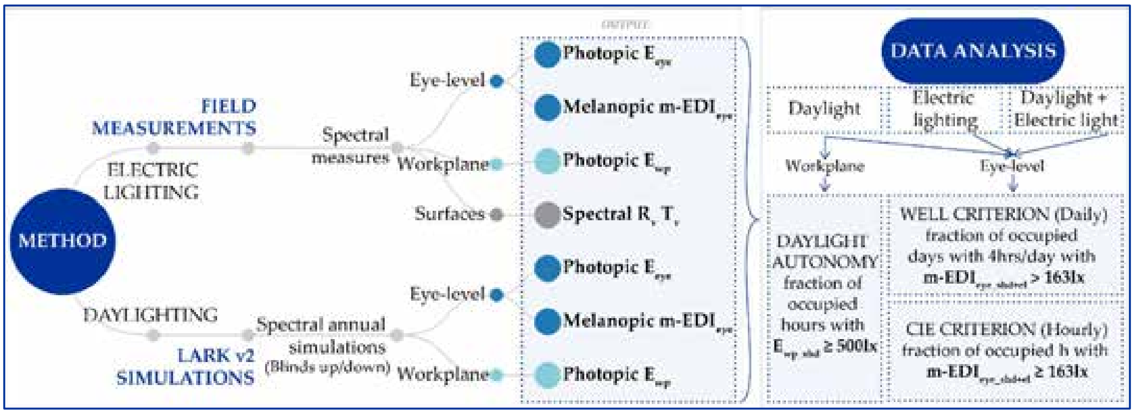


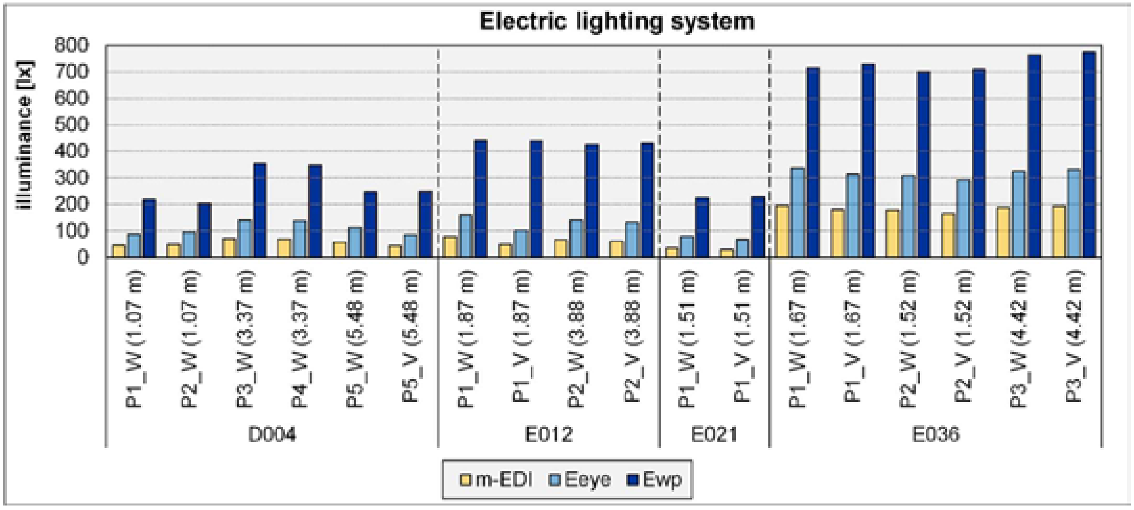
Figure 3.17. Mixed approach outputs, data analysis and results comparison with existing recommendations.

[11] (Giovannini et al., 2023)

3.3.1 Evaluation of lighting conditions

This study presents an electric and daylight analysis within the context of the Polytechnic of Turin offices; the investigation employed both field measurements and simulations to assess such lighting conditions. In the following sections, the results obtained will be analysed and considerations drawn from them, with regard to current regulations (on photopic illuminance) and recommendations (on melanopic illuminance).

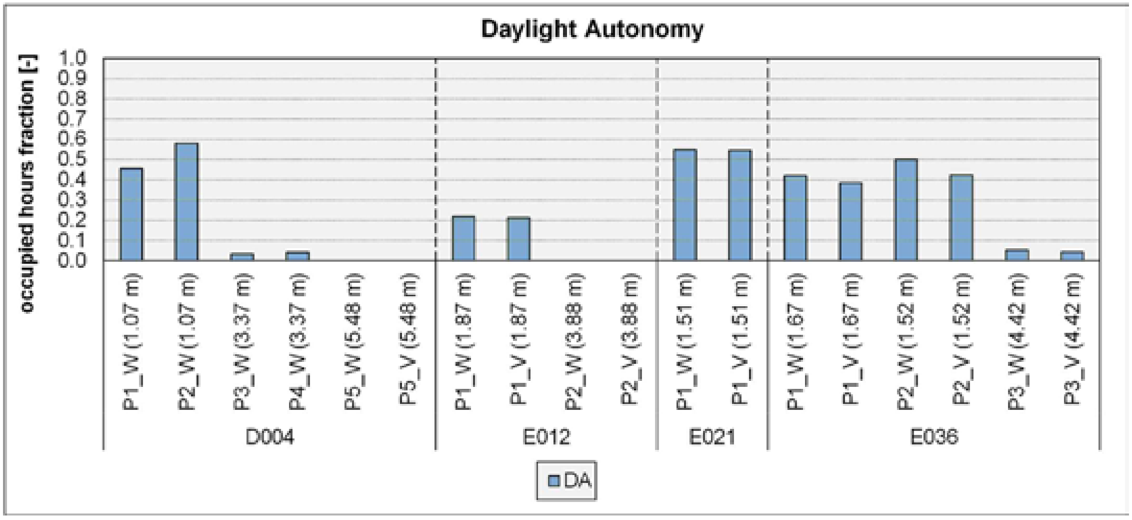
3.3.1.1 Environmental analysis of electric lighting



Graph 3.1. "Results from field measurements: m-EDI$_{eye_el}$, E_{eye_el}, E_{wpe_el} for all the offices". in (Giovannini et al., 2023).

As illustrated in Graph 3.1, field measurements combined results of photopic and melanopic illuminance of electric light, measured both on the workplane and vertically, lead to several observations. According to the EN standard of 500 **lux on the workplane**, only one office (E036) reached the specified value, clearly due to its retrofitted LED lighting system, unlike the fluorescent sources in the other three offices. Office E012, with values between 400 and 500 lux, fell slightly below the threshold. The most critical situations were, however, observed in offices D004 and E021, where the measured values were significantly lower than those specified in the regulations, around 200-300 lux. A similar trend was observed for **m-EDI values**, where office E036 and its LED system recorded values around 165 and 195 lux at every workstation, qualifying for the higher points of the WELL protocol, which requires at least 163 melanopic EDI for 3 points, as detailed in section 1.2.3 of this thesis. Conversely, none of the desk positions analysed in offices D004, E012, and E021 reached even the one-point threshold of 190 melanopic EDI. Furthermore, no office met the CIE recommended value of 250 lux or higher. The difference in lighting systems and the related retrofit clearly played a central role in these results.

3.3.1.2 Daylight from annual simulations



Graph 3.2. "Results from LARK annual simulations: Daylight Autonomy (fraction of time)". in (Giovannini et al., 2023).

Analyzing the **daylight values at the workplane**, simulated through LARK v2 and used to calculate the Daylight Autonomy (DA) metric, two fundamental environmental characteristics must be cited: the amount of visible sky/obstruction from each office, indicated by the VSC value, and the position of each individual desk relative to the window. A significant drop in DA values was, in fact, observed at workstations located more than three meters from the windows. The highest value was recorded in office D004 at the desk closest to the window, while the lowest was in office E021, due to both its distance from the window and a higher VSC rate of 23.7%.

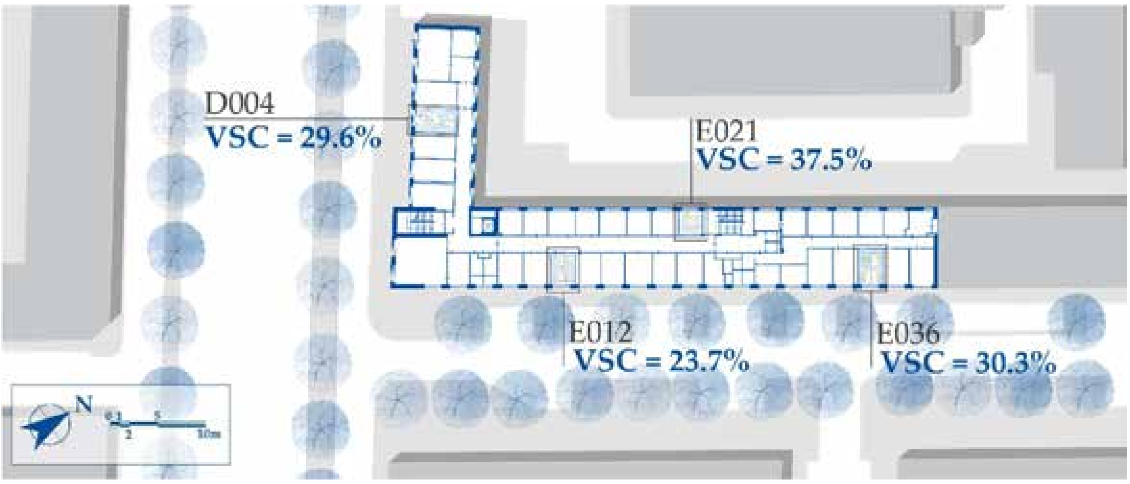
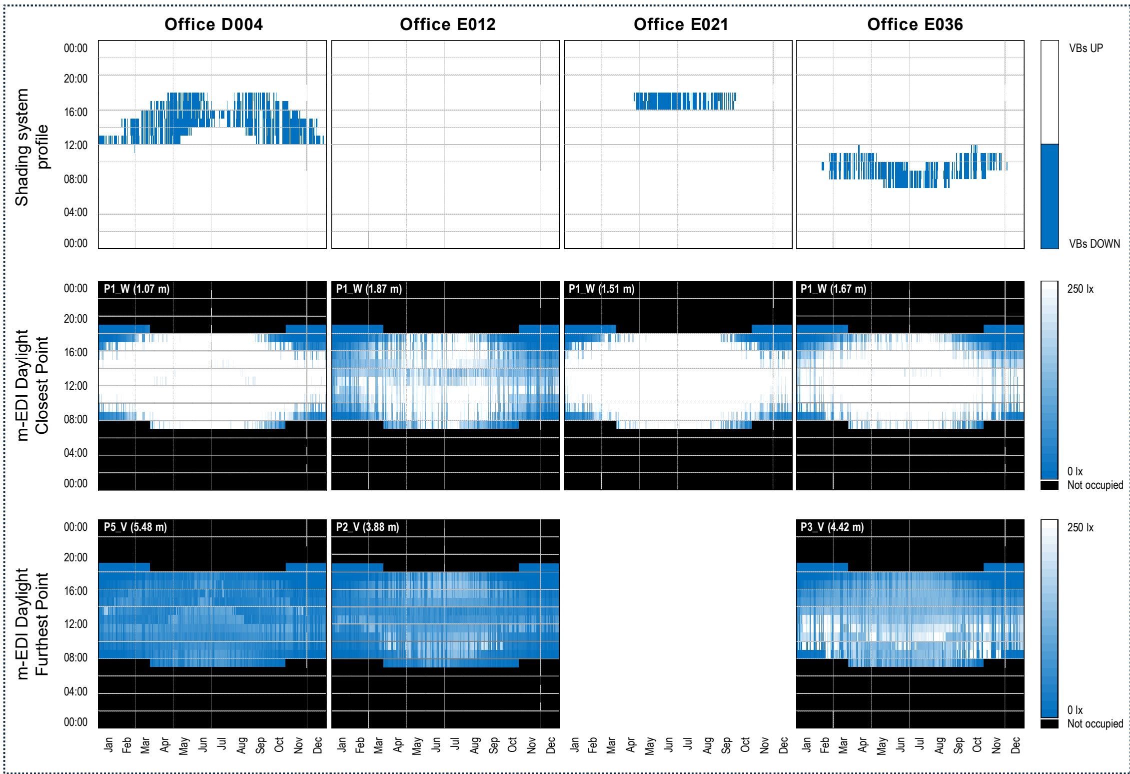


Figure 3.18. Floor plan of case study with context and obstructions and VCS values of the different offices.



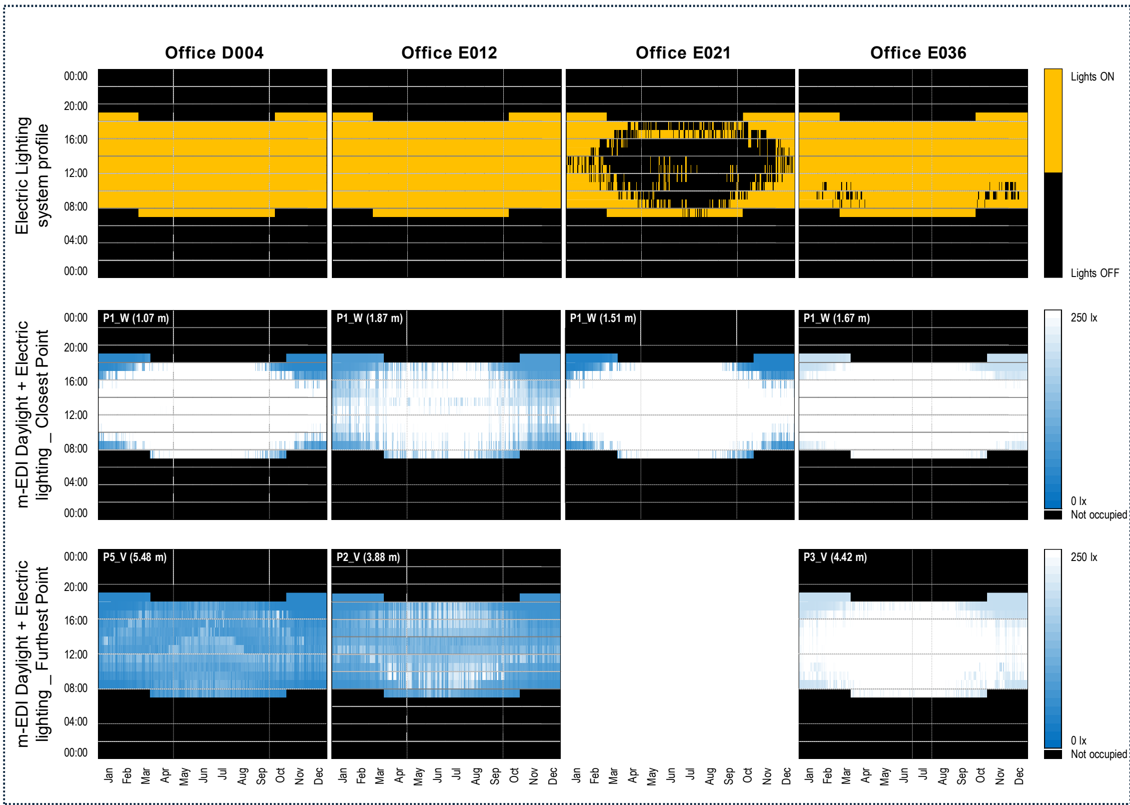
Graph 3.3. “Results from daylight annual simulations (LARK): m-EDI$_{eye_shd}$”. in (Giovannini et al., 2023).

The simulation of **daylight m-EDI values** provided further insights, as illustrated in Graph 3.3. The use of blinds was primarily linked to the orientation of the offices; for instance, occupants of office E036 required blinds mainly in the morning due to its southeast-facing orientation, while offices facing southwest, such as D004, required them after midday. Office E012 (W-WN) had a shading profile limited to a narrow time slot in the late afternoon, while office E012 did not require shading due to external obstructions.

The second and third rows of Graph 3.3. show melanopic illuminance graphs for desks nearest and furthest from the window, a darker colour is indicative of low values and a lighter colour corresponds to high values, up to the colour white for illuminance values from 250 lux upwards. With the exception of early mornings and late evenings in the winter period, all desks situated in proximity to windows in the different offices achieve m-EDI values above the threshold; only office E012, again due to obstructions, showed uneven values. The situation was different for desks furthest from the window: apart from office E021, which had a single occupant close to the opening, values were mostly below the threshold, influenced by both distance and the shading profile. A slight increase in white spots is observable in the graph of office E036.

3.3.1.3 Integration of daylight and electric lighting

By combining the melanopic values of electric light and daylight, considerations can be made about the contributions of both. To ensure adequate illumination for all workstations in an office, the lights needed to remain on throughout the entire duration of the working shift, as shown in Graph 3.4, first row. The exception to this was office E012, which had, again, only one desk requiring lighting and receiving sufficient amounts of it from daylight. In the previous section, it was observed that the outdated fluorescent lighting systems (D004, E012, E021) account for very low melanopic contributions to the environment, particularly in comparison to the LED retrofit of office E036, where values of combined daylight and electric lighting exceed 250 lux almost all year round.

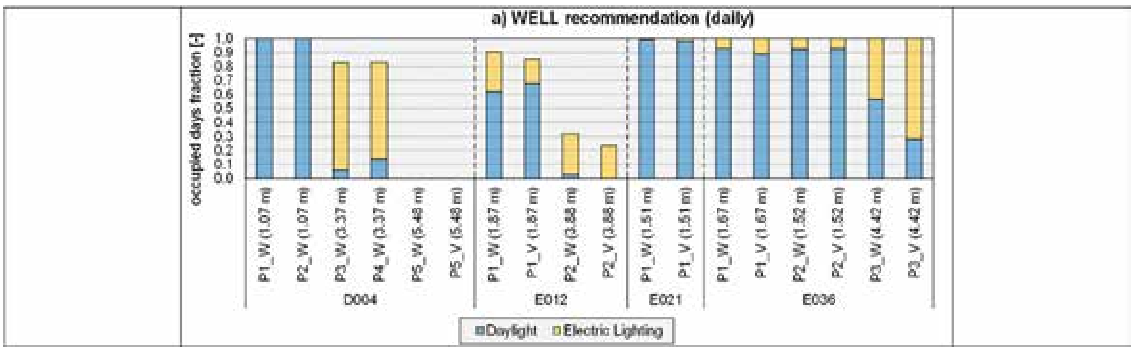


Graph 3.4. "Results combining daylight annual simulations (LARK) and field measurement (electric lighting): m-EDI$_{eye_shd+el}$". in (Giovannini et al., 2023).

3.3.2 Compliance with melanopic recommendations

The findings of this combined methodology provided insights into the performance of lighting systems in office settings, allowing for comparisons and reflections relative to current recommendations.

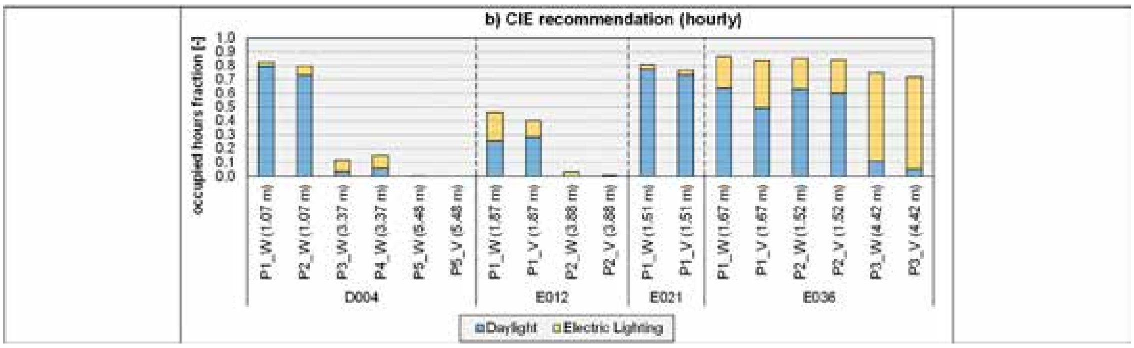
Compliance with WELL recommendations



Graph 3.5. "Compliance of combined electric lighting and daylighting with WELL (3-points credit) recommendations (m-ED_{eye_shd+el} value)". in (Giovannini et al., 2023).

Graph 3.5 shows the percentage of days on which the m-EDI values from both daylight and electric lighting comply with the WELL recommendations, particularly for achieving the 3-point score, resulting in two offices (E021 and E036) qualifying for it. The score was reached due to E021 being a single-desk office with no issues related to window distance and E036 having a recently installed, high-melanopically-performing LED system.

Compliance with CIE recommendations



Graph 3.6. "Compliance of combined electric lighting and daylighting with CIE recommendations (m-ED_{eye_shd+el} value)". in (Giovannini et al., 2023).

Graph 3.6 shows the percentage of days on which the m-EDI values comply with the CIE recommendation (an hour is considered compliant if all workstations show m-EDI ≥ 250 lux). This recommendation is reached once again, for 80% of the time occupied by offices E021 and E036. In office D004, to further emphasise the influence of the distance from the window factor on melanopic values, it can be observed that for desks situated between one and three metres from the window, compliance percentage ranges from approximately 80% down to 15%, respectively.

3.4 Conclusions

The conclusions of this research study were presented in the paper "*Integrative Lighting in Offices: Results from Field Measurements and Annual Daylight Simulations*"[12], as follows:

"Integrative lighting in four offices of the 'Politecnico di Torino' (Turin, Italy) was investigated, in terms of combination of daylighting (simulated on an annual basis through LARK v2) and electric lighting (through field measures). The main results can be summarized as follows:

- *as for daylighting, the combination of orientation, obstruction, and use of blinds mitigated the differences on the melanopic performance for the offices on desks near the window*
- *a huge effect played by the position of the desk was observed: melanopic recommendations were not met through daylighting alone for positions over 3 m from the window*
- *as for electric light, the old lighting systems (fluorescent) did not provide a sufficient illuminance on desks, and accordingly the melanopic content at eye-level was poor; in contrast, the new LED lighting system yielded the highest m-EDI values, mainly due to the high illuminance provided on desk (Ewp > 700 lx); besides, in this office, also the desk farthest from the window qualifies for 3-point WELL recommendation*
- *in general, more research seems to be needed to provide more specific melanopic recommendations, in terms of metrics, target values, and assessment methods, in the perspective of harmonizing the verification of both visual and non-visual effects of light".*

[12] (Giovannini et al., 2023)

List of illustrations, Chapter 3

- Graph 3.4. "*Results combining daylight annual simulations (LARK) and field measurement (electric lighting): m-EDI$_{eye_shd+el}$*". in (Giovannini et al., 2023).
- Graph 3.5. "*Compliance of combined electric lighting and daylighting with WELL (3-points credit) recommendations (m-ED$_{eye_shd+el}$ value)*". in (Giovannini et al., 2023).
- Graph 3.6. "*Compliance of combined electric lighting and daylighting with CIE recommendations (m-ED$_{eye_shd+el}$ value)*". in (Giovannini et al., 2023).

4. Conclusions:

evolution and future prospects of Integrative Lighting

Detailed index

4.1 Development of a discipline in response to human needs

Over the past few decades, architecture has undergone a paradigm shift, with an increasing focus on meeting human needs and the centrality of the individual within the design process. This shift is likely to have originated[1] from the advent of environmental psychology in the 1960s and 1970s, a discipline that explores the influence of environmental factors on human behaviour[2], and consolidated by the publication of "*Designing for human behaviour: architecture and the behavioural sciences*" (1974), a book that marked an important step in the recognition of the importance of considering human behaviour in architectural design, aiming for:

> "*Raising the standards of the designed environment from the present level, which both architects and laymen agree is unsatisfactory, to one which meets human need at as many levels as possible*"[3]

Considering human behaviour as "*anything an individual does in response to internal or external events […] behaviours are physical events that occur in the body and are controlled by the brain*"[4], what was gaining ground in those years was a systemic kind of architecture, which involved analysing the human organism as a system, thus operating from a multitude of perspectives. Concurrently, the phenomenon of participatory architecture was emerging, a design field "*in which groups of people come together to socially co-produce spaces and engage collectively as designers, makers and users or/and occupants of the spatial production*"[5], thus, addressing social issues and individual wellbeing. The union of such topics, including human behaviour, connections and interactions between humans at the social dimension, and systemic architecture, among others, concurs with the Human-Centred Design (HCD) approach. Human-Centred Design focuses first on the need of the individual and the society as a whole, as opposed to a traditional, aesthetic or profit-driven designs[6]. Some early outcomes of human-centred design were evident in approaches directed towards ergonomics and accessibility of spaces. In those very years, in 1961 the American National Standards Institute (ANSI) published a first edition of the ICC/ANSI A117.1 standard entitled "*Accessible and Usable Buildings and Facilities*" which, among other objectives, aimed to facilitate the usability of new and existing buildings for all users, including those with disabilities. In Italy, several years later, law no. 13/1989 entitled "*Provisions to encourage*

[1] As stated by J. Lang et al. in the introductory chapter of Designing for human behavior: architecture and the behavioral sciences (1974), which observed how changes in architectural philosophy of the time were occurring in conjunction with the evolution of the discipline of environmental psychology.
[2] (Devlin, 2018).
[3] (Lang et al., 1974).
[4] (Kwasnicka et al., 2016).
[5] (Calvo et al., 2022).
[6] (Cao, 2024).

the overcoming and elimination of architectural barriers in private buildings"[7] came into force, introducing the issue of architectural barriers and the new challenge of accessibility. On the other hand, the discipline of Human-Centred Design continues to play a significant role in the field of architecture and has been facing recent developments, such as the evaluation of projects through a virtual reality-based user study[8] and parametric modelling software. In simpler terms, a BIM software enables the creation of three-dimensional models of designed environments, which can then be navigated through the use of virtual reality visors, this allows for the comprehension of how a user would interact with the environment, allowing for the collection both subjective and objective data, related to user perceptions, wayfinding, visibility and accessibility, and the understanding of its flaws.

Anthropocentric design (Human-Centred) itself can be summarised in three repeatable steps: design, validation, analysis. That is, architectural designs are validated through use by the individuals themselves, an analysis of their behavioural patterns is made, and modifications to the design are carried out based on the results.

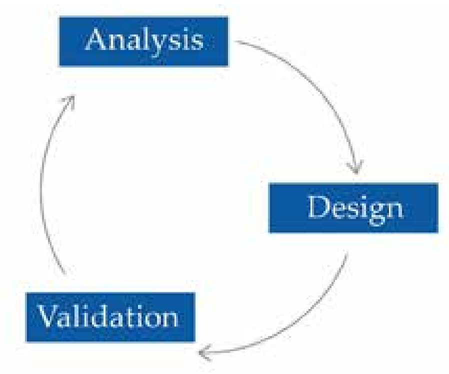


Figure 4.1. Human-Centred design approach in three steps: Design, validation, analysis.

Finally, at the beginning of the 21st century, on the footsteps of the innovations of previous decades, there has been a strong emphasis on issues of quality of life and people's overall wellbeing, also defined as holistic wellbeing, topics often linked to sustainability issues. A first example was the introduction of certifications such as LEED (Leadership in Energy and Environmental Design), which emphasised environmental protection and posed major challenges to improve the quality of life in built spaces. Furthermore, the WELL building standard itself is based on the concept of holistic wellbeing, focusing on various aspects of human wellbeing related to air, water, light, fitness, comfort and mind[9].

[7] Legge 9 gennaio 1989, n. 13, Disposizioni per favorire il superamento e l'eliminazione delle barriere architettoniche negli edifici privati (bosettiegatti.eu).
[8] (Kasparek, 2019).
[9] WELL Building Standard, (2016), Delos Living LLC, New York, NY.

