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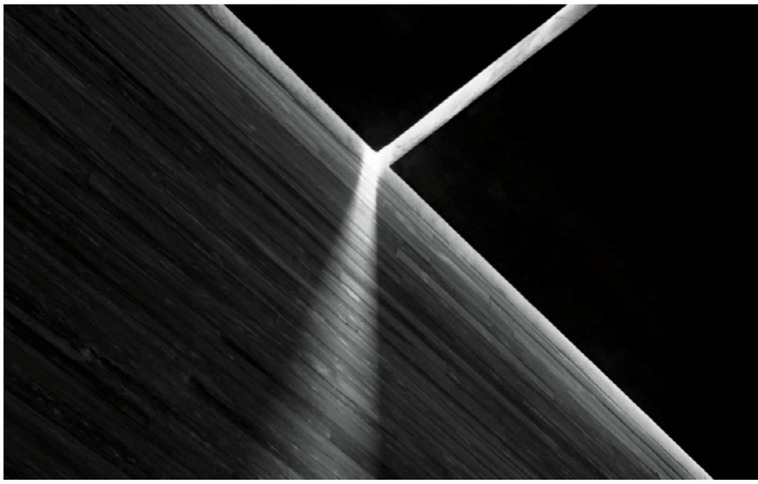
Changing perspectives on daylight: Science, technology, and culture



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Changing perspectives on daylight: Science, technology, and culture

About the cover: Daylight is almost ubiquitous, enabling many diverse life forms to survive and thrive, and affecting us all in a multitude of ways. But do we truly understand its multifaceted nature?

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3 November 2017

Form and function: Lighting the path

This booklet bridges these two principles by focusing on daylight, specifically how human-made structures can best utilize it, and how organisms have evolved in response to it.

"Whether it be the sweeping eagle in his flight, or the open apple blossom, the toiling workhorse, the blithe swan, the branching oak, the winding stream at its base, the drifting clouds, over all the coursing sun, form ever follows function, and this is the law."—American architect Louis Sullivan

Ever since American architect and skyscraper pioneer Louis Sullivan famously wrote in a magazine article that "form ever follows function," this concept has been a touchstone for many modern architects and designers. This principle states that the purpose of a building or object should be the first thing considered before a design is made. Curiously, biology has the opposite tenet, or as Charles Darwin stated in his evolutionary theory, "form precedes function," as one out of a variation of forms results in a more favorable function in a specific environment.

This booklet bridges these two principles by focusing on daylight, specifically how human-made structures can best utilize it, and how organisms have evolved in response to it. Architects, vision scientists, botanists, physicians, engineers, and material scientists contributed to provide a holistic view of this ubiquitous yet elusive topic. The authors aim to stimulate interdisciplinary insights that can identify new ways to promote health and inspire new approaches to built and natural environments.

Sunlight that enters the biosphere is mostly converted into chemical energy. However, ecosystems depend not only on the energy sunlight contains, but also on the critical information it provides. This is especially important for plants—being sessile organisms, they rely on cues from the Sun as to when to flower and where water and carbon should be directed and used. How such effects scale up to the ecosystem level is still up for debate, and undoubtedly impacts current global climate change models.

Light also conveys information to humans. Blue light from computer displays and televisions, regardless of season or time of day, often misinforms our circadian clocks and may have dire consequences for our health. Considering current knowledge on how light influences human physiology and behavior, along with the unresolved research questions in this area, recommendations for optimal lighting will become important for future health care and architecture—be it via increased access to daylight or better artificial lighting construction.

In the arc of history, cultural and technological shifts have estranged us from daylight. Today, Europeans and Americans spend on average 90% of their time indoors. Understanding the factors that determine the form and function of the built environment can lead to further improvements and adaptations, such as better glazing, to fit our actual needs. We need to develop more reliable tools to distinguish what makes natural light so unique, and to explore how electrical lighting solutions can better replicate it, in an effort both to improve human well-being and to create more energy-efficient buildings.

Finally, daylight offers great potential for improved technological and medical applications, as exemplified by artificial photosynthesis and solar disinfection. Distinct disciplinary insights into daylight are converging to offer promising new discoveries.

As our knowledge about the beneficial effects of daylight increases, it is only right that form should follow function when we think of how to build schools, hospitals, and other public spaces, so their occupants will reap its maximum benefits. Nevertheless, the quest to understand how function evolved following form should not be neglected either. Both principles need to be equally considered if we are to harness daylight in an effective, sustainable manner.

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Conveying daylight

This publication hopes to impart to the reader the many surprising and novel insights of recent multidisciplinary research into daylight.

Since the Middle Ages, glassmakers have shown unlimited creativity in harnessing the abundance and fullness of the vivid colors that can be derived from natural light—a talent that earned them the title "conveyors of daylight." Impressive and vibrant effects have been woven into the architecture of churches and other religious buildings by using the ability of stained glass—colored by addition of metallic salts during manufacture—to interact with daylight. The creation and use of stained glass, as an art and a craft, required multidisciplinary skills to conceive inspiring, soaring windows that have resisted both the ravages of time and natural insults such as wind and rain.