The WELL standard, first published in 2013, actually represented a milestone in wellness-centred design, providing specific guidelines for creating environments that improve the health and wellbeing of occupants. On the same lines, the National Institute of Occupational Safety & Health established the Indoor Environmental Quality (IEQ) standard on thermal, air, acoustic and lighting quality, fundamental since indoor spaces are able to impact "*wellbeing, productivity, health, and safety of occupants*"[10] as well as leading to health problems such as the Sick Building Syndrome (SBS) and Building-Related Illness (BRI)[11]. This shows, once again, the potential of design in responding to the health challenges of today's societies[12].

> *"New approaches of analysis are considered by the scientific community, which put occupants' wellbeing at the centre of the evaluation process and reconsider occupants and buildings interactions […] energy and financial evaluations are accompanied by evaluations on occupant's comfort, health, safety, some of which based on subjective perceptions."*[13]

The term holistic and the attention to wellbeing have therefore spread to all disciplines within the broad field of architecture, including lighting design.

> *"A holistic lighting design evaluation requires the inclusion of multiple effects of light."* [14]

4.2 Lighting standards evolution

Integrative Lighting represents a novel field of study based on a spectrum of existing disciplines, it is a synthesis of established knowledge and current research, and as such, it is significantly evolving in recent years. Its development has had an impact on current international lighting standards, which until a few years ago focused exclusively on ensuring visual task and comfort. At present, some non-visual aspects can be found in them, but no specific standard value has yet been established. The following section examines the evolution of lighting design standards at the international levels, focusing on those aspects that may have implications for the future of integrative lighting and its introduction into design standards.

As a premise: The text mainly mentions international organizations for standards such as ISO, CIE, CEN and IES. Specifically, ISO standards refer to the International Standardization Organization, an independent, non-governmental organization that operates globally through hundreds of technical committees on a wide range of topics including technology, manufacturing, safety and health. While, the International

[10] (Leccese et al., 2021).
[11] (Jayasooriya et al., 2022).
[12] (Leason and Nickpour, 2022).
[13] (Leccese et al., 2021).
[14] (Bochnia et al., 2022).

Commission on Illumination, or Commission internationale de l'éclairage (CIE), also an independent world-wide co-operation organisation, deals purely with light and lighting issues, providing standards and guidelines for the illuminated environment. To avoid overlapping on light standards between the ISO, CIE and also IEC (International Electrotechnical Commission) commissions, in 1986 the three organisations signed a Memorandum of Understanding (MoU), which recognizes and distinguishes the objectives of each intitution. Further, a few years later, in 1989, the International Organization for Standardization (ISO) formally recognised the CIE as an international standardisation body, as stated in Council Resolution 10/1989. European Standards (EN) are technical standards developed by CEN (European Committee for Standardisation) in collaboration with CENELEC (European Committee for Electrotechnical Standardisation) and ETSI (European Telecommunications Standards Institute), which serve as guidelines for innovation and new technologies. CEN collaborates with the supranational organism of ISO with the aim of harmonising the various national directives. Finally, the IES (Illuminating Engineering Society) is a recognised authority in terms of illumination, that published tens of standards through its American National Standards Institute (ANSI) along the years.

Figure 4.2. International Commission on Illumination (CIE); International Standardization Organization (ISO); European Committee for Standardisation (CEN); Illuminating Engineering Society (IES) organisations' logos.

Because of the MoU previously mentioned, the CIE took the lead in issuing recommendations on lighting matters. The work of the CIE is spread over seven technical committees divided by topic of investigation, including the committee that deals with reasoning on the principles governing photometry (JTC2), JTC4 dedicated to identifying the role of windows in buildings on vision, health and well-being and the one dedicated specifically to the energy performance of lighting in buildings (JTC6), to name a few. Over the years, the CIE has been crucial to the evolution of indoor lighting standards and guidelines thanks to the enormous amount of research carried out by these committees and international cooperation; and today still represents a key reference for new research contributions to lighting practice. In cases where standards have been approved by both the CIE committee and the ISO organisation, joint ISO/CIE standards may be produced.

The following discussion on indoor lighting evolution will be assisted by the current norms contained in the international standards "ISO 8995-1:2002 - *Lighting of workplaces (Part 1: Indoor)*" which was last reviewed and confirmed in 2018 and "ISO/CIE TR 21783:2022 - *Integrative Lighting*"; with reference also to national and European standards, in particular the "EN 17037:2018 - *Daylight in Buildings*" and the greatly referred to European standard "UNI-EN 12464-1:2021 – *Light and Lighting - Lighting of workplaces*" (replacing the previous "UNI 10380/A1/1999 – *Interior lighting with artificial light*"), including all their multiple revisions and updates.

• ISO 8995-1:2002	*Lighting of workplaces (Part 1: Indoor)*
• ISO/CIE TR 21783:2022	*Integrative Lighting*
• EN 17037:2018	*Daylight in Buildings*
• UNI-EN 12464-1:2021	*Light and Lighting - Lighting of workplaces*

4.2.1. Visual performance

"When they appeared in the first half of the last century, indoor lighting standards had a simple function – to ensure the visibility of tasks."[15]

The primitive norms of lighting literature initially offered only value indications regarding the performance of visual tasks in relation to different functions. References on parameters such as light distribution and intensity or contrast and relative values designed for specific tasks were already present in the first half of the 1900s, where in America, for example, reference was made to the IES standard[16]. Such values, however, were soon proved to be invalid, as pointed out by Tinker, according to which: *"Recommendations for the light intensities needed for specific visual tasks […] are based largely upon misinterpreted data and consequently are not valid"*[17].

[15] (Boyce et al., 2022)
[16] *American Recommended Practice of School Lighting*, 1938.
[17] (Tinker, 1939).

Until 2004, the standards UNI 10380/A1/1999, UNI EN ISO 9241/2001 " *Ergonomic requirements for office work with visual display terminals (VDTs)*" and UNI EN 12464-1/2004 "*Lighting of workplaces. Part 1: Indoor workplaces*" only defined the parameters useful to facilitate lighting design and the limit values for each visual task; without considering ambient values of brightness.

Currently the most widely used indoor lighting standard, *EN 12464-1 Light and Lighting - Lighting of Workplaces - Part 1: Indoor Work Places*, lists as parameters for the performance of visual tasks the maintained average illuminance ($\bar{E}_m$), the illuminance uniformity (U_o), the general colour rendering index (Ra) provided by CIE (and often referred to as the Color Rendering Index, CRI) and the unified glare rating (R_{UGL}), useful in performing visual tasks but at the same time essential for visual comfort.

Another fundamental standard is *ISO 8995 - CIE S 008/E - Lighting of Indoor Work Places*, developed in collaboration with the CIE International Commission on Illumination[18], and consisting on the revision of a first edition (ISO 8995:1989). It contains specification of visual tasks values of parameters such as luminance distribution, illuminance, glare and uniformity of the illuminance.

International standards are usually transposed and adapted by individual states through dedicated legislation, which shows how open they are to interpretation and how, despite the developments of the practice, there are no truly universally accepted values. Thereby demonstrating that the evolution of the standards has not yet reached an end. With reference to the two standards, EN 12464-1 and ISO 8995 - CIE S 008/E, most national legislation includes specific values of: minimum illuminance levels on work planes, minimum illuminance when working on computers, minimum illuminance in the surroundings, luminance ratios near task areas and glare rating other than visual comfort related values.

The following diagrams, although not up-to-date with the latest publications, represent an overview of the indications provided by the different states following the publication of the international standard ISO 8995-1 - CIE S 008/E and how such values vary from each other and from the international indications themselves. The figure represent a reworking of the diagrams provided by C. Martinsons in the "*Guidebook on Energy Efficient Electric Lighting for Buildings*" updated as of 2010.

[18] "*International Standard ISO 8995 was prepared as Standard CIE S 008/E by the International Commission on Illumination, which has been recognized by the ISO Council as an international standardizing body. It was adopted by ISO under a special procedure which requires approval by at least 75 % of the member bodies casting a vote, and is published as a joint ISO/CIE edition.*" ISO 8995 - CIE S 008/E - Lighting of Indoor Work Places.

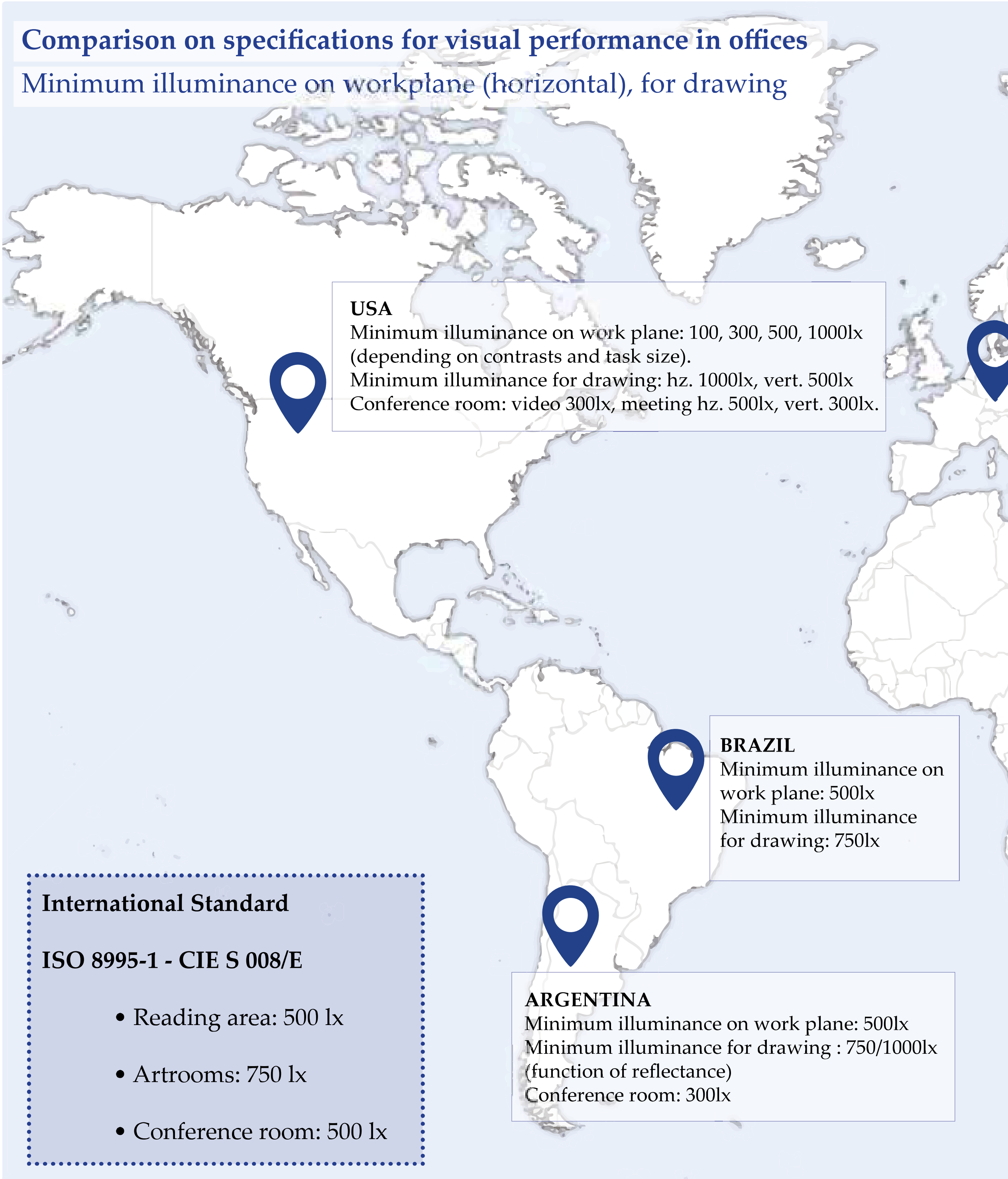

Comparison on specifications for visual performance in offices
Minimum illuminance on workplane (horizontal), for drawing
USA
Minimum illuminance on work plane: 100, 300, 500, 1000lx
(depending on contrasts and task size).
Minimum illuminance for drawing: hz. 1000lx, vert. 500lx
Conference room: video 300lx, meeting hz. 500lx, vert. 300lx.
BRAZIL
Minimum illuminance on
work plane: 500lx
Minimum illuminance
for drawing: 750lx
ARGENTINA
Minimum illuminance on work plane: 500lx
Minimum illuminance for drawing : 750/1000lx
(function of reflectance)
Conference room: 300lx
International Standard
ISO 8995-1 - CIE S 008/E
• Reading area: 500 lx
• Artrooms: 750 lx
• Conference room: 500 lx

Figure 4.4. Minimum illuminance on work plane (horizontal) for drawing and minimum illuminance on conference rooms. From Martinsons C., (2010), Guidebook on Energy Efficient Electric Lighting for Buildings.

4.2.2. Ambient brightness

The UNI 10380 standard as well as the 2004 edition of UNI-EN 12464 still did not provide any value or indication on the aspect of ambient illuminance. It was only with the modification of the UNI-EN 12464 standard in the 2011 publication that values for vertical illuminance and brightness appearance were first introduced. Initially presented solely in the text, these values were subsequently included in the 2021 edition inside the tables, with the designation of $\bar{E}_{m,\ wall}$ (maintained illuminance on walls) and $\bar{E}_{m,\ ceiling}$ (maintained illuminance on ceiling).

> *"Maintained wall and ceiling illuminances ($\bar{E}_{m,\ wall}$, $\bar{E}_{m,\ ceiling}$) have been added to provide for 'brightness appearance of rooms'. This latter set of requirements may be seen as the regulators responding to concerns for attention being given to how lighting influences the appearance of the space and its contents"*[19].

Proper distribution of light within a room not only ensures functional illumination for tasks but also enhances the overall appearance and perception of the space, reflecting a growing concern about how lighting influences the perceptual qualities of an environment. These evolutionary stages of the standard show how in those years lighting practice began to move away from a focus on illuminance values only to a luminance-based approach. To clarify this concept and understand its implications, it is necessary to recall, in extremely simplified terms, how illuminance measures the light that hits a surface and luminance measures the light that reaches the eyes from a surface. The luminance-based approach, therefore, aims to put the perception of the person at the centre of design practice.

4.2.3. Visual comfort

As seen, the initial indoor lighting standards were designed to facilitate visual tasks. Over time, however, they were expanded to include visual discomfort issues[20], thus characterizing the relationship between light and human needs and consequently providing values that ensure visual comfort. This included considerations about amount of light and relative glare, uniformity of lighting, light quality in rendering colours, etc. In terms of terminology, visual comfort can be defined as a subjective response to quantity and quality of light within a given space and time, as in the EN 12665:2011 "*a subjective condition of visual well-being induced by the visual environment*", where the term 'subjective' is used to describe the intrinsic diversity of the human species, particularly in relation to its eye physiology; while the term 'visual environment' encompasses the quantity and distribution of light in space, as well as its emission spectrum. It is important to note that both insufficient and excessive light can cause visual discomfort.

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[19] (Boyce et al., 2022).
[20] ibidem.

Recognizing the importance of vertical illuminance, modern lighting standards increasingly emphasize its measurement and integration into lighting design. Measuring vertical illuminance is, in fact, essential for assessing and achieving visual comfort in various settings, since it influences how individuals perceive and interact with their environment, contributes to spatial perception, address glare, etc.

As an example, the colour rendering index Ra, specified in the EN 12464-1 is an useful parameter for both visual performance and the feeling of comfort. This is because it ensures that the colours of objects and human skin are accurately represented in their natural state.

The inclusion of glare in the lighting standards dates back to at least 1921, when the IES[21] stated as a rule for correct design of workplaces the need to avoid glare by correctly installing luminaires at certain heights, positions and with certain accessories to avoid visual discomfort, but without providing mathematical formulas for such design. In an attempt to avoid glare, the 1942's Australian standard code for the artificial lighting of buildings provided values of specific hights (in meters) and maximum luminances (in cd/m2). Scientists[22], in the following years, determined a reliable estimation of the "*borderline value between comfort and discomfort (or BCD)*"[23] and "*attempted to determine the Position Index for a source below the line of vision*"[24], the last one being a significant contribution, currently incorporated into all contemporary glare metrics. Those were the first years in which glare formulas, functions and scales[25] were assessed. It was then in the '60s that the Luminance Study Panel of the British Illuminating Engineering Society determined a first standard based on such studies, the IES Glare Index. Not long after that, IESNA published, in 1966 the new metric of Visual Comfort Probability (VCP), still in use and recently updated in the IES Lighting Handbook. However, over the years, the standard practice seemed to prefer other metrics, such as the CIE Glare Index (CGI) and the Unified Glare Rating (UGR)[26], discussed in depth and revised in numerous CIE publications such as the "CIE 55-1983: *Discomfort Glare in the Interior Working Environment*", the "CIE 117-1995: *Discomfort Glare in Interior Lighting*", the "CIE 146/147:2002 : *CIE Collection on Glare 2002*" and the most recent "CIE 190:2010 *Calculation and Presentation of*

[21] Code of lighting factories, mills and other work places/American standard, approved Dec. 31, 1921, by American engineering standards committee.
[22] M. Luckiesh and S.K. Guth.
[23] (Jakubiec, 2022).
[24] (Iwata & Tokura, 1997).
[25] Petherbridge and Hopkinson scale model, estimating glare in terms going from "*just intolerable*" to "*just imperceptible*"; Holladay's 12-point subjective scale containing terms like "*barely pleasant*" or "*less comfortable*".
[26] From the IES definitions (ies.org/definitions): "*The Unified Glare Rating, UGR is a measure of the discomfort produced by a lighting system along a psychometric scale of discomfort. *UGR is used in many parts of the world as an alternative to visual comfort probability (VCP).*" *CIE 117-1995, Technical Report: Discomfort Glare In Interior Lighting. Vienna, Austria: CIE; 1995

United Glare Rating Tables for Indoor Lighting Luminaires". As for today, the International Commission on Illumination (CIE) has recognised the Unified Glare Rating (UGR) as the glare standard.

4.2.4.Context modifiers

In recent editions of lighting standards, there has been an increasing shift towards prioritizing user-centric parameters. This evolution is evidenced by the introduction of the modified illuminance value (modified $\bar{E}_m$), a concept that adapts lighting task values based on specific characteristics, including those related to individual differences. This is due to the presence of substantial interindividual differences in light sensitivity[27] between diverse population groups—such as children, seniors, shift workers, and healthcare patients—, which consequently exhibit distinct lighting needs[28]. Such modifier works as follows: "*The 'required' value of* $\bar{E}_m$ *for a category of task or activity area is the value that applies for normal circumstances, but this value may be increased or reduced by one or two steps according to 'common context modifiers'.*" The modified $\bar{E}m$ value, therefore, may be increased by up to two steps above the 'required' value to better suit specific conditions.

This approach ensures that lighting design accommodates both the general requirements of the task and the individual needs of users, enhancing overall visual comfort and performance.

4.2.5.Non-visual health

Latest standards publications are beginning to address the issue of non-visual health and well-being, recognising the role of ipRGCs[29]. This is in line with the conclusions of the CIE deliberations, which, for example, if previously (in the ISO/CIE 2005's edition) only dealt with the photopic and scotopic curves and relative photoreceptors cones and rods, subsequently in the context of the CIE S026:2018 - *CIE alpha-opic action spectra*, identified and described the five new photoreceptor types capable of stimulating non-visual effects and their action spectra, included the melanopsin photopigment and its sensitivity.

Consequently, there is increasing recognition of the role of daylight in lighting standards, not only related to the issue of energy consumption, but also for issues of human well-being. At present, the subject is dealt with in a descriptive manner in the latest publications, but they do not yet present any requirements for design.

[27] (Phillips et al., 2019).
[28] (Lowden et al., 2019); (Riemersma-van der Lek et al., 2008); (White et al., 2013).
[29] ISO/CIE TR 21783:2022 | ISO/CIE TR 21783 - *Light and lighting — Integrative lighting — Non-visual effects*.

In accordance with this discourse, the delineation of appropriate Illuminants took place in parallel. Starting from the I.C.I. 1931's international agreement adopting as colorimetry standards the Illuminants A, B, and C. where in particular, "*Illuminants B and C consist of Illuminant A plus a filter. Illuminant B approximates a blackbody source operating at 4,800 K; it is used by the British as their daylight standard. Illuminant C approximates daylight provided by the combination of direct sun and clear sky light having a color temperature of approximately 6,500 K*"[30]. Subsequently, ISO 11664-2:2007 *Colorimetry, Part 2: CIE standard illuminants* specified two illuminants for use in colorimetry; the CIE standard illuminant A and the CIE standard illuminant D65. This document has, then, been withdrawn and replaced by the EN ISO/CIE 11664-2:2022 where three CIE standard illuminants are established for use in colorimetry: "*CIE standard illuminant A for the representation of typical tungsten-filament lighting, CIE standard illuminant D65 for the representation of average daylight having a correlated colour temperature of approximately 6500 K and CIE standard illuminant D50 for the representation of daylight with a correlated colour temperature of approximately 5000 K*"[31].

4.2.6.Standards future directions

From the initial development of parameters to the subsequent specification of values via the use of tables, and finally to the modification of these parameters or even the integration of further ones, lighting standards continue to evolve in conjunction with research. By observing this evolution, some of the directions that standards are taking are clear. As for now, latest standards insights have been given about the need to maximize the input of daylight, with the integration of electric lighting only when necessary, in an integrative lighting approach. Following this integrative lighting approach the first and foremost step will be the inclusion of the melanopic Equivalent Daylight Illuminance (mel-EDI) parameter in future lighting standards, or include a refined metric on the same line of mel-EDI (ex. a metric able to include both melanopic and cyanopic illuminance[32]); by addressing both visual and non-visual effects of light, these standards will support circadian health, enhance well-being, and promote personalized lighting solutions. This inclusion will be necessary through tables of values considering different environments, people characteristics and contexts. In general, as suggested by J. Alstan Jakubiec, assistant professor at the University of Toronto and currently researching on the topic of comfort and perception, "*As certain certification systems require or suggest continuous monitoring to verify design performance, post-occupancy evaluations of comfort and well-being monitoring would be very welcome in future practice*"[33]. Encouraging the current emphasis on the analysis and development of high-energy performance buildings to be aligned by a parallel attention on general human well-being.

[30] Illuminating Engineering Society, 2nd edition, (1952) New York: IES.
[31] EN ISO/CIE 11664-2:2022 - *Colorimetry Part 2: CIE standard illuminants*.
[32] (Huang et al., 2023).
[33] (Jakubiec, 2022).

4.2.7. Summary

The evolution of lighting standards reflects a progressive understanding of the multifaceted effects of light on humans. From the beginning of the XX century, this evolution has gone through certain steps.

Initially, lighting standards were primarily developed to ensure adequate illumination for visual tasks, such as reading, writing, and doing detailed work. These standards focused on parameters such as illuminance levels, luminance distribution, and contrast to facilitate visibility and visual performance in various environments. Then, a step was made in the direction of ambient brightness, allowing to assess the appearance and the perception of a space. It is at this moment that vertical illuminance starts to gain influence, ultimately becoming more influential than horizontal illuminance in lighting design practice. As the field of lighting design advanced, attention expanded beyond mere task illumination to enclose visual comfort. This shift recognized that lighting could cause visual discomfort through glare, flicker, or inappropriate light distribution and thus was directed towards ensuring that lighting not only enabled visual tasks but also provided a comfortable visual environment. Parameters such as glare indices, uniformity ratios, and flicker rates were introduced to address these concerns, improving the overall visual experience and preventing strain and fatigue. At this stage, attention to different human and environmental characteristics enters the regulations through modified illuminance. In recent years, a significant paradigm shift has been observed with the introduction of non-visual effects of light, starting from the raising importance given to daylight and the necessity to manage it properly. This shift is informed by a growing body of research highlighting the profound impact of light on human circadian rhythms, mood, and overall health. The discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) and the photopigment melanopsin, which influence non-image-forming responses to light, has been pivotal in this regard. These findings have prompted the development of guidelines that consider spectral power distribution, timing, and duration of light exposure to support circadian health and physiological and psychological wellbeing, through the use of specific and newly developed non-visual parameters, such as mel-EDI, that soon needs to be integrated in standards.

This standards evolution highlights the dynamic nature of the field and its responsiveness to emerging scientific insights, paving the way for lighting practices that prioritize holistic human health and wellbeing while expressing the need for further research to standardize these advancements effectively. Indeed, the collected observations and the growing body of evidence clearly prove how Integrative Lighting will be the future of lighting practice. Human needs will be central in this field, as well as in numerous other fields of design, reflecting a comprehensive approach that prioritises health, comfort, and overall quality of life.

4.3. Conclusions: Implications in design guidelines

The standards shift towards human-centric design principles is set to redefine best practices and guidelines, ensuring that the built environment serves to enhance the human experience in multifaceted ways.

However, the above considerations suggest that the purpose of standards is the prevention or elimination of bad lighting, through a series of requirements, but without addressing the methods and approaches to be applied. Then how can good lighting be achieved? By distinguishing between standards and guidelines. Guidelines should actually be formulated *"as to encourage good lighting by providing advice that encourages practitioners to match their lighting solutions to the opportunities presented by different locations and applications"*[34].

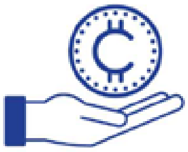
The following is a list of possible design guidelines useful to achieve future Integrative Lighting requirements, derived from the research results observed through the literature review, the findings made through the case study and the observations provided in the bibliography consulted:

- **Accord primary importance to daylight:** The design should maximise the input of daylight, since incorporating natural light into building designs supports circadian health, as advocated by standards like EN 17037:2018 or researchers such as M. Boubekri (2008), which underscores the vital role of daylight in architectural designs, impacting human health and productivity. In order to achieve this, the design of the apertures is crucial, as observed during the case study analysis where the variation of the distance from the apertures radically affects the supply of melanopic light to the eye[35]. Furthermore, the design of daylight cannot be achieved without a careful analysis of location and attention to seasonal variations[36].

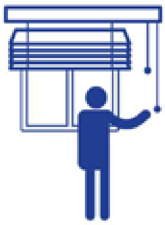
[34] (Boyce et al., 2022).
[35] (Giovannini et al., 2023).
[36] (Ravn et al., 2022).

- **Dynamic lighting systems:** In the case of insufficient daylight to reach the recommended levels, it is required to intervene with the integration of electric lighting. Dynamic lighting systems are suggested since they are able to mimic natural daylight patterns. It is essential to implement dynamic lighting patterns, especially in environments without natural daylight, to combat mental fatigue[37], enhance alertness, and improve cognitive performance and in general to support circadian rhythm stability and improve sleep quality, in fact, strong lighting in the morning and gradually decreasing light in the evening can enhance circadian rhythm alignment[38].

- **Energy-efficient lighting solutions:** Use dimmable luminaires and spectral tuning to adjust lighting based on daylight contributions, façade orientation, and seasonal changes can be another solution to the issues expressed above. Furthermore, this approach can balance both well-being with energy savings.

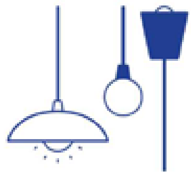


- **Optimizing shading systems:** The demand for high melanopic values at the eye level and the need to maximise daylight result in critical issues, including glare. To compensate for this, the direction should be to design shading systems able to prioritize daylight availability during peak circadian response times (e.g., 9 AM to 1 PM) and to adjust to reduce glare or excess light in the afternoon. This can enhance natural light benefits while maintaining comfort.

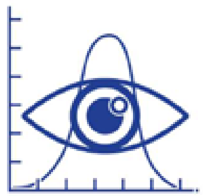


[37] (Li et al., 2022).
[38] (Wang et al., 2022).

- **Direct and indirect lighting strategies:** Another potential solution to the issue of glare while still maintaining the requisite levels is the utilisation of direct or indirect lighting strategies. The adoption of indirect lighting, for instance, can effectively mitigate glare and shadows through diffused lighting. In general, if the use of traditional lighting systems is unable to attain the requisite levels without encountering critical issues such as glare, it becomes necessary to adopt or even develop new lighting systems.



- **Spectral considerations:** More specifically, a designer can also decide whether or not to use a spectrum that stimulates the eye the most, depending on the goals set. For example, it can be useful to opt for light sources with higher colour temperatures (e.g., 6000 K) during the day to enhance circadian stimulation. Avoid high-intensity short-wavelength light exposure in the evening to prevent circadian disruption[39]. "*Priority should always be given to daylight; otherwise, a polychromatic white source with higher spectral irradiance in the short-wavelength part of the visible spectrum could be a supplement*"[40].

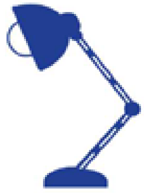


- **Autonomous lighting controls:** The implementation of automated lighting controls represents a viable strategy for optimising circadian lighting exposure. Systems that adjust lighting based on time of day and user activity have the potential to enhance both visual and non-visual benefits. An example can be Luminaire-Level Lighting Control (LLLC) systems[41].

[39] (Bellia et al., 2023).
[40] (Brown et al., 2022).
[41] (Rockcastle & Mahic, 2024).

- **Consideration of architectural features:** Optimize window design[42], glazing properties[43], and interior surface colours[44] can be an excellent approach to maximize non-visual light exposure. High-transmittance, blue-enriched glazing and neutral-coloured walls can enhance circadian entrainment, for example.

- **Task lighting in offices:** Supplement ambient room lighting with high-melanopic-illuminance task lighting[45] has been proved to improve daytime cognition, alertness, and overall well-being without causing visual discomfort. Task lamps supplement eye-level exposure and balance energy efficiency with adequate circadian lighting. Focusing on vertical lighting strategies reduce the load on overhead lighting systems.



- **Recognizing diverse human characteristics:** A final design suggestion that has emerged from the body of information gathered through this thesis, is the importance of considering the different human characteristics and in particular of the occupants, in contrast to the current approach according to which studies for the determination of normative levels were conducted on enucleated eyes, "*even the updated European norms (prEN 12464-1 2019) that are supposed to address the higher lighting needs of the seniors do not take into consideration the possible different characteristics of people*"[46]. This will allow designers to increasingly embrace a Human-Centric perspective.

By following these guidelines, such as addressing light spectrum and time-related issues, improving light modulation and so on, lighting designers can create environments that support both visual comfort and non-visual health benefits, optimizing the overall well-being and performance of building occupants.

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[42] (Giovannini et al., 2023).
[43] (Chen et al., 2019).
[44] (Potočnik & Košir, 2020).
[45] (Grant et al., 2023; Roy et al., 2024)
[46] (Labiris et al., 2021).

List of illustrations, Chapter 4

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Annex A

1.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
1	3	Rockcastle, S., & Mahic, A. (2024). Simulating the annual energy demand to meet non-visual health recommendations from a luminaire level lighting control system. Energy and Buildings, 303, 113772. doi.org/10.1016/j.enbuild.2023.113772	This paper introduces a digital simulation workflow that calculates annual eye-level illuminance and energy demand from daylight and electric lighting sources for an array of view positions across 9-channels of spectral data. This Radiance-based workflow combines parts of the LARK spectral lighting code to offer better spectral resolution and accuracy when computing melanopic lx to evaluate the non-visual health potential for view positions within a digital model. The authors have implemented a series of annual climate-driven simulations and post-processed time-series of resulting data using the R statistical analysis software to compute Equivalent Melanopic Lux (EML) and energy demand (kWh) for an array of view positions and view directions in a digital model. This allows us to compute the energy demand of a given lighting and shading control scenario, which is optimized by hourly daylight availability to meet a recommended level of melanopic lx. This combined workflow uses digital models of an interior space to evaluate the annual potential of non-visual light exposure under different architectural, lighting, and shading control scenarios. This paper demonstrate the utility of this workflow by evaluating a luminaire-level lighting controls (LLLC) system to meet eye-level light exposure recommendations from the WELL Building Institute Feature L03 Circadian Lighting Design and compare the energy demand between targeted melanopic lux thresholds and shading control scenarios.	Building Simulation, Daylight, Energy Demand, Lighting controls, Non-visual health, Shading controls
2	10	Putte, E. V. de, Kindt, S., Bracke, P., Stevens, M., Vansteenkiste, M., Vandevivere, L., & Ryckaert, W. R. (2022). The influence of integrative lighting on sleep and cognitive functioning of shift workers during the morning shift in an assembly plant. *Applied Ergonomics* , *99* , 103618. https://doi.org/10.1016/j.apergo.2021.103618	It is well known that exposure to light at the right time of the day is important to synchronise our circadian rhythm and enhance cognitive functioning. There is, however, a lack of field studies investigating which lighting characteristics are necessary to improve sleep and cognitive functioning. A controlled field study with 80 shift workers was set up, in which the impact of an integrative lighting (IL) scenario was investigated during the morning shift. Two groups were compared: a control group (no change in lighting settings) and a IL-group (exposed to a melanopic Equivalent Daylight Illuminance of 192 lux, i.e., bright light with a high fraction of short-wavelengths). Pre-post measurement of visual comfort, cognitive functioning (D2 task, go-nogo reaction time task) and sleep (MotionWatch8) were performed. The IL-settings ameliorated sleep efficiency and sleep latency during morning shift and enhanced alertness (not inhibition) compared to standard lighting conditions. Changing lighting settings in an industrial setting should be considered as it seems worthwhile for employees' sleep and cognitive performance.	Lighting, Circadian rhythms, Light, Sleep, Cognition, Integrative lighting, Melatonin, Daylight illuminance, circadian rhythm, Sleep research, adult, Humans, practice guideline, illumination, sunlight, cognition, controlled study, human experiment, light exposure, alertness, mental performance, outcome assessment, working time, Assembly plants, attention, comfort, Control groups, factory worker, field study, longitudinal study, morning shift, shift worker, sleep efficiency, sleep quality
3	17	Stebelová, K., Kováčová, K., Dzirbíková, Z., Hanuliak, P., Bacigál, T., Hartman, P., Vargová, A., & Hraška, J. (2024). The effect of spectrally and intensity-modified daylighting on urinary melatonin levels in office workers under real-life conditions. *Building and Environment* , *247* , 111025. doi.org/10.1016/j.buildenv.2023.111025	Light is the main entrainment agent of the circadian system and has an important effect on the synchronization of biological rhythms. Technical innovations in buildings with advanced glazing systems or shadings can lead to changes in daylight spectral composition in indoor spaces. Our study aimed to find out the effect of a short-wavelength light-reduced environment on the main hormone melatonin metabolite 6-sulfatoxymelatonin in urine (u-sMEL) and to test the connection between light exposure from the previous day and u-sMEL. Twenty-two participants spent five consecutive working days in the office under normal daylight conditions (reference) followed by five days in spectrally modified light conditions (experimental). The light environment was modified by the blue light-blocking glazing system, which significantly reduced melanopic illuminance in the experimental week. Three urine samples were collected daily and u-sMEL concentrations were measured by ELISA. Light exposure was monitored at the participant's eye level with LightWatcher and in the office by a stationary spectrophotometer. The reduction of short-wavelength light during the day did not change the concentration of u-sMEL. In the reference week, there was a positive correlation between personal photopic illuminance and u-sMEL. Both morning and work illuminance under reference conditions influenced u-sMEL production. The significant impact of illuminance on u-sMEL was found by evaluation of the mean of all three urine samples. In the experimental week, the correlation between illuminance and u-sMEL was not found. The short-wavelength and intensity reduction in interiors led to changes in the response of the human biological system to light.	Daylight, Lighting, Personal light datalogger, Short-wavelength light reduction, Hormones, Condition, environmental conditions, 6-sulfatoxymelatonin, Datalogger, daylight, Glazes, Glazing systems, hormone, Light reductions, metabolite, Metabolites, Office buildings, Office environments, Short wavelengths, urine, wavelength
4	18	Schledermann, K. M., Bjørner, T., West, A. S., & Hansen, T. S. (2023). Evaluation of staff's perception of a circadian lighting system implemented in a hospital. *Building and Environment* , *242* , 110488. https://doi.org/10.1016/j.buildenv.2023.110488	Natural and electrical lighting have received attention in hospital environments due to their ability to increase hospital staffs' performance, improve shift workers' circadian rhythm and improve patients' recovery. Researchers have investigated health care staffs' satisfaction with their lit work environment in real-life settings; however, staff members' perception of a circadian lighting system (CLS) that operates automatically has yet to be researched. This paper presents the implementation of a CLS installed in a newly built hospital between June 2021–February 2022. Two surveys ($n1 = 63$, $n2 = 48$) and 10 interviews were conducted with staff. Wilcoxon rank-sum test was conducted to compare staff members' responses between the pre-existing lighting (PeL) and circadian lighting system (CLS) at Neuro Intensive Care Unit and Postanesthesia Care Unit. The results showed a statistically significant satisfaction with the CLS compared with the PeL ($p = 0.0003$), and the staff found the CLS easier to use ($p = 0.0011$) and to adjust ($p = 0.0023$). The staff working in rooms with multiple patients appreciated the ability to adjust the lighting to the individual patient. These results supplement the existing body of research by presenting a field-study that illuminates barriers and advantages to consider when implementing CLS in hospitals. We conclude that CLS can complement a complex work environment in hospitals, but it requires close collaboration with occupants and continuous adjustments to the lighting settings for a successful implementation, and long-term use of the lighting system.	Integrative lighting, 24hr lighting System, Circadian lighting, Hospital staff, Perceived satisfaction, Work environment

Selected database								
1. GOAL		**2. OVERVIEW**						**3. METHOD**
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*
This paper demonstrates the utility of this workflow by evaluating a luminaire-level lighting controls (LLLC) system to meet eye-level light exposure recommendations from the WELL Building Institute Feature L03 Circadian Lighting Design and compare the energy demand between targeted melanopic lux thresholds and shading control scenarios.	/	Annual energy demand to meet recommendatio ns	OFFICE	1 open-seating configuration of 88 workstations with North-East, South, West facing windows. 50.9m x 29.6m	Both daylight and electric lighting	(1) Typical meteorological year (TMY3) climate data in referred location. (2) IES lighting system, CCT= 3500K, 76 light fixtures.	Portland, Oregon, USA	*The workflow is based on Radiance, a lighting simulation software tool, and combines parts of the LARK spectral lighting code that expands the 3 channels traditionally produced through Radiance to 9 channels offering better spectral resolution and more accuracy when computing melanopic lux and the metrics that rely on it. This 9-channel approach is then used to compute melanopic lux for an array of view positions and view directions for an annual, climate-driven time-series.*
The purpose of the controlled field study in this paper was to evaluate the effects of integrative lighting (IL) on sleep and different levels of cognition among shift workers on an assembly line in a truck factory.	*(1) Better sleep quality and cognitive performance in the IL condition (high melanopic EDI).*	Sleep quality of shift workers	FACTORY	Assembly plant (no dimension specified)	Electric lighting only	(2) LED lighting system	/	*4 lighting scenarios were created during 2 testing periods, using 2 divisions of participants. In testing period 1 the light settings only fulfilled the minimal requirements compliant with EN1264-1. In testing period 2, division 2 operated as control setting; while, in accordance with the recommendations of the WELL Building standard, the IL settings were adapted in division 1 in order to achieve 218 lux melanopic EDI at eye level during the day (from 6 a.m. until 7 p.m.). In the evening at 7pm the continuous line luminaires were dimmed in order to reach a melanopic EDI value below 100 lux from 8pm onwards. Measurements of visual comfort, sleep and cognition were administered before and after the manipulation of the two different lighting conditions at the two divisions of the production line. The MotionWatch 8 was used as objective measurement of sleep; a self-developed questionnaire was used as measurement of visual comfort; two cognitive performance tasks were applied to measure attention: The D2 test and the Go-Nogo*
The study aimed to find out the effect of a shortwavelength light-reduced environment on the main hormone melatonin metabolite 6-sulfatoxymelatonin in urine (u-sMEL) and to test the connection between light exposure from the previous day and u-sMEL.	/	Urinary melatonin levels in office workers unders spectrally/intens ity modified daylight	OFFICE	2 similarly equipped offices with 6 workstations each. Clear type glazed windows. North-west facing.	Both daylight and electric lighting	(1) Winter months (November, December, January in referred location. 5 days a week; h. 8.00-16.00 (2) Ceiling light fixtures with wide spectrum fluorescent tubes.	Bratislava, Slovakia	*Twenty-two participants spent five consecutive working days in the office under normal daylight conditions (reference) followed by five days in spectrally modified light conditions (experimental). The light environment was modified by the blue light-blocking glazing system, which significantly reduced melanopic illuminance in the experimental week. Three urine samples were collected daily and u-sMEL concentrations were measured by ELISA. Light exposure was monitored at the participant's eye level with LightWatcher and in the office by a stationary spectrophotometer.*
The research question is as follows: Can hospital staff members' satisfaction with the lit environment and their visual comfort be improved by implementing a CLS? The aim was to map out the new CLS lighting installation and to identify the lighting system's advantages and disadvantages.	/	Hospital staff perception of a circadian lighting system implementation	HOSPITAL	3 floors of the hospital	Electric lighting only	(2) Comparison between PeL lighting soluition and a CLS providing a dynamic lighting profile that changes during the day, ranging from 1800 K to 5500 K (CRI 90 at 2500–5500 K), operating automatically.	Copenhagen, Denmark	*This study was an investigation of two lighting conditions: the PeL solution that the department was equipped with when it was built in 2020 and a CLS commissioned by the Neuroscience Centre commissioned and installed in the summer of 2021. The CLS, designed by Chromaviso, has an evidence-based lighting profile that entrains occupants' circadian rhythm. Staff members' working in the neuro-ICU and the PACU participated in this study. The data was collected from two surveys in various stages as a within-group study. Survey 1 (n = 63) was used to collect data about the pre-existing lighting (distributed June 2021). Survey 2 (n = 48) was used to collect data about the implemented CLS (distributed December 2021–February 2022).*

Annex A

1.3

Selected database								
							3. METHOD	
N.	PDF Reference number	TYPOLOGY Environmental analysis/Subject survey	/SOFTWARE USED/	/HARDWARE USED/	/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/	MEASURED/SIMULATED STUDY OBJECT	MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES	/Human-centred MEASURED DATA (physiological variables measured by the hardware)/
1	3	**Environmental analysis - SIMULATION BASED**	Radiance; LARK	/	/	88 workstations	Equivalent Melanopic Lux (EML); Energy demand (kWh)	/
2	10	**Subject survey**	/	**Illuminance meter** Class A (for phoyopic illuminance); **Photospectrometer** Class A (for melanopic EDI); **Motion Watch** 8	**QUESTIONNAIRE** (from "workplace satisfaction questionnaire" (Veitch et al., 2002) and "Office Lighting Survey" (Sivaji et al., 2013) - 7 point scale; **COGNITIVE PERFORMANCE TASKS** (D2 attention test, Go-Nogo task)	Assembly plants. Every 5 m a illuminance measurement was taken on the horizontal working plane (1.20m). m-EDI was measured vertically at eye level on standing position (1.60m): every 5 m a measurement was taken for three different viewing directions (every 120°). The measurement detector was 15° tilted downwards.	Horizontal photopic illuminance; vertical melanopic EDI; CCT	**Motion Watch 8**: Sleep pattern
3	17	**Subject survey**	/	**LightWatcher** (LW; OT sensors, Austria); CL500-A **spectrophotometer** (Konica Minolta, Japan) meaured at eye level (1.2m) photopic illuminance levels Ev and Spectral Power Distribution (SPD). The Equivalent Melanopic Lux (EML) was calculated from these data. Melanopic illuminance Ev, m was determined from the formula Ev, m = 0.9058 EML; **URINE ANALYSIS**	/	Individuals light exposure.	Photopic illuminance Ev; Spectral Power Distribution (SPD); Equivalent Melanopic Lux (EML); Melanopic illuminance Ev	**LightWatcher**: individual measurement of light exposure, recording photopic light intensities in lux (lx); **Daily urine samples:** concentration of u-sMEL
4	18	**Subject survey**	/	**Spectrophotometer** Konika Minolta CL500A	**SURVEYS** with elements from TAM2 - 5 point Likert scale; **INTERVIEWS**;	Comparison between different lighting patterns through subject evaluation	M-EDI; Illuminance	/

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	*RECOMMENDED VAUES ADRESSED*	*REACHING OF RECOMMENDED VALUES*	*TYPOLOGY Long/Medium/Short term*	*/Number of people involved/*	*RESULTS*	*LIMITATIONS*
/	WELL (150EML OR 275 EML between 9am and 1pm)	NOT ALWAYS REACHED	Long term: Annual time-series	/	*(1) The overhead lighting systems designed to meet horizontal illuminance thresholds had difficulty meeting eye-level light exposure recommendations specified by WELL. (2) Shading systems could be optimized to prioritize daylight availability between 9am and 1 pm and then return to normal operation in the afternoon. (3) A lighting design solution that couples daylight with an LLLC system can provide substatial energy savings over a simple ON/OFF system when the target is 150 EML at the eye or 300 lx on the workplane. Further energy savings can be achieved by including portable task lamps to supplement eye-level exposure. (4) Lovering the percentage of workstations that must be compliant with the WELL thresholds could help designers advocate for solutions that promote non-visual health, while being mindful on energy savings. Vertical lighting strategies are another potential way to reduce or eliminate the energy burden on overhead lighting systems and to balance non-visual health performance and lighting energy efficiency.*	Lack of field studies
Questionnaire: visual comfort; **D2 attention test:** basal alertness and concentration; **Go-Nogo task:** concentration and inhibition	Melanopic EDI values of 192 lux	REACHED: Specifically designed to reach the recommended values.	Medium term: 2 weeks	76	*Results show that integrative lighting works in a real industrial setting with shift workers. Both cognitive functioning and sleep quality was enhanced with melanopic EDI values of 192 lux compared with standard lighting settings.*	(1) Emotional wellbeing not adressed. (2) No direct information about the employees drug use. (3) Drop out during testing period. (4) No control for potential gender effects in data due to too few female. (5) No distinction between napping and missing data [Future studies should include daytime napping to get a more comprehensive view about the influence of IL on the 24 h sleep-wake rhythm].
/	CIE S 026/E:2018	/	Long term: 3 months every year for 3 years	22	*The full spectrum light had an impact on night-time melatonin production. There was a positive correlation between illuminance levels and u-sMEL production the following night, but only in reference conditions. No correlation was found in the experimental conditions with reduced short-wavelength spectrum and intensity of light. The morning light has the main impact on night-time melatonin production when the second and third urine were included in the analysis, but not when only the first morning urine was analysed. However, the short-wavelength light reduction during the day did not affect the concentration of melatonin metabolite in urine. The results of our study need further research to clarify, whether the light intensity or its spectral composition, or both, have a greater impact. Our study shows the importance of daylight intensity on the non-visual effects of light.*	(1) Unbalanced sex ratio and chronotypes (results may vary depending on gender). (2) Significant difference in the chronotype score between men and women. (3) The study was conducted during days with a short photoperiod, repeating the study during other seasons would further develop the available knowledge base.
Surveys: (Survey 1) data about the pre-existing lighting experience and expectations, (Survey 2) data about the implemented CLS experience, data on participants' characteristics; **Interviews**: subjective reflections on the indoor hospital lighting, norms, personality traits, job experience, to supplement the survey results	/	/	Medium term: 4 months	111	*Increase in satisfaction with the CLS compared to the PeL: The staff found the CLS more naturalistic, particularly at night; warmer in CCT; perception of coziness also increased between the PeL and CLS at nighttime. Some criticisms related to the brightness (perceived illuminance) around midday and the lack of manually controlling the illuminance. This paper demonstrates a successful implementation of CLS. The increased satisfaction found in this study could be explained by the variability in the lighting during the day; by the lower CCT at night and the diversity in the light settings; and having more autonomy to adjust the lighting.*	The TAM model has some limitations: the variable of user behavior (subjectively evaluated); missing external variables such as age, tasks/role and years of job experience at the unit/place. [Limitations mitigated]. One limitation of the questionnaire was the variable of time, recall bias was also a potential risk of adding the variable of time.

Annex A

2.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
5	23	Wang, T., Li, J., Wang, Y., Dai, S., Shao, R., & Hao, L. (2022). Active interventions of dynamic lighting on human circadian rhythm and sleep quality in confined spaces. *Building and Environment* , *226* , 109766. doi.org/10.1016/j.buildenv.2022.109766	People in closed spaces without daylight for a long time are prone to circadian rhythm desynchrony and sleep disorders. To explore the effects of different lighting patterns on circadian rhythm and sleep, 20 adults were confined in an underground lab by within-subject design for four consecutive weeks with one lighting pattern per week. The static lighting pattern (SLP) was used in the 1st week, then the circadian forward lighting pattern (FLP) in the 2nd and 4th weeks, and the backward lighting pattern (BLP) in the 3rd week. Their salivary melatonin, Karolinska Sleepiness Scale(KSS),core body temperature (CBT), Pittsburgh Sleep Quality Index (PSQI), sleep latency and the number of awakenings were measured. The results showed dim light melatonin onset (DLMO) was delayed by 0.62 h during the 1st week, indicating the backward tendency of circadian rhythm but without significance (p = 0.295). In the 2 nd week, the schedule was forced to bring forward by 2 h, assisted with FLP. The BLP in the 3rd week resulted in a significant delay of 1.87 h in DLMO(p = 0.002) and lower melatonin at bedtime (p = 0.001), with progressively longer sleep latency, lower sleepiness at night and CBT when waking up, and PSQI increased day by day, meaning the gradually deteriorated sleep. In the 4th week, DLMO was significantly shifted forward by 2.13 h (p = 0.003), melatonin at bedtime was higher (p = 0.000), and sleep quality gradually improved. Lighting interventions on KSS, CBT, PSQI and sleep latency showed day-by-day cumulative effects, and the dynamic lighting interventions can help maintain circadian rhythm stability in closed spaces and adapt to shift hours.	Sleep quality, Circadian rhythm, Confined spaces, Core body temperature, Dim light melatonin onset, Healthy lighting
6	33	Li, Y., Fang, W., Guo, B., & Qiu, H. (2022). Diurnal effects of dynamic lighting on alertness, cognition, and mood of mentally fatigued individuals in a daylight deprived environment. In *Lighting Research and Technology* . SAGE Publications Ltd. https://doi.org/10.1177/14771535221138589	This study investigated the non-image forming (NIF) effects of dynamic light on alertness, cognitive performance and mood on mental fatigue, as well as moderation of task difficulty in lighting perception. Sixteen participants completed a psychomotor vigilance test (PVT) and two complex cognitive tasks (multi-attribute task battery-II (MATB-II) and n-back) with low, medium and high difficulty levels under dynamic (4000 to 12 000 K, melanopic equivalent daylight illuminance (EDI) = 224 lx to 420 lx) and static (4000 K, melanopic EDI = 224 lx) lighting with illuminance set at 500 lx on the desk. Psychological, behavioural, biochemical and electrophysiological responses to light were assessed. The results showed that exposure to dynamic light had significant benefits on subjective sleepiness, positive mood and task performance, which may be moderated by task difficulty. The intervention effect of dynamic light on fatigue was also found during an electrophysiological activity due to increase in the amount of attentional resources allocated to the tasks by dynamic light, but was not observed in biochemical measures.	Lighting, Dynamic lighting, Cognitive performance, Behavioral research, Complex cognitive tasks, Daylight illuminance, Electrophysiology, Image forming, Mental fatigue, Multi-attributes, Psychological response, Psychomotor vigilance tests, Task difficulty
7	37	Benedetti, M., Maierová, L., Cajochen, C., Scartezzini, J.-L., & Münch, M. (2022). Optimized office lighting advances melatonin phase and peripheral heat loss prior bedtime. In *Scientific Reports* (Vol. 12, Fascicolo 1). Nature Research. https://doi.org/10.1038/s41598-022-07522-8	Improving indoor lighting conditions at the workplace has the potential to support proper circadian entrainment of hormonal rhythms, sleep, and well-being. We tested the effects of optimized dynamic daylight and electric lighting on circadian phase of melatonin, cortisol and skin temperatures in office workers. We equipped one office room with an automated controller for blinds and electric lighting, optimized for dynamic lighting (= Test room), and a second room without any automated control (= Reference room). Young healthy participants (n = 34) spent five consecutive workdays in each room, where individual light exposure data, skin temperatures and saliva samples for melatonin and cortisol assessments were collected. Vertical illuminance in the Test room was 1177 ± 562 photopic lux (mean ± SD) , which was 320 lux higher than in the Reference room (p < 0.01). Melanopic equivalent daylight (D65) illuminance was 931 ± 484 melanopic lux in the Test room and 730 ± 390 melanopic lux in the Reference room (p < 0.01). Individual light exposures resulted in a 50 min earlier time of half-maximum accumulated illuminance in the Test than the Reference room (p < 0.05). The melatonin secretion onset and peripheral heat loss in the evening occurred significantly earlier with respect to habitual sleeptime in the Test compared to the Reference room (p < 0.05). Our findings suggest that optimized dynamic workplace lighting has the potential to promote earlier melatonin onset and peripheral heat loss prior bedtime, which may be beneficial for persons with a delayed circadian timing system.	Lighting, Light, Sleep, Melatonin, circadian rhythm, light, sleep, Circadian Rhythm, human, Humans, illumination, Body Temperature Regulation, hydrocortisone, Hydrocortisone, melatonin, thermoregulation
8	39	Xu, J., Liu, M., Li, L., & Xia, Z. (2023). Effects of environmental lighting on students' sleep, alertness and mood: A field study in a Chinese boarding school. In *Lighting Research and Technology* . SAGE Publications Ltd. https://doi.org/10.1177/14771535231165263	A field study was conducted in two classrooms to explore the effects of standard and high light levels on sleep, alertness and mood of boarding high school students in Suzhou, China. 79 participants took part in a 7-week study in winter. After 3-week baseline assessments under standard lighting, participants were exposed to 3-week high light levels, separated by a 1-week washout. One group experienced this condition in the morning and the other experienced it in the evening. Horizontal illuminance was recorded in real time during the experiment and converted to eye-level vertical illuminance and equivalent melanopic lux. Sleep wristbands and questionnaires were used. Morning or evening high light levels significantly improved acute alertness during the increased light level hours compared with standard lighting, but there was no significant difference in sleep or mood. Additionally, compared to the evening high light levels, morning condition was significantly associated with longer deep sleep duration, easier falling asleep and lower negative mood. This study is the first to directly correlate high light conditions and timing of light exposure with subjective and objective sleep, alertness and mood of Chinese boarding high school students, which can provide references for the application of healthy lighting in classrooms.	Lighting, Sleep research, Baseline assessment, Condition, Environmental lighting, Exposed to, Falling asleep, Field studies, High lights, High school students, Light level, Real- time, Students