Similarly, a group of some 50 authors came together to produce this booklet, sharing their expertise from a broad range of multidisciplinary fields including neuroscience, photochemistry, medicine, physics, engineering, and architecture. They contribute to an eclectic array of perspectives on daylight, conveying their distinctive outlook on the complex interplay of factors inherent to this natural phenomenon. Chapter 1 opens the booklet with a brief overview of these factors and a summary of the history of research into daylight.

Apart from being a vital energy source for most of Earth's ecosystems, daylight is also a source of information for living organisms, allowing them to optimize both their function and their reaction to their environment, as explored in chapter 2 of this booklet.

How daylight impacts human physiology and behavior through its varying characteristics is the essence of chapter 3. Chapter 4 explores how habitat and lifestyle choices in human societies have gradually estranged many of us from daylight, impacting our health and well-being in a variety of ways.

Daylight is a unique light source—even the most advanced artificial light sources seem pale in comparison. Chapter 5 addresses the challenge of reinventing daylight, which is a ubiquitous, inexhaustible, and free energy source for many renewable technologies. Daylight can also be reimagined as an energy source for artificial photosynthesis and solar disinfection, as discussed in chapter 6.

This publication hopes to impart to the reader the many surprising and novel insights of recent multidisciplinary research into daylight. By supporting the many authors featured in this booklet, and by funding its publication, the recently created international Daylight Academy has given these researchers an opportunity to be conveyors of daylight to the present age, for sake of our collective future.

Prof. Dr. Jean-Louis Scartezzini
Spokesperson of the Daylight Academy Steering Committee
Lausanne, Switzerland

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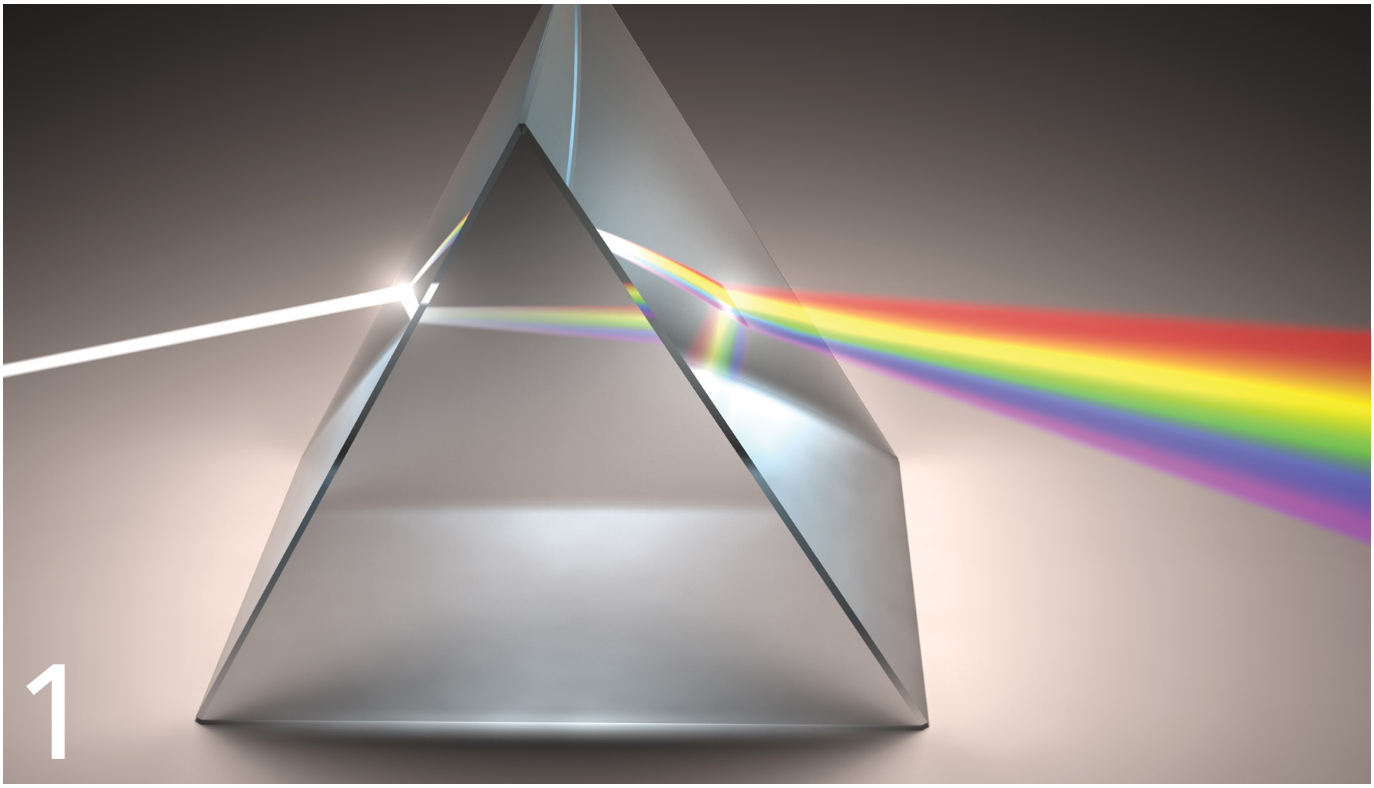