Selected database								
1. GOAL		**2. OVERVIEW**						**3. METHOD**
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*
To explore the effects of different lighting patterns on circadian rhythm and sleep.	*(1) SLP induce backward shift in the circadian phase and disrupt sleep, (2)BLP strengthen these effects, (3) FLP opposite effects.*	Human circadian rhitm and sleep quality	UNDER-GROUND LABORATORY (SET AS AN APARTAMENT BUILDING)	Basement with complete internal living facilities such as an office, conference room, exhi bition rooms, gyms, toilets, showers, etc. Sleep room 6.2x2.8m.	Electric lighting only	(2) LED panel lights with four lighting patterns: static lighting pattern (SLP), backward lighting pattern (BLP), forward lighting pattern (FLP) and DLMO light ing pattern (DLP).	/	*20 adults were confined in an underground lab by within-subject design for four consecutive weeks with one lighting pattern per week. The static lighting pattern (SLP) was used in the 1st week, then the circadian forward lighting pattern (FLP) in the 2nd and 4th weeks, and the backward lighting pattern (BLP) in the 3rd week. Their salivary melatonin, core body temperature (CBT), Pittsburgh Sleep Quality Index (PSQI), sleep latency and the number of awakenings were measured.*
This study collected multimodal data to highlight the diurnal effects of DL on the psychology, physiology and behaviour of fatigued individuals in the late afternoon and examined advanced psychological activity measuring event-related potentials (ERPs). related to cognitive processes by	*(1) DL rendering more benefits by increasing alertness and positive mood, improving cognitive performance and attention.*	Alertness, cognition, mood under dinamic lighting	OFFICE	Office room 3x2m, table 1.2x6m in the middle	Electric lighting only	(2) 4 LED cube: dynamic (4000 to 12 000 K, EDI = 224 lx to 420 lx) and static (4000 K, EDI = 224 lx) lighting with illuminance set at 500 lx on the desk.	/	*Sixteen participants completed a psychomotor vigilance test (PVT) and two complex cognitive tasks (multi-attribute task battery-II (MATB-II) and n-back) with low, medium and high difficulty levels under dynamic (4000 to 12 000 K, melanopic equivalent daylight illuminance (EDI) = 224 lx to 420 lx) and static (4000 K, melanopic EDI = 224 lx) lighting with illuminance set at 500 lx on the desk.*
Test the effects of optimized dynamic daylight and electric lighting on circadian phase of melatonin, cortisol and skin temperatures in office workers.	/	Melatonin phase and heat loss (prior bedtime) in office workers	OFFICE	2 office rooms. One office room equipped with an automated controller for blinds and electric lighting, optimized for dynamic lighting (= Test room), and a second room without any automated control (= Reference room)	Both daylight and electric lighting	Vertical illuminance in Test room = 1177 ± 562 photopic lux , 320 lux higher than Reference room. M-EDI = 931 ± 484 melanopic lux in Test room and 730 ± 390 melanopic lux in Reference room.	Lausanne, Switzerland	*One office room equipped with an automated controller for blinds and electric lighting, optimized for dynamic lighting (= Test room), and a second room without any automated control (= Reference room). Young healthy participants (n = 34) spent five consecutive workdays in each room, where individual light exposure data, skin temperatures and saliva samples for melatonin and cortisol assessments were collected. Vertical illuminance in the Test room was 1177 ± 562 photopic lux (mean ± SD) , which was 320 lux higher than in the Reference room (p < 0.01). Melanopic equivalent daylight (D65) illuminance was 931 ± 484 melanopic lux in the Test room and 730 ± 390 melanopic lux in the Reference room (p < 0.01).*
Explore the effects of standard and high light levels on sleep, alertness and mood of boarding high school students.	*(1) Morning high light levels prompting sleep support, alertness and mood. (2) Evening high light levels eliciting acute alertness, decrease sleep quality and increase negative mood.*	Sleep, alertness and mood in students (under standard and high light levels)	SCHOOL	Two identical classrooms (same furniture layout, window size and schedule, third floor).The windows of the two classrooms faced north and south. All windows had rolling curtains inside.	Both daylight and electric lighting	The standard lighting condition was set at 300 lx with 4000 K (horizontally), the high light condition was set at 500 lx with 6000 K with 274 EML (met the recommended threshold).	Suzhou, China	*After 3-week baseline assessments under standard lighting, participants were exposed to 3-week high light levels, separated by a 1-week washout. One group experienced this condition in the morning and the other experienced it in the evening. Horizontal illuminance was recorded in real time during the experiment and converted to eye-level vertical illuminance and equivalent melanopic lux. Sleep wristbands and questionnaires were used.*

Annex A

2.3

Selected database								
						3. METHOD		
N.	PDF Reference number	TYPOLOGY Environmental analysis/Subject survey	/SOFTWARE USED/	/HARDWARE USED/	/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/	MEASURED/SIMULATED STUDY OBJECT	MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES	/Human-centred MEASURED DATA (physiological variables measured by the hardware)/
5	23	**Subject survey**	/	**Spectrophotometer** Konika Minolta CL500A; **Smart wristband** (Huawei B4 Pro); **SALIVA ANALYSIS, CORE BODY TEMPERATURE (CBT)**	**Karolinska Sleepiness Scale** (KSS) - 9-level Likert scale, **Pittsburgh Sleep Questionnaire; Sleep diary**	Comparison between different lighting patterns through subject evaluation	Melanopic EDI, circadian light (CLA), circadian stimulus (CS)	**Smart wristband** (Huawei B4 Pro): sleep and wake time; **Saliva samples**: (six times per night, on the 2nd, 5th, 16th, 19th, 23rd and 26th days) to evaluate the changing trends of melatonin concentration; **Tympanic temperature**: changes in core body temperature (CBT);
6	33	**Subject survey**	/	**EEG; SALIVA ANALYSIS; Spectrophotometer** Konika Minolta CL500A	**QUESTIONNAIRES** (KSS, PANAS - 5-point Likert-scale, VAS - 10 point Likert scale, BRUMS - 5 point Likert scale)**; 3 COGNITIVE TASKS** PVT, multi-attribute task battery-II (MATB-II) and n-back	Comparison between different lighting patterns through subject evaluation	Melanopic EDI, CCT	**EEG**: neural activity; **Saliva samples**: to detect melatonin secretion during daytime.
7	37	**Subject survey**	/	High Dynamic Range (HDR) **vision sensor**, **spectrometer** (Jeti Specbos 1201), **Wearable light sensors**, **Wireless temperature sensors** (i-Buttons); **SALIVA ANALYSIS**	/	Comparison between different lighting patterns through subject evaluation	Vertical illuminance, Melanopic EDI	**Wireless temperature sensors:** skin temperature; **Saliva samples:** melatonin and cortisol assessments
8	39	**Subject survey**	/	Konica Minolta T-10A **Illuminance Meter**, **Illuminometers** (Luge L99-LX-3), **spectrometer** (SPIC 300); **Sleep wristbands**	**5 QUESTIONNAIRES** Karolinska sleepiness scale (KSS) - Nine point scale, Pittsburgh Sleep Quality Index (PSQI), Positive and Negative Affect Schedule (PANAS) - 5 point scale, Perceived Stress Scale (PSS-10) questionnaire; Subjective Vitality Scale (SVS) questionnaire; Positive and Negative Affect Schedule (PANAS) questionnaire	Comparison between different lighting patterns through subject evaluation	Vertical illuminance, Equivalent Melanopic Lux (EML)	**Sleep wristbands**: to collect sleep data: bedtime, wake time, sleep duration, number of night awakenings, and deep sleep duration; to assess sleep quality

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	RECOMMENDED VAUES ADRESSED	REACHING OF RECOMMENDED VALUES	TYPOLOGY Long/Medium/Short term	/Number of people involved/	RESULTS	LIMITATIONS
Questionnaire: Karolinska Sleepiness Scale (KSS) for alertness; Pittsburgh Sleep Questionnaire; **Sleep diary:** to calculate Pittsburgh Sleep Quality Index (PSQI), sleep latency and sleep efficiency	"Mel-EDI of 250 lx for daytime and Mel-EDI of 10 lx before bedtime; CS of 0.1 in the early evening (5 h before bedtime), further reduced to 0.05 in the late-night (2 h before bedtime)."	REACHED: Specifically designed to reach the recommended values (CS).	Medium term: 4 weeks	20	*In the confined space without daylight, the fixed lighting pattern would lead to the delay of the circadian rhythm of long-term residents. Through dynamic lighting patterns, the phase shift of the circadian rhythm can be induced, and the stability of the sleep rhythm can be maintained. Cumulative effects on melatonin rhythm, KSS scores, CBT, PSQI scores and sleep latency indicate that light history would influence the non-visual effects of light. The gradually decreasing light at night combined with the strong lighting stimulus in the morning has a significant effect on the forward shift of circadian rhythm and the improvement of sleep quality, which has a good effect on correcting the rhythm delay caused by confined spaces or shift work. However, the strong light stimulus before sleep induces the backward shift of the rhythm phase, which will also lead to the deterioration of sleep quality.*	(1) Subjects may be interfered with different lighting patterns. (2) Need to adjust lighting parameters such as spectrum, illuminance and timing for each dynamic lighting pattern to refine the study and derive more effective combinations of lighting parameters. (3) Necessity to consider the differences between ages and genders. (4) Necessity to improve the measuring equipment
4 **Questionnaires:** Karolinska Sleepiness Scale (KSS) for subjective sleepiness, Positive Affect and Negative Affect Scale (PANAS) for subjective mood, Visual Analog Scales (VAS) and Brunel Mood Scale (BRUMS) to assess mental fatigue; 3 **Cognitive tasks:** Psychomotor vigilance test for objective alertness; multi-attribute task battery-ii (matb-ii) to test the executive control function and *n*-back for effect of DL on the working memory	/	REACHED: Specifically designed to reach the recommended values.	Medium term: 2 months	16	*The results showed the active interventional effects of dynamic light on mental fatigue in terms of higher alertness and positive mood, better task performance and more brain activity. These findings suggest that DL could be applied to improve the alertness, cognitive performance and positive mood of fatigued individuals in ICE with daylight deprivation.*	(1) Need to control for confounding variables (sleep–wake schedule, light sensitivity, sleep quality, etc.) (2) need to expand the sample size to investigate the neural mechanisms underlying the diurnal fatigue intervention effects of dynamic light.
/	250 melanopic lux	EXCEEDED	Medium term: 4 weeks	34	*The photopic Ev was higher during the first half of the day, and half-maximum response times of accumulated Ev were significantly earlier in the Test than in the Reference room. The timing of melatonin onset and peripheral heat loss (DPG) occurred significantly earlier in the Test than in the Reference room. These results suggest that the use of an automated controller together with an optimized lighting system during the day has the potential to advance circadian phase markers. Melanopic EDI was higher in the Test than the Reference room, but individual light exposures did not really reflect such large differences. Melatonin onset occurred significantly earlier during the week in the Test than the Reference room. As expected, we observed significant variations of cortisol concentrations during waking which were highest after habitual wake time with no statistically significant differences between conditions.*	(1) Semi-naturalistic approach caused no constraints on light exposures out of the office (may contribute to individual variability of hormonal and light exposure data between conditions and between participants). (2) During the week in the Reference room, participants could use the blinds and electric lighting according to their individual needs.
Questionnaires: KSS as a measure of sleepiness, PSQI to measure sleep quality, PSS-10 to assess participants' thoughts and feelings, SVS to assess participants' perceptions of feeling alive, vital, energetic or energized, alert, awake and optimistic; PANAS for subjective feelings	WELL Building Standard recommending at least 4h of 275EML light exposure at eye level every day	REACHED (274EML)	Medium term: 7 weeks	79	*Morning or evening high light levels significantly improved alertness during the increased light level hours compared with standard lighting, but there was no significant difference in sleep or mood. Moreover, morning high light levels significantly improved sleep quality and negative mood in boarding high school students compared with evening high light levels.*	(1) Lack of a counterbalanced cross-over design (better if each participant acts as their control). (2) Collect real time spectrum data continuously at eye height to produce more accurate data. (3) No analysis of daylight and electric light interaction. (4) Too few wristbands to understand the relationship between lighting and sleep.

Annex A

3.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
9	42	Huang, Y., Hu, Z., Li, J., & Dai, Q. (2023). The impact of cyanopic illuminance on evening light induced circadian effects. In *Building and Environment* (Vol. 242). Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2023.110559	Circadian lighting aims to avoid the negative impacts of artificial lighting on the circadian system. Of particular concern are the negative effects induced by evening light exposure, such as the suppression of melatonin secretion and delayed circadian phase. The melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs) play a key role in the circadian phototransduction processes. Therefore, popular metrics for "circadian illuminance", such as equivalent melanopic lux (EML) and melanopic equivalent daylight D65 illuminance (m-EDI), are based solely on melanopic illuminance. However, some recent studies suggested that visual photo-receptors could also participate in the circadian phototransduction process. Especially, the S-cone-related cyanopic illuminance may also contribute to the light-elicited circadian responses. To investigate the actual role of cyanopic illuminance and the accuracy of the m-EDI and EML metrics, we designed a pair of general-lighting spectra with equivalent melanopic and photopic illuminance but very different cyanopic illuminance (40.5% difference achieved). Human-factor studies were conducted using this pair of spectra, which showed that saliva melatonin concentration and sleep efficiency were significantly higher under the lighting condition with greater cyanopic illuminance. These results suggest that cyanopic illuminance plays an important role in evening-light-induced circadian effects with an inhibitory behavior. On the other hand, cyanopic illuminance alone does not affect KSS-rated subjective alertness. Our findings suggest that incorporating cyanopic illuminance, in addition to melanopic illuminance, can enhance the accuracy of circadian illuminance metrics. This balanced approach can help achieve both precise quantification and convenience in circadian lighting design.	Circadian effect, Lighting, Equivalent melanopic lux, Phototransduction, accuracy assessment, quantitative analysis, circadian rhythm, Hormones, light, Cyanopic illuminance, Evening lighting, Light-induced, Melanopic equivalent daylight d65 illuminance, Melanopic illuminance, Melatonin suppression, Spectra's
10	47	Abboushi, B., & Safranek, S. (2022). DETERMINING CRITICAL POINTS TO CONTROL ELECTRIC LIGHTING TO MEET CIRCADIAN LIGHTING REQUIREMENTS AND MINIMIZE ENERGY USE. In *Simulation Series* (Vol. 54, Fascicolo 1, pp. 85–94). The Society for Modeling and Simulation International. DOI: 10.23919/ANNSIM55834.2022.9859378	Designing electric lighting systems to meet circadian lighting requirements may raise light levels and consequently energy use compared to existing practices. To reduce energy use, electric lighting can be controlled to be dimmed or turned off when sufficient daylight levels are available in space. This requires input from one or a few critical measurement points. However, it is unclear how critical points can be determined to ensure that all occupants receive the needed light levels while reducing electric lighting energy. This paper discusses three approaches for selecting critical points and utilizes annual daylight simulations modified to account for sky spectra and coupled with spectral electric lighting simulations. Among the three evaluated approaches, the use of continuous daylight autonomy (modified to use EML measured at eye positions) is helpful for estimating electric lighting energy for dimmable electric lighting systems, and for identifying energy-saving strategies.	Electric lighting, Circadian lighting, Light level, Spectra's, Critical measurements, Critical point, Energy, Energy conservation, Energy use, Lighting fixtures, Lighting simulation, Lighting systems, Measurement points
11	53	Espinoza-Sanhueza, C., Hébert, M., Lalonde, J.-F., & Demers, C. M. (2024b). Exploring light and colour patterns for remote biophilic northern architecture. In *Indoor and Built Environment* (Vol. 33, Fascicolo 2, pp. 359–376). SAGE Publications Ltd. https://doi.org/10.1177/1420326X231198358	This research explores the effects of light in terms of colour, surface colour configuration and finishes using simple and advanced methods in the development of biophilic lighting ambiances for remote northern architecture. Biophilic light and colour design can benefit inhabitants of subarctic regions, where drastic changes in the natural photoperiod can impact the mind and body. To predict the outcomes of light and colour, this research used reduced-scale models that replicate a north-oriented room and a specially designed mirror-box sky simulator, which emulates the lighting conditions and correlated colour temperature (CCT) of a northern sky. Physical models with distinct surface colour properties and the use of high dynamic range imagery (HDRi) techniques allow the recognition of quantitative effects and lighting attributes of main hue families such as red, green, blue and yellow. The results reveal that the colour and the surface colour configuration significantly modify the spectral properties of a lit ambiance measured in Equivalent Melanopic Lux (EML) and CCT. Surface colour configuration and finishes produce variations in the luminous attributes measured in intensity contrast. This combination of simple and innovative tools could predict light and colour effects in early design stages for responsive architecture in subarctic territories. © The Author(s) 2023.	Light, colour, surface colour configuration, finish, northern architecture, remote design process, biophilic design
12	57	Englezou, M., & Michael, A. (2023). Investigation of the daylight spectrum in an indoor environment using CIE S 026 melanopic metrics. In *Lighting Research and Technology* (Vol. 55, Fascicoli 7–8, pp. 690–711). SAGE Publications Ltd. https://doi.org/10.1177/14771535231204162	Since discovering the intrinsically photosensitive retinal ganglion cells (ipRGCs) and their impact on the circadian rhythm, many disciplines have been researching the physiological and psychological effects of light on humans. However, not much research has been conducted on how the spatial configuration of a room (orientation and gaze direction) changes the light quality and quantity. This research examines the variability of the natural lighting spectrum, focusing on light intensity, the spectrum itself, as well as variations across seasons and hours. The metrics examined are the CIE S 026 melanopic equivalent daylight illuminance (melanopic EDI) and melanopic daylight efficacy ratio (melanopic DER). Field measurements were taken in a room with a south orientation located in Cyprus, using a spectrometer. The main parameters under study were eight gaze directions, four seasons (June, September, December and March) and four different hours each day (09:00, 12:00, 15:00 and 18:00) for 20 positions in the test room. The results show the impact of season, time and gaze direction on the melanopic DER and melanopic EDI. Overall, due to the low sun angle and direct sunlight exposure in the winter, the melanopic EDI was much higher compared to the other three seasons, whereas the melanopic DER had the lowest values. For all seasons and times, most of the cases achieved the minimum recommendation for daytime light exposure of melanopic EDI of more than 250 lx. © The Chartered Institution of Building Services Engineers 2023.	Lighting, Circadian rhythms, Daylight illuminance, Spectra's, Indoor environment, Direction change, Gaze direction, Physiological effects, Psychological effects, Retinal ganglion cells, Spatial configuration

Selected database								
1. GOAL		**2. OVERVIEW**						**3. METHOD**
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*
In this work, we aimed to investigate the impact of cyanopic illuminance on subjects' circadian responses to evening lighting, including melatonin concentration level, subjective alertness and sleep quality, by comparing between two contrast lighting conditions.	*(1) S-cone-related cyanopic illuminance playing a crucial role in the circadian effects of light.*	Circadian effects caused by cyanopic illuminance	UNIVERSITY CAMPUS AND LABORATORY	Lighting lab, 2 workstations	Electric lighting only	(2) 2 electric lighting conditions (n.1= 162lx,99.9EML, 60.5 cyanopic illuminance; n.2= 166lx,99.9EML, 85 cyanopic illuminance)	Shanghai, Cina	*Each participant experienced two general lighting sessions (white light with high color rendering index), including one with lower cyanopic illuminance (denoted as the S− lighting condition), and the other with higher cyanopic illuminance (denoted as the S+ lighting condition). Lighting parameters and spectra were measured using a spectral irradiance colorimeter (SPIC–200BW, EVERFINE) placed near the participants' eyes in the direction of reading. Between the two contrast lighting spectra, while cyanopic illuminance were quite different; photopic illuminance, melanopic illuminance and α-opic illuminance of other photo-receptors were tuned to a similar level.*
In this paper, we evaluate three approaches (LD, DAEML, and cDAEML), one existing and two proposed, that can be used to determine critical points. These approaches are applied to a simulated case-study office space in Golden, Colorado. to discuss how they might inform critical point determination and other design decisions.	/	Measurement points reaching the recommended values	OFFICE	2100 ft2 (195 m2) open-plan office with 40 workstations 0.76m tall. South wall with floor-to-ceiling windows (WWR of 90%). Vertical measurement points were located at each workstation at 1.22 m.	Both daylight and electric lighting	(1) 2018 annual spectral sky conditions: Sky dome spectrum in Golden, CO, USA. (2) Thirty-two 3800 K 2x2 ft (0.61x0.61m) light-emitting diode (LED) luminaires.	Golden, Colorado	*A 2100 ft2 (195 m2) open-plan office model with 40 workstations was used for all lighting simulations. Workstations were assumed to be 2.5 ft (0.76 m) tall and computer monitors were included but not considered to be light sources for this analysis. Vertical measurement points were located at each workstation. A method was established for estimating the EML contributions from daylight combining annual illuminance estimates from Ladybug/Honeybee with spectral measurements. A spectrophotometer collects the global horizontal sky dome spectrum in Golden, CO, USA in 1-nm increments every 5 minutes throughout the entire year. The melanopic to photopic ratio (M/P) was calculated using the daylight spectral power distribution (SPD) for each hour, using the method outlined in WELL; these M/P values were used to convert photopic illuminance at the eye to EML values.*
The research addresses the following questions: What is the impact of variables such as colour, surface colour (SC) configuration and finish on the spectral properties of light in the context of the developing biophilic spaces for northern architecture? How can consistent results be generated to analyze these variables during a remote design process?	*(1) Advanced tools such as a mirror-box artificial sky simulator enabling the assessment of indoor architectural variables by low-cost methods.*	Light and colour patterns (for biophilic architecture)	GENERIC ROOM	Model: generic room (10 m × 7 m × 3 m); specially designed room fitted with a complete 40 LED lamps, ceiling and mirror wall equipment used to simulate characteristics of a northern sky	Electric lighting only	(2) 40 LED lamps; simulating the daylight photoperiod, the frequency of cloudy skies over a year in Cambridge Bay, Nunavut (NU)	Cambridge Bay, Canada	*This research used reduced-scale models replicating a north-oriented room and a specially designed mirror-box sky simulator, which emulates the lighting conditions and correlated colour temperature (CCT) of a northern sky. The variable combinations generated 120 distinct scenarios and three different baseline scenarios at 2700°K, 4500°K and 6500°K, which were compared in terms of EML, CCT and brightness properties.*
The main objective of the study is to explore when and how much the spectral characteristics of natural lighting change in indoor spaces in relation to the seasons and hours during a day. This research examines the variability of the natural lighting spectrum, focusing on light intensity, the spectrum itself, as well as variations across seasons and hours.	/	Daylight spectrum influenced by building parameters indoor	OFFICE	Room (3m x 4m x 2.4m) with a south orientation and with a double window (1.75 m x 1.20 m) on the south wall	Daylight only	(1) Mediterranean hot summer climate (Csa) and a hot semi-arid climate (BSh).	Paralimni, Cyprus	*Field measurements were taken in a room with a south orientation located in Cyprus, using a spectrometer. The main parameters under study were eight gaze directions, four seasons (June, September, December and March) and four different hours each day (09:00, 12:00, 15:00 and 18:00) for 20 positions in the test room. The metrics examined are melanopic EDI and melanopic DER.*

1.1

Annex A

3.3

Selected database								
						3. METHOD		
N.	*PDF Reference number*	*TYPOLOGY Environmental analysis/Subject survey*	*/SOFTWARE USED/*	*/HARDWARE USED/*	*/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/*	*MEASURED/SIMULATED STUDY OBJECT*	*MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES*	*/Human-centred MEASURED DATA (physiological variables measured by the hardware)/*
9	42	**Subject survey**	/	**Actiwatch-L/2/Plus**, Philips Respironics; Spectral irradiance **colorimeter** (SPIC-200BW, EVERFINE); **SALIVA ANALYSIS**	**QUESTIONNAIRE** (KSS-9 point scale)	Comparison between different lighting patterns through subject evaluation	Photopic illuminance (lx), Melanopic illuminance (EML, m-EDI), Cyanopic illuminance, Rhodopic illuminance, Chloropic illuminance, Erythropic illuminance	**Actiwatch-L/2/Plus**: sleep time; **Saliva samples**: salivary melatonin concentration
10	47	**Environmental analysis - SIMULATION BASED**	Rhino3D; ALFA	Spectrophotometer;	/	40 workstations	Melanopic to photopic ratio (M/P) calculated using the daylight spectral power distribution (SPD) and used to conver phoyopic illuminance to EML values	/
11	53	**Environmental analysis - PHYSICAL SIMULATION: REDUCED SCALE MODEL AND SIMULATED SKY**	/	Mirror-box artificial **sky simulator**; **Spectrophotometer** CL200-A Konica Minolta	/	Light and colour patterns	EML; CCT	/
12	57	**Environmental analysis - FIELD MEASUREMENTS**	/	**Spectrometer**	/	Parameters under study: eight gaze directions, four seasons (June, September, December and March), four different hours each day (09:00, 12:00, 15:00 and 18:00) for 20 positions in the test room.	Photopic illuminance (lx), Mel. EDI (lx), Mel. DER, CCT (K)	/

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					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	RECOMMENDED VAUES ADRESSED	REACHING OF RECOMMENDED VALUES	TYPOLOGY Long/Medium/Short term	/Number of people involved/	RESULTS	LIMITATIONS
Questionnaire: KSS for subjective sleepiness;	Melanopic illuminance (Lucas et al.); CIE (m-EDI) and WELL Building Standard (EML); *"the m-EDI value at eye level before bedtime is recommended to be less than 10 lx"*	NOT REACHED (99.9EML, 90.5m-EDI)	Medium term: 3 weeks	18	*Under evening lighting conditions with a fixed melanopic illuminance, a cyanopic illuminance manipulation is done: increased cyanopic illuminance leads to reduced effect of light-induced melatonin suppression and improved sleep quality. This result supports the hypothesis that S-cone-related cyanopic illuminance also plays a crucial role in the circadian effects of light, which shows an inhibitory behavior. On the other hand, manipulating cyanopic illuminance alone does not affect KSS-rated subjective alertness. Currently, the widely-used circadian metrics, including m-EDI and EML, are solely based on melanopic illuminance, which may have limited accuracy in quantifying the circadian effects of light. Therefore, it is recommended to explore the inclusion of cyanopic illuminance, in addition to melanopic illuminance, in developing a more accurate circadian illuminance metric that balances both accuracy and practicality.*	(1) A possibility is that the subjective evaluation method of KSS is not sufficiently powerful to detect the difference in alertness. (2) Challenges in collecting and evaluating sleeping quality data using the Actiwatch: the device can incorrectly identify the wearing status. (3) There are other factors that can affect sleep, (other than melatonin secretion) such as variations in noise and temperature of the sleep environment.
/	The EML thresholds of 150 and 275 m-lux that were set by WELL for a space without 'enhanced daylight' credits were used in this analysis. (WELL v2. Q4 2021).	REACHED (Almost always requiring both daylight and electrical lighting)	Long term: 1 year	/	*Compared to the LD approach, the use of DAEML and cDAEML provides several advantages that can be summarized with the following points: (1) DAEML and cDAEML allow for ranking all measurement points based on annual daylight levels at the eye. This can help evaluate whether the point with lowest DAEML or cDAEML is anomalous, in which case it would likely lead to excessive energy use. (2) Supplemental desktop luminaires or different zoning arrangements can be explored to reduce circadian lighting energy while meeting circadian lighting requirements at all workstations. (3) In situations where a four-hour exposure is appropriate, DAEML and cDAEML can help identify the timing of exposure with lowest lighting energy penalty.*	(1) Assumption: uniform EML from electric lighting across all occupants. In reality, there could be some variation in EML distribution. (2) Assumption that daylight spectrum inside the space will not differ from one measurement point to another. This may not be true close to a colored surface. (3) The measurement points in this analysis assumed static positioning and horizontal view directions, but occupant behavior will influence lighting exposure.
/	150 EML (accepted) and 275 EML (recommended) established by the Well Building Institute	MOSTLY REACHED: 89% of the tested scenarios projected EML values over 275 EML under several colour surface configurations; 11 scenarios did not reach the recommended EML levels	Short term: few days	/	*The results reveal that the colour and the surface colour configuration significantly modify the spectral properties of a lit ambiance measured in Equivalent Melanopic Lux (EML) and CCT (EML and CCT of the overall ambiance are influenced by the colour temperature of the light source). Surface colour configuration and finishes produce variations in the luminous attributes measured in intensity contrast. This combination of simple and innovative tools could predict. However, the melanopic levels decreased as the light source CCTwas decreased. It should be also noted that the baseline scenarios with a neutral colour had a lower CCT than the original light source, with the largest CCT difference of 40% in the 6500°K ambiance.*	/
/	CIE S 026 Melanopic metrics (m-EDI, m-DER)	REACHED: most of the cases achieved the minimum recommendation mel-EDI of more than 250 lx. But the majority of minimum values for all four seasons, all hours and all gaze directions were below the minimum limit for melanopic EDI of 250 lx.	Short term: 4 days (along the year) and 4h each day as representative data (1 day representing each season).	/	*This research focused on the impact of gaze direction, hour and season on the melanopic DER and melanopic EDI. Findings show that winter measurements in the south gaze direction had the highest values of melanopic EDI; even though m-EDI in the winter was much higher compared to the other three seasons, m- DER had the lowest values in winter, which means the daylight spectrum had lower spectral irradiance in the short-wavelength part of the visible spectrum. For all seasons and times, most of the cases met the minimum recommendation (250 lx). Nevertheless, in some cases in summer, spring and autumn, and in specific gaze directions, this was not met.*	(1) Measurements were taken only on specific days and times that are considered important for daylight assessments; not realistic. (2) The measuring procedure took 40 minutes each time, and thus, measurements were prone to changes in daylighting conditions. (3) The method used for measurements of specific gaze directions in vertical positions does not provide the possibility to estimate the impact of having continuous movements in gaze direction.

Annex A

4.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
13	59	Lo Verso, V. R. M., Giovannini, L., Valetti, L., & Pellegrino, A. (2023). Integrative Lighting in Classrooms: Preliminary Results from Simulations and Field Measurements. In *Buildings* (Vol. 13, Fascicolo 9). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/buildings13092128	The paper presents results from a study on integrative lighting in real middle school classrooms located in a school building in Turin, Italy. The contribution of both daylighting and electric lighting was considered. Besides the existing configuration of electric lighting systems (fluorescent luminaires), a set of six possible retrofitting solutions was considered, all using LED luminaires. The research addressed two main objectives: (i) To verify if the circadian values (melanopic equivalent daylight illuminance m-EDI) in the classrooms could meet the recommended values reported in recent literature, for instance, in the WELL protocol, (ii) to assess the influence on integrative lighting (photopic and melanopic illuminances) played by the electric lighting, as a function of the different lighting systems, and by daylighting, as a function of different room orientations and sky conditions. Results showed that the existing spaces benefit from high daylighting amount, whilst the existing lighting systems provide an insufficient m-EDI. Even when last-generation LED lighting systems were ideally used for retrofitting, no solution was able to meet the three-point WELL recommendation, while two solutions only allowed the one-point recommendation to be met. Some design implications concerned with the results were critically discussed. © 2023 by the authors.	integrative lighting; lighting in classroom; ALFA simulations; non-visual effect of light;circadian measures
14	60	Fostervold, K. I., & Eilertsen, D. E. (2022). Implementing integrative lighting in conventional office luminaires: Effects on melatonin secretion and sleepiness. In *Lighting Research and Technology* (Vol. 54, Fascicolo 8, pp. 778–797). SAGE Publications Ltd. https://doi.org/10.1177/14771535221123237	The discovery of intrinsically photosensitive retinal ganglion cells in the eye and their interaction with melatonin has shown that light has significant effects beyond vision. The present study compared the effect of an integrative lighting system, providing low-intensity melanopic illuminance with the effect of an ordinary, qualitatively equivalent, electric lighting system. The study utilised a 2 × 7 randomised mixed experimental design. The sample consisted of 13 women and 11 men. Salivary melatonin secretion and subjectively perceived sleepiness in the evening were measured every half hour during 3 hours of light exposure. The chronobiologic typology (stability and amplitude) and trait-like negative and positive affect were measured once and analysed as covariates. The results showed a general increasing linear effect for both melatonin and sleepiness. A significant nonlinear effect of time was present in the group exposed to integrative lighting, indicating delayed melatonin secretion. The findings were stable across all levels of the examined covariates. These results confirm that the integrative lighting system produces effects beyond vision under otherwise ordinary lighting conditions. Furthermore, the results corroborate research suggesting that melatonin secretion and sleepiness may not be directly linked. The integrative lighting system provides new opportunities to develop indoor electric lighting resembling daylight. © The Chartered Institution of Building Services Engineers 2022.	Hormones, Exposed to, Lighting fixtures, Lighting systems, Light exposure, Retinal ganglion cells, Covariates, Effect of time, Low-intensity, Negative affects, Nonlinear effect, Positive affects
15	63	Bessman, S. C., Harrison, E. M., Easterling, A. P., Snider, M. N., Preilipper, S. M. M., & Glickman, G. L. (2023). Hybrid effectiveness-implementation study of two novel spectrally engineered lighting interventions for shiftworkers on a high-security watchfloor. In *SLEEP Advances* (Vol. 4, Fascicolo 1). Oxford University Press. https://doi.org/10.1093/sleepadvances/zpad051	Shiftwork leads to myriad negative health and safety outcomes. Lighting countermeasures can benefit shiftworkers via physiological effects of light (e.g. alerting, circadian adjustment), and short-wavelength light is the most potent for eliciting those responses; however, limited work indicates it may not be required for alerting. We developed similar-appearing light boxes (correlated color temperature: 3000-3375 K; photopic illuminance: 260-296 lux), enriched (SW+, melanopic EDI: 294 lux) or attenuated (SW-, melanopic EDI: 103 lux) in short-wavelength energy, and implemented them on a high-security watchfloor. Efficacy and feasibility of these two novel lighting interventions were assessed in personnel working 12-hour night shifts (n = 47) in this within-participants, crossover study. For each intervention condition, light boxes were arranged across the front of the watchfloor and illuminated the entire shift; blue-blocking glasses were worn post-shift and before sleep; and sleep masks were used while sleeping. Comparisons between baseline and intervention conditions included alertness, sleep, mood, quality of life (QOL), and implementation measures. On-shift alertness (Karolinska Sleepiness Scale) increased in SW- compared to baseline, while changes in SW+ were more limited. Under SW+, both mood and sleep improved. Psychomotor vigilance task performance did not vary by condition; however, perceived performance and QOL were higher, and reported caffeine consumption and sleep onset latency were lower, under SW-. For both interventions, satisfaction and comfort were high, and fewer symptoms and negative feelings were reported. The addition of spectrally engineered lights to this unique work environment improved sleep, alertness, and mood without compromising visual comfort and satisfaction. © The Author(s)	alertness; circadian; implementation; intervention; light; melanopic; shiftwork; sleep; spectrum.
16	68	He, M., Chen, H., Li, S., Ru, T., Chen, Q., & Zhou, G. (2023). Evening prolonged relatively low melanopic equivalent daylight illuminance light exposure increases arousal before and during sleep without altering sleep structure. In *Journal of Sleep Research* . John Wiley and Sons Inc. https://doi.org/10.1111/jsr.14113	Light can influence many psychophysiological functions beyond vision, including alertness, circadian rhythm, and sleep, namely the non-image forming (NIF) effects of light. Melanopic equivalent daylight illuminance (mel-EDI) is currently recommended as the predictor of the NIF effects of light. Although light dose is also critical for entraining and regulating circadian cycle, it is still unknown whether relatively low mel-EDI light exposure for prolonged duration in the evening would affect pre-sleep arousal and subsequent sleep. In all, 18 healthy college students (10 females, mean [standard deviation] age 21.67 [2.03] years) underwent 2 experimental nights with a 1 week interval in a simulated bedroom environment. During experimental nights, participants were either exposed to high or low mel-EDI light (73 versus 38 lx mel-EDI, 90 versus 87 photopic lx at eye level, 150 photopic lx at table level) for 3.5 h before regular bedtime, and their sleep was monitored by polysomnography. Subjective sleepiness, mood, and resting-state electroencephalography during light exposure were also investigated. Results showed no significant differences in sleep structure and sleep quality between the two light conditions, whereas 3.5 h of exposure to high versus low mel-EDI light induced marginally higher physiological arousal in terms of a lower delta but higher beta power density before sleep, as well as a lower delta power density during sleep. Moreover, participants felt happier before sleep under exposure to high versus low mel-EDI light. These findings together with the current literature suggest that evening prolonged relatively low mel-EDI light exposure may mildly increase arousal before and during sleep but affected sleep structure less. © 2023 European Sleep Research Society.	arousal, evening light, melanopic equivalent daylight illuminance (EDI), sleep, electroencephalography (EEG), sleep quality

Selected database								
1. GOAL		2. OVERVIEW						3. METHOD
RESEARCH GOAL	HYPOTESIS STATEMENT	SUBJECT OF INVESTIGATION	ENVIRONMENT	N. ROOMS, FEATURES AND DIMENSIONS	LIGHT SOURCE	(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT	LOCATION	METHOD
Two main objectives: (1) To verify if the circadian values (m-EDI) in the classrooms could meet the recommended values reported in recent literature (WELL protocol), (2) to assess the influence on integrative lighting (photopic and melanopic illuminances) played by the electric lighting, as a function of the different lighting systems, and by daylighting, as a function of different room orientations and sky conditions.	/	Circadian values and influence on integrative lighting in classrooms	CLASSROOM	3 classrooms: similar geometrical (6.6m x 7.4m x 3.2m) and photometric properties in terms of room size and materials; but 3 different orientations: east, south, west.	Both daylight and electric lighting	(1) Three different orientations and different sky conditions (clear and overcast). (2) Existing configuration (fluorescent luminaires 300lx) + six possible retrofitting solutions (LED luminaires 500lx).	Turin, Italy	*The research relied on a combination of approaches: (i) Simulations to characterize photopic and melanopic illuminances for daylighting, (ii) field measurements to char- acterize photopic and melanopic illuminances in the classrooms for the existing elec- tric lighting systems, (iii) simulations to evaluate the photopic and melanopic illumi- nances in the classrooms due to different types of proposed retrofit LED lighting systems, (iv) combination of results to analyze the integrative lighting resulting from the combination of daylight and electric light.*
The aim of the present study was to investigate the effect of prolonged exposure to an integrative electric lighting system on melatonin secretion and perceived sleepiness, compared to the effect of a typical but qualitatively and functionally equivalent electric lighting system.	/	Melatonin secretion and sleepiness in officeworkers, effect of integrative lighting system	OFFICE	Six one-person cell offices (10.5 m2), on the same floor in the same office building; similar room layouts.	Electric lighting only	(2) Mean values: Standard lighting 294 lx e 158 lux m-EDI; Integrative lighting 289 lx e 199 lux m-EDI; data collected in winter months to minimize daylight exposure	Oslo, Norway	*The experiment utilised a 2 (SPD) × 7 (time of measurement) mixed experimental design with randomised allocation of subjects to two lighting conditions. The difference in SPD constituted the between-subjects factor in the design and the seven measurement sessions across time, constituted levels of the within-subjects factor. All procedures except for the manipulation of SPD were identical for the two lighting conditions. The luminaires in the three offices providing the experimental conditions were fitted with the integrative lighting system.The sample consisted of 13 women and 11 men. Salivary melatonin secretion and subjectively perceived sleepiness in the evening were measured every half hour during 3 hours of light exposure*
The near-cone metameric lights used in this study were designed to minimize disparities in both visual task performance and participant expectations while resulting in significantly different melanopic EDIs (above and below the recommended daytime levels), aiming to elicit differential physiological responses.	*(1) SW+ eliciting broad physiological effects, (2) SW– enhancing alertness while minimizing alterations in circadian rhythms.*	Alertness, sleep, mood and quality of life in shiftworkers exposed to spectrally engineered light source.	OFFICE	Watchfloor. No windows, 17 overhead fluorescent lights, ~45 monitors of various sizes. Six light boxes set up along the front counter of the watchfloor and directed into the main space.	Electric lighting only	(2) Similar-appearing light boxes (CCT 3000–3375 K; E 260–296 lux), enriched (SW+, mel-EDI: 294 lux) or attenuated (SW-, mel-EDI: 103 lux) in short-wavelength energy. (July-September)	Norfolk, Virginia (USA)	*We developed similar-appearing light boxes (correlated color temperature: 3000–3375 K; photopic illuminance: 260–296 lux), enriched (SW+, melanopic EDI: 294 lux) or attenuated (SW-, melanopic EDI: 103 lux) in short-wavelength energy, and implemented them on a high-security watchfloor. Efficacy and feasibility of these two novel lighting interventions were assessed in personnel working 12-hour night shifts (n = 47) in this within-participants, crossover study. For each intervention condition, light boxes were arranged across the front of the watch floor and illuminated the entire shift; blue-blocking glasses were worn post-shift and before sleep; and sleep masks were used while sleeping.*
The present study investigated whether exposure to high versus low mel-EDI for prolonged time (3.5 h) at night would influence pre-sleep physiology and sleep in a laboratory environment.	/	Sleepiness, mood, resing state on university students exposed to low m-EDI in the evening	BEDROOM	Sleep laboratory, 2 rooms simulating a bedroom: with one bed, two tables, a bookshelf, and a separate bathroom. Windows blocked with curtains.	Electric lighting only	(2) High or low mel-EDI light (73 versus 38 lx mel-EDI, 90 versus 87 photopic lx at eye level, 150 photopic lx at table level) for 3.5 h before regular bedtime	Guangzhou, China	*The study employed a within-subjects design with Light condition (73 versus 38 lx mel-EDI, 150 photopic lx at table level) as an independent factor, termed 'high mel-EDI' and 'low mel-EDI'. Participants underwent one acclimatisation night and two experimental nights in the laboratory with an interval of one week. On each experimental night, participants were under exposure to either high or low EDI light for 3.5 h. The order of the two light conditions was counterbalanced across participants.*

Annex A

4.3

Selected database								
							3. METHOD	
N.	PDF Reference number	TYPOLOGY Environmental analysis/Subject survey	/SOFTWARE USED/	/HARDWARE USED/	/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/	MEASURED/SIMULATED STUDY OBJECT	MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES	/Human-centred MEASURED DATA (physiological variables measured by the hardware)/
13	59	**Environmental analysis - SIMULATION BASED and FIELD MEASUREMENTS**	ALFA, Lark (v2), Owl, ClimateStudio,	**Spectrophotometer** Gigahertz BTS256-EF	/	20 measurement points, 27 combination of orientations—sky conditions—day considered	EML, m-EDI	/
14	60	**Subject survey**	/	JETI Specbos 1201 **Spectroradiometer**; **SALIVA ANALYSIS**	**QUESTIONNAIRE** (KSS 9-point Scale)	Comparison between different lighting patterns through subject evaluation	Photopic illuminance (lx), Mel. EDI (lx)	**Saliva samples:** measurements on salivary melatonin secretion;
15	63	**Subject survey**	/	SpectraScan **Spectroradiometer** PR-670 (PhotoResearch, North Syracuse, NY, USA); **Actigraph watch**	**QUESTIONNAIRE:** World Health Organization Health and Performance Questionnaire (HPQ); **TEST:** Karolinska sleepiness scale – KSS, 9-point scale, PSYCHOMOTOR VIGILANCE TASK (PVT); **SURVEYS** (Survey with the reduced HorneOstberg Morningness Eveningness Scale (MEQ); Survey of shiftworkers (SOS); Survey containing QOL Index); **SLEEP DIARY**	Comparison between different lighting patterns through subject evaluation	CCT, Photopic illuminance, m-EDI	**Actigraph watch**: to continuously measure activity and photic exposure patterns, measures of sleep consolidation: sleep efficiency; average sleep bout (the average length in minutes of each uninterrupted sleep bout); and average wake bout.
16	68	**Subject survey**	Profusion Polysomnography 3.0 software (Compumedics Ltd., Melbourne, Australia): for sleep structure	**Actiwatch** Spectrum PRO, Philips Respironics; **EEG;** electrodes for PSG recordings; **spectroradiometer** (JETI Specbos 1201)	**QUESTIONNAIRE**: Karolinska Sleepiness Scale (KSS) – 9 point scale; Activation–Deactivation Adjective Check List (AD ACL) – 5 point likert scale; Groningen Sleep Quality Scale (GSQS) – Yes or no answers.	Comparison between different lighting patterns through subject evaluation	Photopic illuminance, m-EDI, CCT	**Actiwatch**: sleep/wake data and sleep dynamics; **EEG**: Physiological arousal before sleep; **Electrodes:** for polysomnographic (PSG) recordings

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	RECOMMENDED VAUES ADRESSED	REACHING OF RECOMMENDED VALUES	TYPOLOGY Long/Medium/Short term	/Number of people involved/	RESULTS	LIMITATIONS
/	WELL (150EML OR 275 EML)	NOT ALWAYS REACHED: daylight alone was always sufficient to meet the requirements under a clear sky without blinds	Long term: Annual time-series	/	*Although daylight is the primary light source in classrooms , it is not always sufficient to provide the recommended circadian entrainment, particularly when shading devices are used to control glare or overcast sky conditions are prevalent. The required vertical m-EDI should be achieved through the electric lighting contribution, but existing electric lighting systems, such as the one analyzed in this study, are designed to provide a target illuminance on the horizontal plane and might not be adequate to provide a sufficient vertical illuminance at the eye level. Furthermore, as shown in the study, the spectral power distribution of light sources could be poor in short wavelengths, thus further lowering the electric lighting contribution to circadian entrainment.*	/
Questionnaire: KSS for subjectively perceived sleepiness	/	REACHED: Desks are provided with 150 equivalent melanopic lux from the electric lights.	Short term: few hours	24	*Directed low-intensity melanopic illuminance provided by an integrated electric lighting system affects melatonin secretion in the body. Effects beyond vision are obtainable without significant deviations from ordinary lighting conditions and without the use of specialised luminaires. Showing that sleepiness and acute changes in melatonin secretion are not directly linked, the current results substantiate previous findings as well as the assumption that sleepiness and melatonin secretion are independent processes, but still indirectly associated. Relatively high correlations between perceived sleepiness and NA, chronobiological stability (CTI-R-FR) and chronobiological amplitude (CT-I-LV).*	(1) Perceived lighting quality assessments were not considered
Questionnaire: HPQ to estimate the workplace costs of health problems; **Test**: KSS and PVT for alertness; **Surveys:** MEQ to assess chronotype; SOS for demographics, work, and circadian and sleep health; QOL Index for satisfaction and importance of 33 items; and original questions about the intervention. **Consensus Sleep diary**: sleep quality (5-point Likert scale); sleep duration; sleep onset latency (minutes to fall asleep); wake after sleep onset (WASO, minutes awake after initiating sleep); clock times for sleep onset, midsleep and wake; and caffeine use (in mg);	CIE S 026/E:2018	REACHED: Specifically designed to reach the recommended values.	Medium term: 48 day period	47	*Both interventions yielded positive benefits; however, the pattern of results was not identical under the two conditions, nor was it always consistent between objective and subjective measures. Strenght (1): manipulation of melanopic EDI without significant alterations in visual stimulation: white-appearing, near-metameric light boxes of similar photopic intensities but distinct biological potencies. Strenght (2): the sizable implementation component: The photopic lux levels of our light boxes are more similar to the control comparison; partly responsible for the relatively lower levels of symptoms (e.g. glare, headache) reported. Improvements in sleep, alertness, mood, and QOL for night shiftworkers. Augmentation of the lighting in a unique work environment to improve sleep, alertness, and mood without compromising visual comfort and satisfaction. More work is needed to tease apart the various factors contributing to the differences between results. We would have expected that short-wavelength-enriched light would demonstrate more sustained physiological effects compared to short-wavelength-attenuated light, but we did not find that to be true across all measures.*	(1) No reliably assess individual photic exposure patterns, should implement with photosensors near the head in the direction of gaze. (2) The high-security nature of the watchfloor posed unique additional challenges. (3) Differences in dataset composition and size between outcomes, which could account for the lack of correspondence between objective and subjective outcomes
Questionnaire: KSS for subjective sleepiness; AD ACL to assess subjective positive and negative mood; GSQS for subjective sleep quality	CIE: relatively low mel-EDI (<10 lx mel-EDI) at least 3 h before bedtime	REACHED: Specifically designed to reach the recommended values.	Short term: 2 days	18	*Weakly confirm to the alerting effect of high mel-EDI light at night. The subjective sleepiness did not differ between the two light conditions. Moreover, participants felt happier in the high versus low mel-EDI condition, whereas no significant difference in negative mood was found. Thus, this may suggest that high mel-EDI at night increased the level of arousal of a positive mood. The present findings, complemented by previous studies, suggest that exposure to high mel-EDI but lower photopic illuminance at night could mildly enhance physiological arousal. No significant influences on subjective sleep quality. Participants showed relatively higher arousal during sleep after exposure to high versus low mel-EDI before bedtime. No statistical differences in subjective sleepiness and mood between the two light conditions. Moderate evidence that high versus low mel-EDI light induced no significant influence on sleep structure, whereas weak to moderate evidence on physiological arousal before and during sleep. The effects of relatively low mel-EDI light on nocturnal sleep at night may depend on the prolonged duration of light exposure. In addition, sleep EEGs represent a more sensitive indicator to assess the NIF effect of light on sleep.*	(1) the light exposure history preceding the experimental light intervention was not assessed; (2) the sample size of the present study was relatively small (3) the difference between the two employed light conditions is slight (merely 35 lx mel-EDI); (4) circadian rhythm markers (e.g., melatonin level) were not measured before bedtime, so no exploration on the relationship between evening light, circadian rhythm, and nocturnal sleep.

Annex A

5.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
17	69	Bellia, L., Fragliasso, F., Seraceni, M., & Sodano, G. (2023). Integrative Lighting Design: How to Optimize Visual and Non-visual Effects in a Cell Office. In *Journal of Daylighting* (Vol. 10, Fascicolo 2, pp. 192–203). Solarlits. https://doi.org/10.15627/jd.2023.16	The objective of this paper is to outline fundamental principles for the electric lighting design of workplace environments such as offices. The study considers both the suggested guidelines and values for non-visual light design and the specifications for visual tasks dictated by the EN 12464-1:2021. When properly balanced, the two distinct procedures – for the visual task and for the non-visual responses-can lead to an integrated lighting design: This integration ensures that the office environment provides both well-being and optimal visibility for tasks that require good lighting conditions. Various lighting scenarios, using only electric lighting, were analysed under different conditions and parameters (three different photometries, three different spectra and three environmental wall reflectance configurations). The choice of luminaire photometry is critical in achieving a well-rounded integrated design, as observed in the examination of various scenarios. Depending on the goals set, the designer can also decide whether to use a spectrum that stimulates the eye the most: Different spectra with similar correlated colour temperatures were compared to evaluate the impact on design purposes. The next step of the research work is to consider the daylight into the project and an evaluation of the potential energy savings it can offer. © 2023 The Author(s).	Human centric lighting, Chronobiology, ipRGCs, Non-visual effects of light
18	75	Grant, L. K., Crosthwaite, P. C., Mayer, M. D., Wang, W., Stickgold, R., St. Hilaire, M. A., Lockley, S. W., & Rahman, S. A. (2023). Supplementation of ambient lighting with a task lamp improves daytime alertness and cognitive performance in sleep-restricted individuals. In *Sleep* (Vol. 46, Fascicolo 8). Oxford University Press. https://doi.org/10.1093/sleep/zsad096	We examined the impact of adding a single-high-melanopic-illuminance task lamp in an otherwise low-melanopic-illuminance environment on alertness, neurobehavioral performance, learning, and mood during an 8-h simulated workday. Sixteen healthy young adults [mean(±SD) age = 24.2 ± 2.9, 8F] participated in a 3-day inpatient study with two 8-h simulated workdays and were randomized to either ambient fluorescent room light (~30 melanopic EDI lux, 50 lux), or room light supplemented with a light emitting diode task lamp (~250 melanopic EDI lux, 210 lux) in a cross-over design. Alertness, mood, and cognitive performance were assessed throughout the light exposure and compared between conditions using linear mixed models. The primary outcome measure of percentage correct responses on the addition task was significantly improved relative to baseline in the supplemented condition (3.15% ± 1.18%), compared to the ambient conditions (0.93% ± 1.1%; FDR-adj q = 0.005). Additionally, reaction time and attentional failures on the psychomotor vigilance tasks were significantly improved with exposure to supplemented compared to ambient lighting (all, FDR-adj q ≤ 0.030). Furthermore, subjective measures of sleepiness, alertness, happiness, health, mood, and motivation were also significantly better in the supplemented, compared to ambient conditions (all, FDR-adj q ≤ 0.036). There was no difference in mood disturbance, affect, declarative memory, or motor learning between the conditions (all, FDR-adj q ≥ 0.308). Conclusions: Our results show that supplementing ambient lighting with a high-melanopic-illuminance task lamp can improve daytime alertness and cognition. Therefore, high-melanopic-illuminance task lighting may be effective when incorporated into existing suboptimal lighting environments. © 2023 The Author(s).	Lighting, Sleep, Cognition, sleep, adult, human, Humans, illumination, cognition, Article, controlled study, human experiment, light exposure, alertness, crossover procedure, declarative memory, dietary supplement, fluorescent lighting, hospital patient, light intensity, mental performance, mood, mood disorder, motivation, motor learning, outcome assessment, psychomotor vigilance task, randomized controlled trial, reaction time, somnolence, supplementation, task performance, wakefulness, wellbeing, working time
19	79	Bochnia, A.-K., Ruohonen, S. M., Pajuste, M., & Hansen, E. K. (2022). Evaluating an integrative lighting design for elderly homes—A mixed methods approach. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1099, Fascicolo 1). Institute of Physics. https://doi.org/10.1088/1755-1315/1099/1/012028	The experience of light in a space and the physiological effect of light combined is complex to study. Methods which combine parameters from the fields of the biological, visual and atmospheric effects of light through a combination of both qualitative and quantitative data collection on site, seem more important than ever to validate the potentials of integrative lighting. A case study, conducted in two elderly homes in Copenhagen and Aarhus, in Denmark, is used to evaluate a mixed methods approach, assessing an integrative lighting design solution. Luminaires with circadian settings are implemented as a supplementary lighting with the aim of supporting various objectives, including biological stimulation and a homely atmosphere in the elderly homes. To evaluate the implementation of the lighting, a convergent mixed methods approach is used, collecting quantitative and qualitative data. In parallel to collecting quantitative measurements, such as melanopic equivalent daylight illuminance (mEDI) and photopic lux, semi-structured interviews based on questionnaires and card-sorting, on the same subjects, are carried out. To evaluate the approach for evaluating the implementation of this integrative lighting design, three criteria are introduced: a) integration, b) flexibility and c) validity. The integration of results enabled to compare the different methods and findings to identify and study correlations, differences or contradictions. That was conducted across the three topics: biological, visual, and atmospheric effects of the integrative lighting design solution. A framework for a holistic approach for evaluating lighting in elderly homes was defined, with an indication of the need for further development in an iterative process. © Published under licence by IOP Publishing Ltd.	/
20	84	Ravn, M., Mach, G., Hansen, E. K., & Triantafyllidis, G. (2022). Simulating Physiological Potentials of Daylight Variables in Lighting Design. In *Sustainability (Switzerland)* (Vol. 14, Fascicolo 2). MDPI. https://doi.org/10.3390/su14020881	A holistic approach to daylight dynamics in our built environment can have beneficial outcomes for both physiological and visual effects on humans. Simulations of how daylight variables affect light levels on the horizontal work plane are compared to their physiological effects, measured as melanopic EDI (Melanopic Equivalent Daylight Illuminance) on a vertical plane. The melanopic EDI levels were calculated in a simulated office space in ALFA software (Adaptive Lighting for Alertness) employing the daylight variables of orientation, time of day, season, sky conditions and spatial orientation. Results were analyzed for how daylight design can contribute to the physiological effects of dynamic light in office buildings. Daylight is shown to be a sufficient light source in the majority of cases to meet the recommended values of EDI and provide the suggested horizontal lx level according to the Danish Standards. A mapping of daylight conditions, focusing on the specific factors presented here, can provide guidelines in the design process and future smart building systems. The complex interrelationship between these parameters is important to acknowledge when working with daylight dynamics as a sustainable element in architecture and lighting design. © 2022 by the authors. Licensee MDPI, Basel, Switzerland.	physiology, daylight, building, holistic approach, physiological response, software

Selected database									
1. GOAL		2. OVERVIEW						3. METHOD	
RESEARCH GOAL	HYPOTESIS STATEMENT	SUBJECT OF INVESTIGATION	ENVIRONMENT	N. ROOMS, FEATURES AND DIMENSIONS	LIGHT SOURCE	(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT	LOCATION	METHOD	
The objective of this paper is to outline fundamental principles for the electric lighting design of workplace environments such as offices. The study considers both the suggested guidelines and values for non-visual light design and the specifications for visual tasks dictated by the EN 12464-1:2021. The purpose of this work is to bring out how an integrative approach to lighting design requires careful choices to balance visual and non-visual needs.	/	27 lighting scenarios and whether they reached the recommended NV values together with visual values	OFFICE	Office: 4.0 m wide, 4.0 m deep and 3.0 m high. The task area was set at 80 cm from the floor and the occupant's eye - in a sitting position - at 120 cm from the floor	Electric lighting only	(2) 27 lighting scenarios, 3 lighting solutions: direct light-direct/indirect-indirect. For each three different LED spectral power distributions at CCTs=3000 K - 4000 K - 6000 K	/	*Different lighting system solutions are proposed starting from a simple case study. Taking advantage of the dimming of the luminous flux emitted by the luminaires, twenty-seven different lighting scenarios have been developed. The protocol is divided into two procedures A and B. Procedure A consists in arranging and setting the luminaires in such a way as to guarantee 500 lx on the task area and also comply with the other requirements of EN 12464-1. Procedure B starts from the same settings and varying the luminaires fluxes to achieve the necessary eye illuminances to fulfil the CS and mel-EDI requirements (CS=30%, mel-EDI=250 lux). DIALux software was used for the simulations of the office space.*	
We examined the impact of adding a single-high-melanopic-illuminance task lamp in an otherwise low-melanopic-illuminance environment on alertness, neurobehavioral performance, learning, and mood during an 8-h simulated workday.	*(1) Improvement of non-visual alerting effects using supplemental high-melanopic-illuminance task lighting.*	Neurobehavioural performance and subjective sleepiness, mood, health and well being on participants exposed to high melanopic illuminance task lamps.	OFFICE	Office with no windows	Electric lighting only	(2) 1.ambient fluorescent room lighting (~30 mel-EDI lux and ~50 photopic lux); 2.ambient fluorescent room lighting and high-melanopic illuminance light emitting diode (LED) task lamp (~250 mel-EDI lux and ~210 photopic lux).	Boston, Massachusetts (USA)	*Sixteen healthy young adults [mean(±SD) age = 24.2 ± 2.9, 8F] participated in a 3-day inpatient study with two 8-h simulated workdays and were randomized to either ambient fluorescent room light (~30 melanopic EDI lux, 50 lux), or room light supplemented with a light emitting diode task lamp (~250 melanopic EDI lux, 210 lux) in a cross-over design. Alertness, mood, and cognitive performance were assessed throughout the light exposure and compared between conditions using linear mixed models.*	
A case study, conducted in two elderly homes in Copenhagen and Aarhus, in Denmark, is used to evaluate a mixed methods approach, assessing an integrative lighting design solution. Luminaires with circadian settings are implemented as a supplementary lighting with the aim of supporting various objectives, including biological stimulation and a homely atmosphere in the elderly homes.	*(1) Integrative approach able to form a holistic evaluation, applying methods from quantitative and qualitative research.*	Biological, visual and atmospheric effects of the integrative lighting solutions on elderly homes	ELDERLY HOME	4 apartment in total (2 in Aarthus and 2 in Copenhagen)	Both daylight and electric lighting	(1) Month of April 2022 (2) Three different types of light fixtures. 1: SolMate for circadian dark lighting setting; 2-3: NightMate and BathMate, for evening and night time.	Copenhagen and Aarhus, in Denmark	*Mixed method approach: Quantitative methos: measurements of the m-EDI from the field of view of the observer, all the task lighting measurements were taken at 9pm, for the measurement, all the other light sources were turned off, except for the fixtures implemented in the ILD solution. Qualitative Methods. For the qualitative research, semi-structured interviews were conducted, using card sorting as a projective technique. The interviews were based on questionnaires.*	
The experiment aims to understand how changes in season, weather, time of day and orientation affect the daylight conditions in our buildings, focusing exclusively on the daylight intake's ability to meet either the melanopic EDI Ix recommendations or the Danish horizontal lx standards for office spaces	*(1) Finding imputs for Integrative Lighting.*	Daylight intake/ability to reach recommended values in regard to chang in season, wheater, time of day and orientation	OFFICE	Simulated office 6.2 x 4.3 x 2.6 m, two side windows with a size of 1.35 x 0.85 m, window orientations of north, east, west, south were used. 4 workstations.	Daylight only	(1) Simulations on the 21st of December, June and March, September (summer and winter solstice + spring/fall equinox measures). Clear sky, partly cloudy and overcast.	Copenhagen, Denmark	*To study the impact and the relation of daylight dynamics to melanopic EDI levels, as well as their relation to horizontal illuminance levels, two experiments have been conducted with the ALFA simulation tool. First, we examine how simulations of daylight dynamics with the variables of time of day, season, orientation and sky type meet 250 melanopic EDI, the minimum recommendation during daytime to support alertness, the circadian rhythm and a good night's sleep. Secondly, we examine how calculations of dynamic daylight, using the same variables, meet Danish standards for 500 horizontal lx.*	

Annex A

5.3

Selected database								
						3. METHOD		
N.	PDF Reference number	TYPOLOGY Environmental analysis/Subject survey	/SOFTWARE USED/	/HARDWARE USED/	/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/	MEASURED/SIMULATED STUDY OBJECT	MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES	/Human-centred MEASURED DATA (physiological variables measured by the hardware)/
17	69	**Environmental analysis - SIMULATION BASED**	DIALux	/	/	27 lighting scenarios	CCT; Ē (lux); Ev (lux); Ev/Ē; CLA (W/m2); CS (%); mel-EDI (lux)	/
18	75	**Subject survey**	/	Wrist-worn actigraphy (**Actiwatch**, MiniMitter Company, Inc., Sunriver, OR); PR-650 SpectraScan **Colorimeter** with CR-650 cosine receptor	**TASKS:** Psychomotor Vigilance Task (PVT), 2-min Addition Task (AT), motor sequence task (MST) and word pairs (WP) tasks; **QUESTIONNAIRES**: Karolinska Sleepiness Scale (KSS); and Visual Analog Scales (VAS); PANAS questionnarire - 5 point scale; Profile of mood states (POMS)	Neurobeavioural performance and subjective sleepiness, mood, healt and well being in participants exposed to high melanopic illuminance TASK LAMP.	Photopic illuminance; m-EDI; m-DER	**Actiwatch**: to confirm a constant 7-h sleep/dark schedule
19	79	**Environmental analysis - FIELD MEASUREMENTS AND Subject survey**	/	**Spectrometer** by GL Spectis (1.0 touch + flicker) (180° hemisphere sensor); Voltcraft **lux meter** MS-200 to measure task lighting.	**INTERVIEWS based on QUESTIONNAIRES**	Biological, visual and atmospheric effects of ILD solutions.	Melanopic daylight illuminance (mEDI); Photopic lux. (the measurements were taken five times a day (at 9am, 12am, 3pm, 6pm and 9pm)).	/
20	84	**Environmental analysis - SIMULATION BASED**	LFA, Rhinoceros	/	/	Daylight intake in office environment for circadian values.	melanopic EDI (Melanopic Equivalent Daylight Illuminance) on a vertical plane	/

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	*RECOMMENDED VAUES ADRESSED*	*REACHING OF RECOMMENDED VALUES*	*TYPOLOGY Long/Medium/Short term*	*/Number of people involved/*	*RESULTS*	*LIMITATIONS*
/	Adressed: Rea et al. Circadian Stimulus (CS) Lucas et al. model on which the CIE S 026 based the Equivalent Daylight Illuminance (EDI); Used in the study: CIE standard and the WELL recommendations, expressing the values in mel-EDI [lux]	REACHED: (A): Not always (B): Specifically designed to reach the recommended values.	Short term: few measurements	/	*In this work, the luminaire that gave the best results for both cases – visual and non-visual – is the direct/indirect one: it was the best option in an office environment, when the goal is to adequately stimulate our circadian system during the day. Looking instead at the spectra – which anyway play a significant role – we see that, as the colour temperature increases and gets closer to the CCT of the D65, we have increasingly better values. It should be noted that with 6000 K it is almost always possible to satisfy the parameters required by the non-visual. With lower colour temperatures this is not true. Environmental conformation – such as the position of the luminaires and the reflectance of the walls – becomes a key factor, in this case.*	(1) Absence of daylight: need further investigation
Tasks: PVT for sustained attention, AT for working memory and processing speed, MST and WP to assess procedural learning and declarative memory; **Questionnaires**: KSS for subjective sleepiness, VAS for alertness, health and well-being, PANAS measure positive and negative affect, POMS for mood disturbance	50 melanopic ED	REACHED in the supplemented condition	Short term: 3 days	16	*In this study, we found improvement in daytime cognition and alertness outcomes through supplementation of sub-optimal ambient room lighting with high-melanopic-illuminance task lighting. Consistent with previous studies, we found that exposure to higher melanopic illuminance improved subjective sleepiness, alertness and wellbeing, and objective measures of neurobehavioral performance and working memory. Additionally, the supplemented lighting condition was not associated with adverse visual experience or discomfort as compared to the dimmer and low-melanopic-strength ambient condition and there was, for some items on the Headache and Eye Strain Scale, a trend toward the supplemented lighting condition being rated as more favorable. Further investigation of the benefits of task lamps at the work surface is necessary.*	(1) potential disconnect between laboratory and field-based studies, and studies in healthy controls compared to patient populations, which may lead to apparent inconsistencies. (2) current study cannot determine relative photoreceptor contribution in the responses (3) short duration of experiment
Interviews: on the perception of light in relation to the feeling of homeliness	CIE	REACHED: Specifically designed to reach the recommended values. BUT illuminance levels for task lighting NOT REACHED.	Medium term: 24 days	20	*The summaries are provided both as numerical values regarding how many of the measurement positions reached the target values, and as number and tendency of responses per each interview question. The inspection of the summarized results reveals correlations, differences, and contradictions in the data, both within the topics and across. A contradiction within a topic can be found in the results regarding circadian rhythm of the residents, where the measurements point mostly towards positive values, while the interview data shows no positive change. Therefore, the result on the topic of circadian rhythm is inconclusive regarding the residents. The effect of light on the circadian rhythm of staff is as well inconclusive since no qualitative data was collected. Conflicting results: where the ILD solution support the circadian rhythm, the task lighting is not sufficient in photopic illuminance. Successful comparable data from the quantitative and qualitative methods were, however, obtained with regard to the circadian rhythms of the elderly.*	Reason for contradictions might lie in the set target values, methods used for evaluation, or in the lighting design solution itself, such as the programmed light curve over the day. (1) Better to focus on a single topic and fewer research questions. (2) Short implementation period.
/	CIE recommendations: 250 melanopic EDI during the day	REACHED: Daylight is shown to provide a sufficient light source in the majority of cases to meet the recommended values of melanopic EDI (78/108 calculations) and horizontal lx level (60/108 calculations)	Short term: 4 days (along the year) and 3h each day as representative data (1 day representing each season).	/	*The results of the experiment can be divided into categories of time, weather conditions, architectural design choices and lighting conditions, as guidelines for understanding daylight qualities and the need for additional electrical light. Apart from seasonal changes, time of day is connected to window orientation, the only parameter controlled and designed by the architect and lighting designer. The weather conditions have an overall impact depending on seasonal changes, and since sky conditions can change several times during the day, it is the most acute and dynamic of the four factors. The complex interrelationship between these parameters is important to acknowledge when working with daylight dynamics as a sustainable element in architecture.The winter calculations for morning and overcast conditions resulted in low values for both the horizontal lx and melanopic EDI lx. During these periods, additional electrical lighting will be needed to meet the recommendations. There can be conflicting criteria, but if we unfold the potential within each criterion by studying how daylight variations can meet the specific needs, it may inspire new approaches for working with the complex interplay between daylight and electrical light.*	(1) Horizontal lx measurements may not be the most relevant method in modern office environments since our workflows and tasks have changed. (2) The horizontal work plane lx and melanopic EDI lx are only two criteria in the complex process of integrative lighting designing. (3) The tool presented for simulating melanopic EDI lux is relevant toward integrating the complex parameter physiological effects, however it is still a simulation.

Annex A

6.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
21	89	Lee, J., & Boubekri, M. (2022). INTRODUCTION OF NEW DAYLIGHTING METRICS FOR HEALTH, WELLBEING, AND FEASIBILITY: A STUDY OF THE INDOOR BUILDING ENVIRONMENT. In *Journal of Green Building* (Vol. 17, Fascicolo 1, pp. 105–126). College Publishing. https://doi.org/10.3992/jgb.17.1.105	This study investigates the applicability of a new daylighting metric based on human health, an emerging framework for evaluating the effect of daylight on building occupants. Procedures based on modeling annual daylight availability are used to determine the mapping of daylight distribution on a daily, seasonal, and yearly basis. Literature review and experimental studies were performed to propose the new daylighting metrics for health and wellbeing. The proposed metrics have two broad criteria, including daylighting level, timing, and duration. The two details are as follows: (1) 400 lux for 5 hours (2K lux·h) in the daytime; and (2) 500 lux for 1 hour (0.5K lux·h) in the early morning, 8AM-9AM. To verify the applicability of the proposed daylighting metrics to current buildings, sample buildings were selected and daily, spatial and seasonal differences were simulated through computer visualization techniques. Moreover, we evaluated the application of the daylighting metric on the building layout and compared the new daylighting metric for health and wellbeing with conventional daylighting metrics. © 2022, College Publishing. All rights reserved.	Daylighting, Daylight, Circadian rhythms, Health, Wellbeing, Buildings, Human health, Building environment, Literature reviews, 'current, Daylight availability, Daylighting metric, Health and wellbeing
22	110	Englezou, M., & Michael, A. (2022). Evaluation of visual and non-visual effects of daylighting in healthcare patient rooms using climate-based daylight metrics and melanopic metrics. *E3S Web of Conferences* , *362* . https://doi.org/10.1051/e3sconf/202236201003	Daylight access in healthcare facilities is essential for creating comfortable ambiance conditions for the patients during their accommodation in a hospital. The aim of this paper is to investigate how the window size, the location (Paralimni in Cyprus and Brussels in Belgium), the room orientation and patients' gaze direction have an impact on visual and non-visual effects. This research focuses on hospitals' most typical patient room: the double room (3.50m * 5.50m). The building parameters under study arc eight orientations and three window sizes. Moreover, other parameters are the timing (season and hour in a day), the patient placement inside the room, and the patient gaze directions. For this study, computer simulations are used for daylight assessment using climatc-bascd daylight metrics and CIE S026 melanopic metrics for non-visual effects. Research findings show that it is possible to examine design options through a comprehensive investigation of climatc-bascd daylight metrics and CIE S 026 melanopic metrics for optimised performance for visual and non-visual effects.	/
23	115	Favero, F., Lowden, A., Bresin, R., & Ejhed, J. (2023). Study of the Effects of Daylighting and Artificial Lighting at 59° Latitude on Mental States, Behaviour and Perception. *Sustainability* , *15* , 1144. https://doi.org/10.3390/su15021144	Although there is a documented preference for daylighting over artificial electric lighting indoors, there are comparatively few investigations of behaviour and perception in indoor day-lit spaces at high latitudes during winter. We report a pilot study designed to examine the effects of static artificial lighting conditions (ALC) and dynamic daylighting conditions (DLC) on the behaviour and perception of two groups of participants. Each group (n = 9 for ALC and n = 8 for DLC) experienced one of the two conditions for three consecutive days, from sunrise to sunset. The main results of this study show the following: indoor light exposure in February in Stockholm can be maintained over 1000 lx only with daylight for most of the working day, a value similar to outdoor workers' exposure in Scandinavia; these values can be over the recommended Melanopic Equivalent Daylight Illuminance threshold; and this exposure reduces sleepiness and increases amount of activity compared to a static artificial lighting condition. Mood and feeling of time passing are also affected, but we do not exactly know by which variable, either personal or group dynamics, view or variation of the lighting exposure. The small sample size does not support inferential statistics; however, these significant effects might be large enough to be of importance in practice. From a sustainability point of view, daylighting can benefit energy saving strategies and well-being, even in the Scandinavian winter.	lighting design; lighting perception; temporal perception; multidisciplinary approach; Scandinavian winter; sustainable environments
24	123	Potočnik, J., & Košir, M. (2021). Influence of geometrical and optical building parameters on the circadian daylighting of an office. *Journal of Building Engineering* , *42* , 102402. https://doi.org/10.1016/j.jobe.2021.102402	An average working individual in today's society spends a considerable amount of a typical day in an office environment. This, in turn, can negatively influence her or his circadian system if the indoor built environment is not designed to provide adequate luminous conditions. Therefore, the presented paper's main objective was to address the extent to which indoor built environment parameters influence the characteristics of the indoor non-visual and visual luminous environment. To answer the stated question, a statistical analysis of parametric simulations using multispectral software ALFA was carried out for a sample cellular office in Ljubljana, Slovenia. The influence of room, geometrical (depth, width, and window to wall ratio), and optical (reflectance of walls, ceiling, and floor and glazing transmissivity) parameters was studied for four cardinal occupant view directions. The results show that the window is the most influential building element as the window to wall ratio and glazing transmissivity are the most influential geometrical and optical parameters. However, it was exposed that this is not entirely true for occupant positions deeper in space and facing away from the window, as the influence of all studied building parameters changes according to the view orientation and position in relation to the window.	Daylighting; Circadian daylighting; Indoor lighting environment; Photobiology; Healthy lighting

Selected database									
1. GOAL		2. OVERVIEW						3. METHOD	
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*	
This study aims to analyze the relationships between some characteristics of daylight, namely light intensity, light spectrum, the duration of exposure to daylight, and the timing of exposure and some human health indicators. Based on these relationships between daylight and health, our study will generate new daylighting metrics targeting health and well-being of building occupants.	/	Characteristics of daylight: light intensity, light spectrum, duration of exposure to light of day, timing of exposure and some human healt indicators	OFFICE BUILDING	4 offices one oriented in each direction from a database consisting of 300 rooms randomly selected from 3,000 rooms in approximately 70 buildings at the University of Illinois.	Both daylight and electric lighting	(1) Annual simulations. One condition without windows one exposed to daylight. Same level of light but greater exposure to blue light in the daylight condition.	Champaign, Illinois (USA); Seoul, Korea	*To verify the applicability of the proposed daylighting metrics to current buildings, sample buildings were selected and daily, spatial and seasonal differences were simulated through computer visualization techniques.*	
The aim of this paper is to investigate how the window size, the location, the room orientation and patients' gaze direction have an impact on visual and non-visual effects.	/	Window size, location, room orientation, timing (season and hour of day) and patients gaze direction impact on visual and non visual effects	HOSPITAL, PATIENT ROOM	Hospitals' most typical patient room: double room (3.5m x 5.5m). Eight orientations and 3 window sizes analysed	Daylight only	(1) Weather files of Typical Meteorological Years for the given locations. Only clear and Overcast skies used	Paralimni, Cyprus; Brussels, Belgium	*This study evaluates natural lighting performance in a typical hospital patient room (3.50m*5.50m). Three different window-to-wall ratios and eight orientations (South, North, East, West, South-East, South- west, North-East, North-West) are under study. In addition, the analysis includes an investigation of two locations; Brussels in Belgium (Lat. 50.85° N, Long. 4.36° E) and Paralimni in Cyprus (Lat. 35.05° N, Long. 33.99° E). For this study, computer simulations are carried out using climate-based daylight metrics for the visual effects and CIE S026 melanopic metrics for the non-visual effects. For the study the software Climate Studio and ALFA in Rhinoceros 7 were used.*	
Pilot study designed to examine the effects of static artificial lighting conditions (ALC) and dynamic daylighting conditions (DLC) on the behaviour and perception of two groups of participants	/	Effects of daylight and artificial lighting on mental state, behaviour and perception	STUDY ROOM	2 studyrooms on fifth and third floor of same building. ALC = 8x8x3.9m; DLC = 8x6x3.9m.	Both daylight and electric lighting	Artificial lighting condition (ALC) without view; A day-lit only condition with view (DLC). (1) Month of February in given location; overcast and intermediate weather.	Stockholm, Sweden	*In this investigation, we designed the following: An artificial lighting condition (ALC) without view; A day-lit only condition with view (DLC). We examined the effects of these lighting conditions using a multidisciplinary approach that combined methods from psychology and lighting design. Participants experienced one of the two classrooms furnished as study rooms during a three-day experiment.*	
The present paper's main objective is to study the importance of WWR, glazing transmissivity, wall, ceiling and floor reflectance, room depth, width and view orientation on indoor non-visual and visual luminous content, using statistical techniques on a case of a simple cellular office.	/	Depth, width, w-t-w ratio, reflectance of wall, ceiling, floor, glazing trasmittivity, viwe direction influence on visual and non visual effects	OFFICE	Different simulated model, from a minimum of 9m2 to a maximum of 64m2. WWR varied between 20 and 40 %. 180 possible geometrical room variations, 11 selected. 27 materials with diffusely reflecting surfaces	Daylight only	(1) Single point in time (21st of March at noon solar time) for Ljubljana, Slovenia. A uniform overcast sky type was generated, which resulted in external horizontal global illuminance (Eext,v) of 37161 lx	Ljubljana, Slovenia	*A statistical analysis of parametric simulations using multispectral software ALFA was carried out for a sample cellular office in Ljubljana, Slovenia. The influence of room, geometrical (depth, width, and window to wall ratio), and optical (reflectance of walls, ceiling, and floor and glazing transmissivity) parameters was studied for four cardinal occupant view directions.*	

Annex A

6.3

Selected database								
						3. METHOD		
N.	*PDF Reference number*	*TYPOLOGY Environmental analysis/Subject survey*	*/SOFTWARE USED/*	*/HARDWARE USED/*	*/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/*	*MEASURED/SIMULATED STUDY OBJECT*	*MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES*	*/Human-centred MEASURED DATA (physiological variables measured by the hardware)/*
21	89	**Subject survey**	Grasshopper and Design Iterate Validate Adapt (DIVA) for daylighting metric simulation;	**Actiwatch** spectrum plus (INDICATORS OF SLEEP QUALITY AND QUANTITY)	**SURVEYS**: Short Form-36 (SF-36) and Pittsburgh's Sleep Quality Index (PSQI)	Daylight distribution on a daily, seasonal, and yearly basis; TCharacteristics of daylight: light intensity, light spectrum, duration and timing of exposure to daylight, and some human health indicators.	Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (aSE), Mean hourly Illuminance (MHI), Useful daylight illuminance (UDI), Daylight factor (DF); EML; photopic illuminance.	**Actiwatch spectrum plus:** Early morning light exposure (lux), Daily light exposure (lux), Sleep onset latency, Sleep efficiency (%), Wake after sleep onset, Sleep time, Sleep fragmentation
22	110	**Environmental analysis - SIMULATION BASED**	Climate Studio; Rhinoceros 7; Radiance; ALFA	/	/	3 seasons (21/12, 21/06; 21/03), 5 hours each day (7 a.m., 9a.m., 12p.m., 3p.m., 5p.m.) 4 placements of the patients, for each placement 3 gaze directions at 1.3m	Useful Daylight Illuminance, Spatial Daylight Autonomy; Annual Sunlight Exposure; Melanopic/Photopic ratio; EML; m-DER; m-EDI	/
23	115	**Subject survey**	Software ReluxPro, Relux Informatik AG (Basel Switzerland) to calculate daylight factor	**ACTIGRAPH** (motion loggers)	**Wake diary**: Karolinska Sleepiness Scale (KSS) (9 point scale) and mood ratings filled every hour; **SURVEYS**; **QUESTIONNAIRES**	Static artificial lighting condition (ALC) and Dynamic daylight condition (DLC) on mental state, behaviuor and perception	CCT, Photopic illuminance, CRI Ra; uniformity Uo; m-EDI	**Actigraph:** illuminance values every minute, activity data were scored for sleep (duration, efficiency, bedtime and waking up time)
24	123	**Environmental analysis - SIMULATION BASED**	ALFA; Rhinoceros 6; Libradtran software to reproduce spectral luminous sky conditions; statistical software Rstudio	/	/	Influence of room, geometrical (depth, width, and window to wall ratio), and optical (reflectance of walls, ceiling, and floor and glazing transmissivity) parameters was studied for four cardinal occupant view directions, on visual and non visual effects	Photopic Illuminance, Melanopic Illuminance, Circadian Light (CLA); Useful daylight illuminance (UDI)	/

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	*RECOMMENDED VAUES ADRESSED*	*REACHING OF RECOMMENDED VALUES*	*TYPOLOGY Long/Medium/Short term*	*/Number of people involved/*	*RESULTS*	*LIMITATIONS*
Surveys: SF-36 and PSQI as indicator of mental and physical health	Circadian Stimuli; Circadian Lux (CLA) by Figueiro, M. et al. (CLA ≥ 0.3); WELL building standard:at least 226 lux (equivalent to the 250 equivalent Melanopic Lux); Equivalent Melanopic Lux (EML) by Lucas et al.	/	Medium term: 2 weeks	50	*The orientation with the most considerable difference between DHW (M) and DHW (D) is to the East, mainly related to the sun rising in the East in the morning. In terms of spatial distribution, the values of sDA, DHW (M), and DHW (D) are highest near the window. As a supplement to new daylighting metrics, it is necessary to use glare-related metrics or UDI among conventional daylighting metrics. The values of sDA, DHW (M), and DHW (D) all have a correlation within a specific range of four directions. Therefore, when the particular sDA value is secured, the remaining daylight measurement standard could be satisfied. In terms of seasonal changes, most dates during the year generally show similar trends for DHW (D) and DHW (M) values. In winter, metric results often fall below 20%; conversely, in summer, the metric value is typically more than 80%. Comparing the correlation with conventional daylighting metrics, in the case of DHW (D), sDA and MHI are highly correlated with DHW (D). Correlation with sDA is especially high.*	(1) The proposed metrics are related to daylight and cannot be replaced by simply having the same level of artificial lighting; (2) only computer simulation cases in US were used to verify new daylight metrics; (3) additional verification is needed to propose the new metric, by comparing more sample sizes and various conditions such as duration
/	CIE S026 melanopic metrics; Melanopic EDI of at least 250lx through the day; WELL Building Standard; (Spatial Daylight Autonomy)	NOT ALWAYS REACHED. UDI: more than 58%; sDA up to 100% in most cases; ASE over 10% only in Paralimni in 5 orientations. m-EDI not always	Long term: Annual time-series	/	*There are possibilities to achieve sufficient lighting levels inside the rooms while mantaining low possibilities for glare or solar heat gains. The North, North-East, and North-West orientations show the highest percentage in the UDI 300-3000 lux category and the lowest in UDI with more than 3000 lux and the ASE Main parameters affecting melanopic metrics are the orientation and the timing during the day. The window to wall ratio has an impact only for South, South West and South East orientations (direct sunlight). Higher the w-t-w ratio, higher the m-EDI increase. All the direct sunlight situations have a m-DER of less than 1.0. The weather conditions of the sky also significantly affect the melanopic EDI and melanopic DER for both locations. Depending on the orientation, North has more cases with melanopic DER higher than 1.0, which is related to more blue-enriched lighting, while at the same time, those cases have melanopic EDI of more than 250 lux.*	(1) Not possible to directly correlate the climate-based and melanopic metrics to find the best optimizations techniques for improved visual and non visual effects.
Wake diary: KSS for slepiness and mood ratings, **Questionnaires**: for perception of temporal and lighting parameters and subjective impressions of the space	CIE; 250 Melanopic Equivalent Daylight Illuminance (Melanopic EDI) lx	NOT ALWAYS REACHED: Melanopic EDI values in a day in February in DLC are over 250 Melanopic EDI lx in the interval 9–15 h, and over 140 Melanopic EDI lx in the interval 15–16 h.	Short term: 3 days	17	*We found significant correlation between sleepiness and daily illuminance, and mood is better in the daylight condition, independent of light exposure. Although an increase in light exposure was significantly related to an increase in activity, there is no advance or delay of the sleep cycle during night. Daily exposure relates also to the perception of duration of the day; Light exposure and lighting conditions affected the perception of pace, but not the perception of speed and time passing. Sleepiness is time-dependent and shows a circadian effect, complementary to vitality. Mood is a more stable state than sleepiness and, in our study, showed a relationship to lighting condition. The current results support the recent recommendations for melanopic equivalent daylight illuminance over 250 lx during the day.We also see an opportunity to complement daylighting with dynamic artificial lighting systems that are synchronised to local seasonal daylight conditions.*	(1) Small sample size (17); (2) being the average age of the participants 29 yo, the results might be limited to the lower range of the working population (3) The strong correlation between illuminance values measured at the wrist with Actiwatches and on the horizontal surface contradicts a previous study that examined wrist measurements in the field
/	CIE; WELL Building Standard; Circadian Stimuli (CS) or Circadian Light (CLA); Figueiro et al. 0.3 CS	/	Short term: 1 day (winter solstice)	/	*The results show that the window is the most influential building element as the window to wall ratio and glazing transmissivity are the most influential geometrical and optical parameters. Therefore, attention has to be given to window design at early design phases when there is the largest potential to impact the final (daylighting) performance of a building. However, it was exposed that this is not entirely true for occupant positions deeper in space and facing away from the window, as the influence of all studied building parameters changes according to the view orientation and position in relation to the window.*	(1) selected geometrical set-up of the office; (2) the statistical study findings are limited to overcast sky conditions at mid-latitudes but are applicable for all orientations and daylit time of the day while the sky is overcast; (3) shading devices would considerably influence indoor visual formation (another layer of complexity.

Annex A

7.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
25	124	Zeng, Y., Sun, H., & Lin, B. (2021). Optimized lighting energy consumption for non-visual effects: A case study in office spaces based on field test and simulation. *Building and Environment* , *205* , 108238. https://doi.org/10.1016/j.buildenv.2021.108238	Recently, the non-visual effects of the light environment have received increasing attention. Some standards have proposed evaluation metrics for non-visual effects in office spaces to ensure the health and well-being of occupants. Non-visual metrics are new requirements for indoor light environments, whose impacts on lighting adjustment and ultimate lighting energy performance are currently unknown. Therefore, this study aimed to present a workflow to obtain optimal light outputs considering non-visual lighting requirements, in addition to traditional visual requirements. This workflow was implemented to calculate the annual lighting energy consumption under different light correlated color temperatures (CCTs), daylight conditions, and standard requirements for an actual office scenario. As deduced from the results, adding non-visual requirements may significantly increase the lighting energy consumption by 57 %. Furthermore, daylight and light with a higher CCT are beneficial for non-visual energy-saving. The additional non-visual requirements will not increase the lighting energy consumption under favorable daylight conditions. The 5500 K light can save up to 20 % of the annual lighting power consumption than the 4000 K light. The presented workflow and conclusions contribute to engineering office environments with enhanced lighting, better circadian stimulus, and improved office lighting energy efficiency.	Light environment; Non-visual effects; Lighting control; Daylight harvesting; Energy consumption
26	125	Safranek, S., Collier, J. M., Wilkerson, A., & Davis, R. G. (2020). Energy impact of human health and wellness lighting recommendations for office and classroom applications. *Energy and Buildings* , *226* , 110365. https://doi.org/10.1016/j.enbuild.2020.110365	The goal of this investigation was to evaluate potential energy impacts of circadian lighting design recommendations that are gaining attention in a variety of common applications such as offices and classrooms. The renewed focus on health along with advances in solid-state lighting technology capabilities has underscored that there is still much to learn regarding the relationship between light and human physiology. The energy implications of designing to address these possible physiological effects are not yet fully understood. Beyond the fact that the basic metric of luminous efficacy (lumens per watt) does not cover these other effects, the emerging science seems to indicate that addressing a holistic view of the human needs in most applications may mean a need for increased light and associated energy use by electric lighting systems. Two applications, an open office and a classroom, were simulated and lumen output, spectral characteristics, surface reflectance distribution, and desk orientation were varied to explore the magnitude of potential effects. Meeting current Illuminating Engineering Society (IES) illuminance recommendations did not satisfy existing equivalent melanopic lux and circadian stimulus recommendations for any of the office and classroom simulations. In some cases, satisfying circadian metric recommendations required an average illuminance that was more than double the IES recommendations, which may negatively impact lighting quality. Using results from 45 unique simulation conditions, it was estimated that lighting energy use may increase between 10% and 100% because of increased luminaire light levels used to meet circadian lighting design recommendations listed in current building standards such as WELL v2 Q2 2019, UL Design Guideline 24480, and CHPS Core Criteria 3.0.	Circadian Lighting; Lighting Simulation; Solid-State Lighting
27	134	Boubekri, M., Lee, J., MacNaughton, P., Woo, M., Schuyler, L., Tinianov, B., & Satish, U. (2020). The Impact of Optimized Daylight and Views on the Sleep Duration and Cognitive Performance of Office Workers. *International Journal of Environmental Research and Public Health* , *17* (9). https://doi.org/10.3390/ijerph17093219	A growing awareness has recently emerged on the health benefits of exposure to daylight and views. Daylight exposure is linked to circadian rhythm regulation, which can have significant impacts on sleep quality and cognitive function. Views of nature have also been shown to impact emotional affect and performance. This study explores the impact of optimized daylight and views on the sleep and cognitive performance of office workers. Thirty knowledge workers spent one week working in each of two office environments with identical layouts, furnishings, and orientations; however, one was outfitted with electrochromic glass and the other with traditional blinds, producing lighting conditions of 40.6 and 316 equivalent melanopic lux, respectively. Participants in the optimized daylight and views condition slept 37 min longer as measured by wrist-worn actigraphs and scored 42% higher on cognitive simulations designed to test their higher order decision-making performance. Both sleep and cognitive function were impacted after one day in the space, yet the impacts became more significant over the course of the week. The positive effect of optimized daylight and views on cognitive function was comparable for almost all participants, while increases in sleep duration were significantly greater for those with the lowest baseline sleep duration. This study stresses the significance of designing with daylight in order to optimize the sleep quality and performance of office workers.	daylight; views; health building; cognitive function; productivity; sleep
28	138	Chen, X., Zhang, X., & Du, J. (2019). Glazing type (colour and transmittance), daylighting, and human performances at a workspace: A full-scale experiment in Beijing. *Building and Environment* , *153* , 168–185. https://doi.org/10.1016/j.buildenv.2019.02.034	This study presents a human experiment of effects of glazing types (colour and transmittance) on participants' alertness and mood, working performance, and self-reported satisfaction in a full-scale office in Beijing, China. Seven glazing systems were tested in a winter period (17th Nov 2017–15th Jan 2018). Research methods included lighting measurements, KSS (Karolinska Sleepiness Scale) sleepiness evaluation, PANAS (Positive and Negative Affect Schedule) mood survey, reaction time test (GO/NOGO), and self-reported questionnaires. Key findings are as follows: Circadian Stimulus (CS) can be used as an indicator of alertness and mood in a daylit workspace. If a higher CS level (≥0.3) can be achieved, glazing colour and transmittance would not significantly affect human's alertness and sleepiness. A low CS level (<0.3) would bring in significant negative mood to occupants. On the other hand, the improvement of occupants' mood would be achieved through increasing glazing visual transmittance and/or decreasing its colour saturation. Self-reported satisfactions show that a preference will be given to the glazing systems with neutral colour and/or higher transmittance in terms of visual performance. It is unknown why the glazing systems with a medium CCT of 4400 K or a higher CCT of 8100 K can deliver shorter response time (RT) and better working performance in a reaction time task. It would be necessary to carry on investigations into the human performances and light colour, especially under daylighting conditions.	Glazing colour and transmittance, Alertness and mood, Working performance, Self-reported satisfaction, Office, Beijing

Selected database								
1. GOAL		2. OVERVIEW						3. METHOD
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*
This study aimed to present a workflow to obtain optimal light outputs considering non-visual lighting requirements, in addition to traditional visual requirements.	/	Workflow to obtain optimal light outputs considering non visual lighting recommendations in addition to traditional visual requirements	OFFICE	(5.5 m x 3.6 m x 2.4 m), glass windows oriented north. Six workstations at the center, 0.75 m above the floor. North (worst scenario) and East orientations simulated.	Both daylight and electric lighting	(1) Daylight measurement from January 8th, 2021 (clear sky). (2) Three adjustable LED lights, were implemented on the ceiling. 2 cases: 4000 K and 5500 K CCT.	Beijing, China	*To optimize the lighting energy consumption considering non-visual effects, a calculation workflow was proposed using linear programming. According to the calculation workflow, daylight illuminance is calculated using simulation software. Then the electric lights are used to supplement the illuminance to fulfill the visual and non-visual standard requirements. Taking a real office scene as an example, a field test was conducted of the light and daylight conditions, ran a year-round simulation, and calculated the final lighting energy consumption value. In addition, several different calculations were performed with varied parameters.*
The goal of this investigation is to evaluate potential energy impacts of circadian lighting design recommendations that are gaining attention in a variety of common applications such as offices and classrooms.	*(1) Integrative Lighting need both increased light and energy use by electric lighting systems.*	Energy impact of NV recommendations	OFFICE; CLASSROOM	Office: 192 m2 with five rows of desks for eight desks. Floor-to-ceiling windows in long wall. 27 different combinations of 9 parameters. Classroom: 70m2 with 31 seating positions, no windows, and two teaching locations.	Electric lighting only	Different simulations: increased luminaire light levels used to meet circadian lighting design recommendations	/	*Three-dimensional computer models were developed for two space types. The simulations detailed in this article used the software tool Adaptive Lighting for Alertness (ALFA) (Solemma LLC), which considers SRDs for surfaces and SPDs for light sources, both of which are discretized into 81 values, about 5-nm increments, across the visible spectrum.*
This study stresses the significance of designing with daylight in order to optimize the sleep quality and performance of office workers.	*(1) Optimized daylight conditions, achieved by use of EC glass, results in improved sleep and real-world productivity among office workers.*	Sleep duration and cognitive performance of office workers from optimized daylight and view	OFFICE	Identical layouts, furnishings, and orientations; but one outfitted with (1) electrochromic glass and the other with (2) traditional blinds. Four rows of workstations perpendicular to the window.	Daylight only	(1) Lighting conditions of 40.6 and 316 equivalent melanopic lux. (November; Environmental conditions were assessed using Awair Omni)	Durham, North Carolina (USA)	*This study utilized a case-crossover design to test the effect of exposure to daylight and views during office hours on objectively measured cognitive function and sleep. Thirty knowledge workers spent one week working in each of two office environments with identical layouts, furnishings, and orientations; however, one was outfitted with electrochromic glass and the other with traditional blinds, producing lighting conditions of 40.6 and 316 equivalent melanopic lux, respectively.*
This study presents a human experiment of effects of glazing types (colour and transmittance) on participants' alertness and mood, working performance, and self-reported satisfaction in a full-scale office in Beijing, China.	/	Alertness, mood, working performance, self reported satisfaction of office workers from different glazing types.	OFFICE	Office room, facing South, 4 sitting positions, 6.3 x 3.2 x x3.8m	Daylight only	(1) Winter period	Beijing, China	*Seven glazing systems were tested in a winter period (17th Nov 2017–15th Jan 2018). Research methods included lighting measurements, KSS (Karolinska Sleepiness Scale) sleepiness evaluation, PANAS (Positive and Negative Affect Schedule) mood survey, reaction time test (GO/NOGO), and self-reported questionnaires.*

Annex A

7.3

Selected database								
						3. METHOD		
N.	PDF Reference number	TYPOLOGY Environmental analysis/Subject survey	/SOFTWARE USED/	/HARDWARE USED/	/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/	MEASURED/SIMULATED STUDY OBJECT	MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES	/Human-centred MEASURED DATA (physiological variables measured by the hardware)/
25	124	**Environmental analysis - SIMULATION BASED**	RADIANCE based DAYSIM software (for daylight calculations), and ECOTECT as the modeling interface from which the DAYSIM was launched	EVERFINE SPIC-300 spectrum and illuminance meter; Konica Minolta spectrophotometer.	/	Workflow to obtain optimal light outputs considering non-visual lighting requirements, in addition to traditional visual requirements	Photopic illuminance; EML; CCT	/
26	125	**Environmental analysis - SIMULATION BASED**	ALFA	/	/	Energy impact of non visual lighting recommendations	Horizontal illuminance; EML; CS	/
27	134	**Subject survey**	Strategic Management Simulation (SMS) assessment (a validated computer-based simulation software)	**Awair Omni** devices, measuring temperature, relative humidity, air quality, noise and light levels every 5 min; spectrometer (LI-COR model LI-180); WATCH **ACTIGRAPHS**: ActiGraph wgt3x containing an ambient light sensor	**SURVEYS** (Daily, baseline, weekly and PSQI)	Sleep and cognitive performance of office workers on optimized daylight and view	Environmental conditions; CCT; CRI; Illuminance; EML; CS	**Actigraph**: activity metrics (including steps, kCals, inclinometer, and active and sedentary bouts) and sleep metrics (including total sleep time, estimated sleep and wake times, sleep efficiency, sleep latency, and wake time after sleep onset); the ambient light sensor continuously collected personal light exposure
28	138	**Subject survey**	/	**Spectrophotometer** (KONICA MINOLTA: CM-2600D); KONICA MINOLTA **Luminance Meter** LS-150	**QUESTIONNAIRES**; KSS (Karolinska Sleepiness Scale), PANAS (Positive and Negative Affect Schedule), Pittsburgh Sleep Quality Index (PSQI), self-reported questionnaires; **TEST** (GO/NOGO).	Alertness and mood, working performance, and self-reported satisfaction on office workers from different glazing types	CS; CCT; Spectral transmittance	/

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	*RECOMMENDED VAUES ADRESSED*	*REACHING OF RECOMMENDED VALUES*	*TYPOLOGY Long/Medium/Short term*	*/Number of people involved/*	*RESULTS*	*LIMITATIONS*
/	200 EML threshold on the occupant's view of 75 % or more workstations between 9:00 a.m. and 1:00 p.m. for US WELL Building Standard; 250 EML in the assessment standard for healthy buildings in China (2016)	REACHED	Long term: Annual time-series	/	*Compared with traditional visual requirements, non-visual metrics only bring a significant increase in lighting energy consumption in the cases of bad daylight conditions. The lighting energy consumption does not increase (≤5 %) under the best daylight condition, regardless of the 200 EML or 250 EML requirements. However, it increases by 57 % for the 250 EML requirement under the most unfavorable daylight condition (a windowless office), indicating that non-visual metric is dominant in the lighting adjustments in the cases with poor daylight. In fact, daylight determines which one of the visual and non-visual requirements is dominant. Daylight and light with a higher CCT are beneficial for non-visual energy-saving. The 5500 K light can save up to 20 % of the annual lighting power consumption than the 4000 K light.*	(1) Considering daylight and energy consumption, air conditioning energy consumption should also be taken into account; (2) The characteristics of the lights and office layouts can influence lighting energy consumption; (3) future research is needed to determine non-visual compliance values in indoor environments.
/	EML; CS; WELL v2 Q2 2019, UL Design Guideline 24480, and CHPS Core Criteria 3.0.	NOT ALWAYS REACHED: Not reached for any of the simulations. In some cases, satisfying circadian advice required an average illuminance more than double the IES, negatively impacting lighting quality.	Long term: Annual time-series	/	*Using results from 45 unique simulation conditions, it was estimated that lighting energy use may increase between 10% and 100% because of increased luminaire light levels used to meet circadian lighting design recommendations. Results from further research may show more efficient ways to meet design recommendations through varied light distribution or optimized spectral characteristics or continue to express the energy penalties that these recommendations present in realistic settings.*	/
Daily surveys: lifestyle, behaviors, health, metacognitive status, and environmental perceptions; **Baseline and weekly surveys:** general health factors and experiences in each work environment; **PSQI** survey: for Sleep quality	Circadian Stimulus (CS)	/	Medium term: 1 week	30	*Participants in the optimized daylight and views condition slept 37 min longer as measured by wrist-worn actigraphs and scored 42% higher on cognitive simulations designed to test their higher order decision-making performance. Both sleep and cognitive function were impacted after one day in the space, yet the impacts became more significant over the course of the week. The positive effect of optimized daylight and views on cognitive function was comparable for almost all participants, while increases in sleep duration were significantly greater for those with the lowest baseline sleep duration.*	(1) Different office configurations and window treatments will lead to different daylighting conditions. (2) The offices tested in this study compare typical blinds to EC glass, so the impact of windowless offices or offices with no blinds cannot be determined with these data. (3) orientation impact blind usage (4) blinds had position fixed (5) not suitable for other settings
Questionnaires: KSS for sleepiness evaluation, PANAS as mood survey, PSQI for sleep quality assessment; **Test**: GO/NOGO test for reaction time; **Self-reported questionnaires:** satisfaction and visual performances	Circadian Stimulus (CS)	REACHED: Circadian Light (CLA) and Circadian Stimulus (CS) were achieved	Medium term: 2 months	11	*Circadian Stimulus (CS) can be used as an indicator of alertness and mood in a daylit workspace. If a higher CS level (≥0.3) can be achieved, glazing colour and transmittance would not significantly affect human's alertness and sleepiness. A low CS level (< 0.3) would bring in significant negative mood to occupants. On the other hand, the improvement of occupants' mood would be achieved through increasing glazing visual transmittance and/or decreasing its colour saturation. Self-reported satisfactions show that a preference will be given to the glazing systems with neutral colour and/or higher transmittance in terms of visual performance. It is unknown why the glazing systems with a medium CCT of 4400 K or a higher CCT of 8100 K can deliver shorter response time (RT) and better working performance in a reaction time task. It would be necessary to carry on investigations into the human performances and light colour, especially under daylighting conditions.*	(1) Small sample size; (2) specific climate conditions; (3) specific glazing type and workspace.

Annex A

8.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
29	139	Figueiro, M. G., Steverson, B., Heerwagen, J., Kampschroer, K., Hunter, C. M., Gonzales, K., Plitnick, B., & Rea, M. S. (2017). The impact of daytime light exposures on sleep and mood in office workers. *Sleep Health* , *3* (3), 204–215. https://doi.org/10.1016/j.sleh.2017.03.005	Background: By affecting the internal timing mechanisms of the brain, light regulates human physiology and behavior, perhaps most notably the sleep–wake cycle. Humans spend over 90% of their waking hours indoors, yet light in the built environment is not designed to affect circadian rhythms. Objective: Using a device calibrated to measure light that is effective for the circadian system (circadianeffective light), collect personal light exposures in office workers and relate them to their sleep and mood. Setting: The research was conducted in 5 buildings managed by the US General Services Administration. Participants: This study recruited 109 participants (69 females), of whom 81 (54 females) participated in both winter and summer. Measurements: Self-reported measures of mood and sleep, and objective measures of circadian-effective light and activity rhythms were collected for 7 consecutive days. Results: Compared to office workers receiving low levels of circadian-effective light in the morning, receiving high levels in the morning is associated with reduced sleep onset latency (especially in winter), increased phasor magnitudes (a measure of circadian entrainment), and increased sleep quality. High levels of circadian-effective light during the entire day are also associated with increased phasor magnitudes, reduced depression, and increased sleep quality. Conclusions: The present study is the first to measure personal light exposures in office workers using a calibrated device that measures circadian-effective light and relate those light measures to mood, stress, and sleep. The study's results underscore the importance of daytime light exposures for sleep health.	Light exposure Circadian rhythms Sleep Mood Phasor analysis
30	140	Potočnik, J., & Košir, M. (2020). Influence of commercial glazing and wall colours on the resulting non-visual daylight conditions of an office. *Building and Environment* , *171* , 106627. https://doi.org/10.1016/j.buildenv.2019.106627	Daylight is ever more recognised as a major synchroniser of circadian rhythms, linking us to the 24 h solar day. However, the time that urbanised humans spend outdoors has decreased substantially during the last century, which highlights the importance of appropriate indoor daylighting. Quality and quantity of daylight in indoor environments are primarily modulated by the characteristics of the building envelope. In this context, a combined experimental and simulation study of a cellular office model was executed in order to evaluate the impact of different glazing types and internal wall colours on the non-visual potential of daylight. In particular, the impact of seven glazing types and six different wall cover hues at three reflectance levels was determined. Among these, three glazing types and three wall colours of equal reflectance were further evaluated through diurnal simulations of the indoor luminous environment. Low-e glazing with high visual transmittance and blue coloured wall were indicated as combinations with the highest non-visual entrainment, while the opposite is true for the combination of bronze tinted solar protective glazing and orange walls. In general, better non-visual environment can be achieved using materials characterised by higher spectrally neutral transmissivity or reflectance than with those characterised by spectrally non-neutral properties and of lower transmissivity or reflectance.	daylighting; spectral reflectance and transmissivity; circadian lighting; wall colour; glazing type; non-visual effect of light;
31	142	Potočnik, J., & Košir, M. (2019, dicembre). *In-situ Determined Circadian and Visual Daylighting Potential of an Office,* Conference: International Conference on Sustainable Built Environment, SBE 19 Seoul, Smart Building and City for Durability & Sustainability.	. An experiment was designed in order to evaluate daylighting of a real cellular office, where a hypothetical worker's perceived luminous environment was monitored in order to assess the relation between circadian potential and visual demands. The results demonstrate that control over the horizontal illuminance through shading of the workplace significantly affects the level of received vertical photopic and melanopic illuminance, but has no noteworthy impact on spectral composition of daylight. Therefore, it resulted in relatively constant ratios between melanopic and photopic illuminance during the analysed days. However, we can conclude that maintaining individual's horizontal illuminance at a fixed level can affect the circadian potential of received daylight to some extent, which can, in turn, represent a conflict between circadian and visual lighting demands	Sustainability in the Built Environment
32	143	Giovannini, L., Lo Verso, V. R. M., Valetti, L., Godoy Daltrozo, J., & Pellegrino, A. (2023, settembre). *Integrative lighting in offices: results from field measurements and annual daylight simulations* . https://doi.org/10.25039/x50.2023.OP016	Integrative lighting conditions in four offices of the university 'Politecnico di Torino' (Turin, Italy) were investigated, in terms of combination of daylighting and electric lighting. The research addressed two objectives: (i) to verify if the lighting conditions could meet the recommendations proposed in recent literature (CIE or WELL protocol) concerning light exposure for appropriate non-visual responses (melanopic equivalent daylight illuminance m-EDI); ii) to assess the influence on integrative lighting (photopic and melanopic illuminances) played by daylighting as a function of different room depth and orientation, by electric lighting, as a function of different lighting systems and by the combination of both. Electric lighting was assessed through field measurements, while daylighting through annual simulations using LARK v2. Results showed that CIE requirements were not met in any office, while WELL recommendations were met only for the positions closest to the window (within 1.87 m).	Integrative lighting in offices, LARK v2, simulations, measurements.

Selected database								
1. GOAL		**2. OVERVIEW**						**3. METHOD**
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*
Measuring light that is effective for the circadian system, collecting personal light exposures in office workers and relating them to their sleep and mood.	*(1) Morning circadian stimulus (CS) of ≤0.1 being less synchronized to the natural day–night cycle than a morning CS ≥0.3. (2) Morning CS ≥0.3 equalling to better sleep quality and mood.*	Sleep and mood of office workers from daylight exposure	OFFICE	Different offices in different office buildings, different orientations	Daylight only	(1) Summer and winter period	Washington/Seattle/Portland/Grand Junction (USA)	*Using the Rea's mathematical model of human circadian phototransduction (phototransductionmodel), the spectral irradiance measured at the cornea is first converted into CLA, reflecting the spectral sensitivity of the circadian system, and then, second, transformed into the CS, reflecting the absolute sensitivity of the circadian system. The Daysimeter, a calibrated device that continuously measures light and motion,was used to collect personal light-exposure and activity data. Participants completed 5 questionnaires concerning mood and sleep habits at the end of the study.*
Evaluate the impact of different glazing types and internal wall colours on the non-visual potential of daylight.	*(1) Material colours rich in shortwave reflected light inducing higher response of the non-visual system.*	Glazing and wall colour parameters on non visual daylight conditions of an office	OFFICE	Office: 3.0 m wide, 4.0 m deep and 2.6 m high, equipped with a single north oriented window of 1.4 by 0.9 m, corresponding to a window-to-wall ratio of 16 % and window-to-floor ratio of 10.5 %.	Daylight only	(1) sky conditions corresponding to CIE clear sky with low turbidity	Ljubljana, Slovenia	*The evaluation of luminous and spectral aspects of indoor environment under various spectral reflectances of walls and spectral transmissivities of glazing was performed using both an in-situ scale model and a real scale simulation model of a typical cellular office. Use of Rhinoceros and ALFA.*
The correlation between the achieved melanopic illuminance and the occurrence of daylight-caused glare expressed through Daylight Glare Probability (DGP) is of interest, as the two might be mutually excluding.	/	Daylight potential (circadian and visual) of an office	OFFICE	Floor area of 13m2 (5.0 x 2.6 m x 2.38m). White walls and ceiling, blue floor. One south oriented window (A=1.98m2, visual transmittance=0.75) with a manually operated external rolling shutter. Two workplace configurations.	Daylight only	(1) Partly cloudy sky conditions with interchanging periods of clear and overcast conditions.	Ljubljana, Slovenia	*Measurements of the indoor luminous environment characteristics were executed in a real office. Collected daylight spectral distribution data (SPD) were used to calculate the equivalent melanopic illuminance (Emv) expressed in EML values, determined using the Lucas et al. (2014).*
The goal is outlining a framework of the integrative lighting conditions that can exist in typical offices, considering the whole occupancy timeframe. Further objectives of the study were: (i) to check the compliance of the lighting conditions with the requirements currently reported in recent literature and in the WELL protocol; (ii) to critically analyse the requirements with respect to their applicability in existing buildings; (iii) to assess the influence on integrative lighting played by electric lighting and daylighting.	/	Office workstations' photopic and melanopic values	OFFICE	4 offices: differ for orientation, obstruction settings, room depth, colours, number and position of workstations, and lighting systems. One window 4.8m2.	Both daylight and electric lighting	(1) Annual simulations of daylight, weather file of Turin	Turin, Italy	*Electric lighting was assessed through field measurements, while daylighting through annual simulations using LARK v2.*

Annex A

8.3

Selected database								
						3. METHOD		
N.	*PDF Reference number*	*TYPOLOGY Environmental analysis/Subject survey*	*/SOFTWARE USED/*	*/HARDWARE USED/*	*/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/*	*MEASURED/SIMULATED STUDY OBJECT*	*MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES*	*/Human-centred MEASURED DATA (physiological variables measured by the hardware)/*
29	139	**Subject survey**	/	**ACTIWATCH**: Daysimeter, a calibrated device that continuously measures light and motion; OBJECTIVE MEASURES of circadian-effective light and activity rhythms	**QUESTIONNAIRES** on mood and sleep: Center for Epidemiologic Studies Depression Scale (CES-D) questionnaire; Perceived Stress Scale (PSS-10) - 5-point scale; Pittsburgh Sleep Quality Index (PSQI) questionnaire - 3-point scale; Positive and Negative Affect Schedule (PANAS) questionnaire - 5-point scale; Patient-Reported Outcomes Measurement Information System (PROMIS); **SLEEP DIARY**	Sleep and mood of office workers from daylight exposure	CS; CLA	**Actiwatch**: continuously measures light and motion,collect personal light-exposure and activity data
30	140	**Environmental analysis - SIMULATION BASED and FIELD MEASUREMENTS**	Rhinoceros v5; ALFA	Perkin Elmer Lambda 950 UV-Vis-NIR **spectrophotometer**; **spectrometers** StellarNet BLACK-Comet; **spectrometer** (sensor point S2); Almemo FLA 603-VL4, V(λ) calibrated lux meters; Almemo 5960-2 **data logger**;	/	Influence of commercial glazing (7 glazing types) and wall colours (6) on the resulting non-visual daylight conditions of an office	Spectral irradiance and illuminance; CS; EML	/
31	142	**Environmental analysis - FIELD MEASUREMENTS**	/	Almemo FLA603–VL4, V(λ)-calibrated lux meters; StellarNet BLACK–Comet concave grating **spectrometer**	/	Daylight potential of an office	Ev; SPD; EML; Emv/Ev ratio; Daylight Glare Probability (DGP)	/
32	143	**Environmental analysis - SIMULATION BASED and FIELD MEASUREMENTS**	LARK v2	Contact **spectro-photometer** Minolta M-600; Gigahertz **spectrophotometer**;	/	Workstations phtopic and melanopic values	Photopic and melanopic illuminances; daylight autonomy DA	/

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	*RECOMMENDED VAUES ADRESSED*	*REACHING OF RECOMMENDED VALUES*	*TYPOLOGY Long/Medium/Short term*	*/Number of people involved/*	*RESULTS*	*LIMITATIONS*
5 **Questionnaires** (mood and sleep habits): **CES-D** to measure depressive symptoms; **PSS-10** for thoughts and feelings; **PSQI** for sleep quality and patterns; **PANAS** for subjective feelings about 10 positive affects and 10 negative affects; **PROMIS** for sleep quality; **Sleep diary**: bedtime and wake time, sleep latency, quality of sleep, and any naps taken	Circadian light (CLA); circadian stimulus (CS)	NOT ALWAYS REACHED	Medium term: 7 days	109	*The presence of daylight in a building does not necessarily ensure high CS exposure for workers. Most of the buildings studied here were designed to maximize daylight availability in the space, yet CS exposures did not always reach the desired criterion level of 0.3. Furniture placement, window shade positions, desk space locations and orientations, and visual and thermal comfort need to be taken into consideration when attempting to maximize exposure to CS in an office environment. Nevertheless, while much has been discussed about the detrimental effects of evening or night light on sleep and health, little attention has been paid to the importance of daytime light exposures, especially in winter months, on sleep health. The present results can be considered as a first step toward promoting the adoption of new, more meaningful metrics for field research, providing the sleep research community with new ways to measure and quantify circadian-effective light.*	/
/	Circadian Stimulus (CS) - above 0.3; EML; CIE; WELL Building Standard - a minimum of 75 % of workstations should receive at least 200 EML on a vertical plane 1.2 m above the floor level between 9:00 and 13:00	NOT ALWAYS REACHED:	Short term: 2 days	/	*The results of the presented study clearly emphasize the importance of considering the spectral properties of indoor opaque surfaces and transparent building envelope elements when evaluating the circadian effects of daylight. Overall, it can be established that indoor environments, with building elements characterised by higher values of τvis and Rvis, will result in higher non-visual potential.Low-e glazing with high visual transmittance and blue coloured wall were indicated as combinations with the highest non-visual entrainment, while the opposite is true for the combination of bronze tinted solar protective glazing and orange walls. In general, better non-visual environment can be achieved using materials characterised by higher spectrally neutral transmissivity or reflectance than with those characterised by spectrally non-neutral properties and of lower transmissivity or reflectance.*	(1) taking into account the virtual impossibility of predicting the final indoor wall colours, designers trying to optimise the luminous environment in buildings should, whenever possible, opt for spectrally neutral glazing of highest possible visual transmittance in respect to the energy efficiency and visual comfort criteria
/	EML; CIE	REACHED	Short term: 2 days	/	*The presented study demonstrated that the use of a roller shutter for the prevention of daylight induced discomfort glare, was very effective at both workplace configurations. Taking into account the drop in illuminance it could be concluded that measures for glare prevention can have a negative impact on the non-visual potential to some extent. However, not to a critical point, since the minimum Emv achieved in the case when glare was prevented was still aboce 350 EML for both configuration 1 and configuration 2. Furthermore, the results showed that the ratio between visual and non-visual illuminance remained almost unchanged due to spectrally neutral colour of the roller shutter, which might not be true in case of coloured ones, as seen from the study of Potočnik et al. (2019) where coloured walls and windows significantly affected the Emv/Ev ratio.*	(1) the absolute effect of movable shading on the non-visual potential in buildings is still not totally clear due to lack of knowledge about the amount of light needed for proper circadian entrainment
/	CIE: at least 250 lx m-EDI throughout the day, a maximum of 10 lx three hours before bedtime and a maximum of 1 lx during the night (CIE 2019).; WELL	NOT ALWAYS REACHED: 1 office would qualify for the 3 point credit of the WELL protocol, while the other offices values were far below recommendations. Considering CIE 250lx not one office could comply with it.	Long term: Annual time-series	/	*(1) As for daylighting, the combination of orientation, obstruction, and use of blinds mitigated the differences on the melanopic performance for the offices on desks near the window. (2) A huge effect played by the position of the desk was observed: melanopic recommendations were not met through daylighting alone for positions over 3 m from the window. (3) As for electric light, the old lighting systems (fluorescent) did not provide a sufficient illuminance on desks, and accordingly the melanopic content at eye-level was poor; in contrast, the new LED lighting system yielded the highest m-EDI values, mainly due to the high illuminance provided on desk (Ewp > 700 lx); besides, in this office, also the desk farthest from the window qualifies for 3-point WELL recommendation*	More research seems to be needed to provide more specific melanopic recommendations, in terms of metrics, target values, and assessment methods, to harmonize the verification of both visual and non-visual effects of light.

Annex A

9.1

Selected database				
BIBLIOGRAPHY				
N.	*PDF Reference number*	*Bibliographic reference*	*Abstract*	*Key words*
33	144	Prayag, A., Jost-Boissard, S., Avouac, P., Dumortier, D., & Gronfier, C. (2019). Dynamics of Non-visual Responses in Humans: As Fast as Lightning? *Frontiers in Neuroscience* , *13* . https://doi.org/10.3389/fnins.2019.00126	The eye drives non-visual (NV) responses to light, including circadian resetting, pupillary reflex and alerting effects. Initially thought to depend on melanopsin-expressing retinal ganglion cells (ipRGCs), classical photopigments play a modulatory role in some of these responses. As most studies have investigated only a limited number of NV functions, generally under conditions of relatively high light levels and long duration of exposure, whether NV functions share similar irradiance sensitivities and response dynamics during light exposure is unknown. We addressed this issue using light exposure paradigms spectrally and spatially tuned to target mainly cones or ipRGCs, and by measuring longitudinally (50 min) several NV responses in 28 men. We demonstrate that the response dynamics of NV functions are faster than previously thought. We find that the brain, the heart, and thermoregulation are activated within 1 to 5 min of light exposure. Further, we show that NV functions do not share the same response sensitivities. While the half-maximum response is only ~48 s for the tonic pupil diameter, it is ~12 min for EEG gamma activity. Most NV responses seem to be saturated by low light levels, as low as 90 melanopic lux. Our results also reveal that it is possible to maintain optimal visual performance while modulating NV responses. Our findings have real-life implications. On one hand, light therapy paradigms should be re-evaluated with lower intensities and shorter durations, with the potential of improving patients' compliance. On the other hand, the significant impact of low intensity and short duration light exposures on NV physiology should make us reconsider the potential health consequences of light exposure before bedtime, in particular on sleep and circadian physiology.	light, non-visual, circadian, duration response curve, EEG, pupil, temperature, heart rate
34	145	S. Ezpeleta, E. Orduna-Hospital, T. Solana, J. Aporta, I. Pinilla, & A. Sánchez-Cano. (2021). *Analysis of Photopic and Melanopic Lighting in Teaching Environments* . *11* (10), 439. https://doi.org/10.3390/buildings11100439	Daylight and lighting seem to be a key tool for people's well-being, however, there are no specific and agreed recommendations that address both photopic and melanopic aspects in educational environments. The present work analyzed melanopic light in four teaching environments considering photopic indoor lighting, daylight depending on the window orientation, location of the observer in the room, and their line of view. The façade direction, daylight at 11.00 a.m. for six months from October to March, and the characteristics of each classroom, such as reflectance of the surfaces, location of the luminaires and their spectral and spatial power distributions, or calculation points affecting the melanopic light reaching the corneal vertical plane of a hypothetical control observer were studied. For this evaluation, classrooms were experimentally treated and simulated using DialuxEvo software, and the computer-generated values resembled the experimental values. Once the study was performed, an improvement proposal, based on LED lighting, was made to optimize the classroom lighting considering the melanopic requirements, which we ensured that users who passed through these classrooms had an adequate amount light at any time of the day. Our results simplify to the greatest lighting projects and enable designers to carry out optimized evaluations of specific environments from both the photometric and circadian perspectives.	daylight; circadian light; spectral power distribution; well-being; lighting projects; teaching environments

Selected database								
1. GOAL		**2. OVERVIEW**						**3. METHOD**
RESEARCH GOAL	*HYPOTESIS STATEMENT*	*SUBJECT OF INVESTIGATION*	*ENVIRONMENT*	*N. ROOMS, FEATURES AND DIMENSIONS*	*LIGHT SOURCE*	*(1)SKY CONDITIONS/ (2)TYPOLOGY OF LIGHT*	*LOCATION*	*METHOD*
The present study was designed to take into account, not only the differences in spectral sensitivity between photoreceptors, but also their differences in response dynamics and spatial distribution over the retina. We hypothesized that NV responses are influenced simultaneously by the spectral content/intensity, duration and spatial distribution of light exposure.	*(1) Blue-enriched white lights producing higher NV response levels (2) Higher photoreceptor stimulation equals to an increase of NV response levels (3) Non-visual responses possess specific response dynamics.*	Non visual responses in humans	LABORATORY	Work/sitting station. Light positioned overhead.	Electric lighting only	Light pulses in dim white light conditions. Within each light pulse, switch on of a blue-enriched white light (BE) or a red-enriched white light (RE) spectrum. Melanopic lux content of ~230 for BE, and ~90 for RE.	/	*Subjects were exposed to four randomized 50-min light pulses between 19:00 and 23:00 with 10 min rest in dim white light conditions between each pulse (Figure 1). Within each light pulse, a blue-enriched white light (BE) or a red-enriched white light (RE) spectrum was switched on at 19:10. The BE or RE lights were used to stimulate ipRGCs differentially throughout the 50-min light exposure. The melanopic lux content was ~230 for BE, compared to ~90 melanopic lux for RE. After a first minute of full field light exposure to either BE or RE spectrum, a central white light spot was additionally turned on, and both lights remained on until the end of the pulse (min 50).*
The present work analyzed melanopic light in four teaching environments considering photopic indoor lighting, daylight depending on the window orientation, location of the observer in the room, and their line of view.	*(1) Spectral contribution, window orientations, or location of the sun may affect lit environment.*	Wheter spaces comply or not with melanopic metrics	CLASSROOM	4 classrooms with windows with different orientations	Both daylight and electric lighting	(1) 6 months (October-March) (2) LED implementation post field measurements/ simulation	Zaragoza, Spain	*The current paper analyzed the lighting of four classrooms located in buildings in Zaragoza (Spain) that are used for educational activities. The procedure was divided into two parts. (1) Four classrooms with windows with different orientations were selected to assess the daylight illumination over six months. Experimental measurements were performed at several points in each room with indoor lighting and daylighting. The parameters measured were photopic illuminance and SPD at horizontal and three vertical planes. From these results, melanopic contributions were calculated according to the CIE standard and WELL recommendations in m-lux. (2) Simulated spaces with DialuxEvo were constructed from the real dimensions and characteristics of each classroom.*

Annex A

9.3

Selected database								
						3. METHOD		
N.	PDF Reference number	TYPOLOGY Environmental analysis/Subject survey	/SOFTWARE USED/	/HARDWARE USED/	/RESEARCH INSTRUMENT ON HUMANS USED: QUESTIONNAIRE, SURVEY, TASK/	MEASURED/SIMULATED STUDY OBJECT	MEASURED/ SIMULATED ENVIRONMENTAL VARIABLES	/Human-centred MEASURED DATA (physiological variables measured by the hardware)/
33	144	**Subject survey**	/	Wrist **actigraph** (Actisleep, Actitrac, United States); **EEG signals** with Vitaport-4 digital recorder - TEMEC Instruments; **Pupil Diameter** with ViewPoint Eye Tracker - Arrington Research Inc.**;** **Skin temperature** with iButtons - Dallas SemiConductors; **ECG** with Vitaport-4 digital system **Salivary Melatonin analysis; spectroradiometer** (JETI, Jena, Germany) for illuminances and spatial distribution of light exposure	**QUESTIONNAIRES:** Pittsburg Sleep Quality Index Questionnaire (PSQI), Horne and Ostberg Chronotype Questionnaire (MEQ), Visual analog scales (VAS); **TESTS:** Landolt Ring Test (LRT), Functional Acuity Contrast Test (F.A.C.T.), Farnworth D-15 (D-15), Karolinska Drowsiness Test (KDT), Addition test (ADD), Psychomotor Vigilance Test (PVT), 2-back test (2-B)	Non visual responses in humans	EML, illuminances and spatial distribution of light exposure	**Actigraph**: to check compliance with regular sleep-wake schedule; **Saliva analysis:** for melatonin concentrations; **EEG-ECG-Skin temperature-Pupil diameter:** to measure brain, heart, and thermoregulation activation after light exposure
34	145	**Environmental analysis - SIMULATION BASED and FIELD MEASUREMENTS**	DialuxEvo software;	**Spectroradiometer** (model Avaspec-1024, Avantes, Apeldoorn, The Netherlands, with NPL E01110063/DDK calibration and NIST traceability).	/	Whether spaces complied with melanopic metrics	SPD in irradiance; photopic illuminance; m-EDI; UGR; Uo; CRI	/

Selected database						
					4. CONCLUSIONS	
/Human-centred MEASURED DATA (subjective variables measured by questionnaire, ecc.)/	*RECOMMENDED VAUES ADRESSED*	*REACHING OF RECOMMENDED VALUES*	*TYPOLOGY Long/Medium/Short term*	*/Number of people involved/*	*RESULTS*	*LIMITATIONS*
Questionnaires: **PSQI** for general health, sleep quality, **MEQ** for their sleep-wake behavior, **VAS** for subjective levels of alertness, stress level, visual acuity and mood; **Tests**: **LRT** for visual acuity, **F.A.C.T**. for contrast vision, **D-15** for color vision, **KDT** to ensure artifact-free objective measurements, **ADD – PVT - 2-B** for cognitive test performance	/	/	Short term: few hours	28	*The response dynamics of NV functions are faster than previously thought. We find that the brain, the heart, and thermoregulation are activated within 1 to 5 min of light exposure. Further, we show that NV functions do not share the same response sensitivities. While the half-maximum response is only ~48 s for the tonic pupil diameter, it is ~12 min for EEG gamma activity. Most NV responses seem to be saturated by low light levels, as low as 90 melanopic lux. Our results also reveal that it is possible to maintain optimal visual performance while modulating NV responses. Our findings have real-life implications. On one hand, light therapy paradigms should be re-evaluated with lower intensities and shorter durations, with the potential of improving patients' compliance. On the other hand, the significant impact of low intensity and short duration light exposures on NV physiology should make us reconsider the potential health consequences of light exposure before bedtime, in particular on sleep and circadian physiology.*	(1) Relatively limited range of intensities were used in our study; this might explain the absence of difference between light pulses for some responses; (2) Specific time (different times = different results); (3) central white light spots did not specifically target cones or ipRGCs in terms of spatial distribution; (4) no gender differences assessed (only men)
/	CIE standard and WELL recommendations in m-lux (150 m-lux to 250 m-lux depending on the functions of the room.)	NOT ALWAYS REACHED: very low levels of melanopic light were measured in the four rooms considering that they have educational purposes from 9.00 a.m. to 9.00 p.m., every day from September to July	Long term: 6 months	/	*The impact of circadian illumination is directly related to the SPD characteristics of incident light on the cornea, and the illumination at the horizontal working plane is not directly relevant. Because photopic and melanopic illuminances are related by the MAF factor, indoor lighting may be improved by varying the SPD and photopic illuminance levels to complement daylight contributions based on month and façade orientation while considering dimmable luminaires as the best solution to promote well-being and save electrical consumption. This study provides background information for developing lighting projects from a global perspective and provides clues and a method to transform traditional lights into well-being lights.*	(1) further studies focused on the influence of the spectral reflectance of the surfaces or more profound knowledge of subjective behavior in addition to optimal conditions for performing visual tasks are needed to assess healthy and comfortable real-life environments

Annex - Glossary

action spectrum

spectral sensitivity for an effect triggered by light. The action spectrum for the sensitivity of the eye is the V(lambda) curve. The c(lamda) function proposed by Prof. Gall corresponds aprox. to the action of spectrum for night-time melatonin suppression by light.

ambient light

the general lighting of the visual environment is provided by the ambient light. It is the light which is already present in the screen without any additional lighting.

angle of view

angle at which an object under view is perceived, measure for the size of the image of the object on the retina of the eye.

biological clock

self-sustained oscillators which generate biologic rhythms in absence of external periodic input (e. g., at the gene level in individual cells).

biological rhythm

a cyclical, repeated variation in a biological function.

blackbody

a temperature radiator of uniform temperature whose radiant exitance in all parts of the spectrum is the maximum obtainable from any temperature radiator at the same temperature. Such a radiator is called a blackbody because it will absorb all the radiant energy that falls upon it. All other temperature radiators may be classed as non-blackbodies. They radiate less in some or all wavelength intervals than a blackbody of the same size and the same temperature.

chronobiology

the science of investigating and objectively quantifying phenomena and mechanisms of the biologic time structure, including the rhythmic manifestations of life. Term derived from: Chronos (time), bios (life), and logos (science).

circadian

meaning "about a day;" any rhythm can be described as circadian if its period is approximately 24h.

circadian clock

the endogenous, molecular mechanism which accounts for observable circadian rhythms in an organism's activities (including locomotion, sleep-wake cycles, metabolism and more).

circadian rhythm

circa-rhythm of metabolic, physiological or behavioral processes with a naturally synchronized period of 24 hours (the term ‘circadian’ is derived from the Latin circa meaning about and diem meaning day).

Colour Rendering Index

measurement of the ability of a light source to reproduce the colour's vibrancy accurately compared to the reference illuminant (natural light). Light sources with a poor CRI (a lower number on the scale which goes from 0 to 100) will change how some colours appear.

colour temperature

this term defines whether a light source appears 'cool', 'neutral' or 'warm'; this is indicated by the Correlated Colour Temperature (CCT). Colour temperature is measured on the Kelvin (K) scale; lamps with a warm appearance have a CCT of 2700-3000K and are considered appropriate for domestic settings; neutral lamps of 4000K and cool lamps of around 6000K are used more often in offices and retail. Very cool temperatures of 6000K plus can start to look almost blue-white and are used in car LED headlights

correlated colour temperature

the temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions; [K].

daylight factor

ratio of the illuminance at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, excluding the contribution of direct sunlight to both illuminances.

direct lighting

lighting by means of luminaires having a distribution of luminous intensity such that the fraction of the emitted luminous flux directly reaching the working plane, assumed to be unbounded, is 90 % to 100 %.

discomfort glare

glare that causes discomfort without necessarily impairing the vision of the objects.

diurnal

an organism that displays activity during the day (in light conditions) and during subjective day (in constant conditions).

electroencephalogram (EEG)

a measurement of brain wave activity. This data is collected through sensors on the scalp.

endogenous

growing or working from within an organism; intrinsic.

endogenous rhythm

an oscillating system capable of self-sustained oscillations.

entrainment

the coupling of an observable rhythm in an organism to a zeitgeber resulting in shared period, where (in contrast to masking) this change is caused by an alteration of the endogenous clock that schedules the observable rhythm.

fluorescent lamp

a discharge lamp of the low-pressure mercury type in which most of the light is emitted by one or several layers of phosphors excited by the ultraviolet radiation from the discharge.

hypothalamus

a small brain structure at the base of the diencephalon. The structure is involved in functions including homeostasis, emotion, thirst, hunger, circadian rhythms, and control of the autonomic nervous system.

illuminance

quotient of the luminous flux incident on an element of the surface containing the point, by the area of that element; [lx].

indirect lighting

lighting by means of luminaires having a distribution of luminous intensity such that the fraction of the emitted luminous flux directly reaching the working plane, assumed to be unbounded, is 0 to 10%.

jet lag

desynchronization and its clinical effect after rapid movement over several time zones (after movements over time zones, e.g. transmeridian flights).

light emitting diode (LED)

solid state device embodying a p-n junction, emitting optical radiation when excited by an electric current.

lumen (lm)

SI unit of luminous flux; luminous flux emitted in unit solid angle by a uniform point source having a luminous intensity of 1 candela.

luminaire

apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes, except the lamps themselves, all the parts necessary for fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting them to the electric supply.

luminance

the luminous flux emitted in a given direction divided by the product of the projected area of the source element perpendicular to the direction and the solid angle containing that direction; [cd*m^2].

luminous flux

quantity derived from radiant flux by evaluating the radiation according to its action upon the CIE standard photometric observer; unit: [lm].

luminous intensity

the quotient of the luminous flux leaving the source and propagated in the element of solid angle containing the given direction by the solid angle; [cd].

lux (lx)

SI unit of illuminance; illuminance produced on a surface of area 1 square meter by a luminous flux of 1 lumen uniformly distributed over that surface.

melatonin

a hormone produced rhythmically in vertebrates by the pineal gland, a pea sized organ at the center of the human brain.

pacemaker

a functional entity capable of self-sustaining oscillations.

photoperiod

(a.k.a. Day Length) the duration of light in an external light-dark cycle.

radiation

emission or transfer of energy in the form of electromagnetic waves with the associated photons.

reflectance

ratio of the reflected radiant or luminous flux to the incident flux in the given conditions.

shift work

transient or permanent change in work schedule in relation to the social surroundings.

spectrum

display or specification of the monochromatic components of the radiation considered.

suprachiasmatic nucleus (SCN)

group of neurons situated above the optic chiasm in the vertebrate hypothalamus exhibiting an endogenous circadian oscillation acting as circadian pacemaker, receiving external phase information via the retina.

synchronization

state in which two or more oscillations have the same frequency due to mutual or unilateral influences (referring both to entrainment and to masking).

ultraviolet radiation

optical radiation for which the wavelengths are shorter than those for visible radiation.

visual comfort

subjective condition of visual well-being induced by the visual environment.

visual performance

performance of the visual system as measured for instance by the speed and accuracy with which a visual task is performed.

visual task

visual elements of the work being done.

workplace

designated area in which the work activities are carried out during work hours.

zeitgeber:

from the German "time giver" or "synchronizer", a zeitgeber is any external time cue that is effective in entraining an organism.

References for glossary*: Centre for Chronobiology, UPK Basel; Martinsons C., (2010); IES Illuminating engineering Society.*

Annex - Abbreviations

ALAN	Artificial Light At Night
CCT	Correlated Colour Temperature
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CG	Ciliary Ganglion
CLA	Circadian Light
CRI	Colour Rendering Index
CS	Circadian Stimulus
DA	Daylight Autonomy
DA_{CON}	Continuous Daylight Autonomy
DF	Daylight Factor
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
DGPs	Simplified DGP
DSP	Delayed Sleep Phase Disorder
EEG	Electroencephalogram
EML	Equivalent Melanopic Lux
EW	Edinger-Westphal nucleus
IEC	International Electrotechnical Commission
IF	Image Forming
IGL	Intergeniculate Leaflet
IML	Intermediolateral Nucleus
ipRGC	intrinsically photoreceptive Retinal Ganglion Cells
LD	Lowest daylight
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LLLC	Luminaire level lighting controls

mel-EDI	melanopic Equivalent Daylight Illuminance
NIF	Non-Image Forming
OPN	Olivary Pretectal Nucleus
PSQ	Pittsburgh Sleep Questionnaire
PVN	Paraventricular Nucleus
PVT	Psychomotor Vigilance Test
RHT	Retinohypothalamic Tract
SAD	Seasonal Affective Disorder
SCG	Superior Cervical Ganglion
SCN	Suprachiasmatic Nucleus
SOL	Sleep Onset Latency
SPD	Spectral Power Distribution
SPZ	Subparaventricular Zone of The Hypothalamus
SWD	Shift Work Disorder
TTFLs	Transcription–Translation Feedback Loops
UGR	Unified Glare Rating
VLPO	Ventrolateral Preoptic Nucleus
WFR	Window Floor Ratio
WWR	Window-To-Wall Ratio
KSS	Karolinska Sleepiness Scale

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Architecture is not about designing buildings,
but about providing settings for human life.

— Pallasmaa, J. (2005). *The Eyes of the Skin: Architecture and the Senses*. Wiley.