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Daylight: Contexts and concepts

Brian Norton[1], Michael Balick[2], Richard Hobday[3], Colin Fournier[4], Jean-Louis Scartezzini[5], Judit Solt[6], and Artur Braun[7]

Multidisciplinary research on daylight can identify interventions that promote health, including changes in lifestyle and cultural attitudes, and new approaches to built and natural environments. The aim of this publication is to explore the many surprising and novel insights provided by contemporary research into this complex subject. In this chapter we will provide the reader with a brief look into the history of daylight research and introduce some of the important topics that will be covered in more depth in later chapters.

Introduction

Most species evolved in environments bathed in daylight. Perception of the Sun's apparent daily journey through the sky is integral to the experience of life for both animals and plants, and key to appreciating the passage of time. Furthermore, spatial awareness of the Sun's position in the sky is crucial for many organisms; for example, many migratory birds and animals depend on such lighting cues for navigation.

Human history

The scientific understanding of daylight has diverse roots, from work in 1604 by Johannes Kepler that explained the mechanics of the human eye, to Sir Isaac Newton's 1672 work on the refraction of light through a prism. Intentionally directing daylight into buildings also has a long history (*1*). Classical Roman architects designed villas and public baths for solar heating and sunbathing (*2*). Conversely, taxes were levied on the number of windows in buildings in England, France, Ireland, and Scotland. In England, this tax remained in place from 1696 until 1851, leading to the construction of many buildings with inadequate lighting and ventilation (*3*). By the mid-19th century, physicians and scientists began to appreciate the health benefits of daylight. In 1883, Cohn reported a relationship between deficient daylight illumination and myopia in children (*4*), and in 1877 Downes and Blunt (*5*) showed that daylight could kill bacteria through glass. Koch, in 1890, reported that sunlight was lethal to the tubercle bacillus (*2*), and in 1903, the Nobel Prize for Medicine was awarded to Finsen for successfully treating lupus vulgaris—caused by the tuberculosis bacterium—with sunlight (*6*).

In the 1920s, modernist architects such as Le Corbusier endorsed the hygienic and health-giving properties of

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daylight in schools, hospitals, and domestic buildings. However, the 1960s saw a shift toward deep-plan, electrically lit buildings in which interior daylighting was deemed unnecessary because there was little evidence that daylight was better than artificial fluorescent lighting. Electricity, air-conditioning, and elevators enabled buildings to be larger, taller, and deeper. Consequently, screened off from daylight, many people spend their days in artificially lit spaces, neither enjoying the amenity of daylight nor directly aware of the presence and position of the Sun in the sky. Today, clinical research has reaffirmed the benefits of daylight; for example, hospital patients recover more quickly in daylit wards and prefer being in natural light to recuperating under artificial light (*7*). Unfortunately, rickets—the classic disease caused by sunlight deprivation—is seeing a resurgence, 80 years after it was thought to have been eliminated, as more people receive insufficient vitamin D from their diet and limited exposure to sunlight (*8*). Although eyes need daylight if they are to develop properly, many children in modern urban environments are deprived of it. Consequently, over the last 30 years, myopia has reached epidemic levels in many countries. Children completing secondary schools in Taiwan, Singapore, Hong Kong, and other parts of East Asia often need glasses or contact lenses—up to one-fifth of them develop severe myopia (*9*).

Plants have also played a critical part in human development, harnessing the Sun's energy to produce food as well as valuable chemicals. About 25% of today's prescription pharmaceutical products—some 135 drugs—are derived from plants; the healing properties of many were discovered prior to industrialization. More than 4 billion people use whole-plant extracts for some part of their primary health care. Of the more than 400,000 species of higher plants, at least 14,000 have been cataloged as having traditional uses in primary health care, but the chemical composition of only 1%–2% of the world's flora has been comprehensively screened for medical potential (*10*).

Origins, distribution, and dynamics of daylight

Daylight originates in the Sun's interior, where nuclear fusion combines four hydrogen protons to form one helium atom, releasing energy that is dissipated from the outer surface of the Sun as solar radiation. The intensity of this radiation varies over time and across the Earth's surface, as the solar elevation changes annually due to the Earth's orbit around the Sun, and as solar radiation is selectively attenuated by absorption and scattering by ozone, water vapor, carbon dioxide (CO_2), nitrogen, oxygen, aerosols, dust particles, and clouds. Apart from latitudinal variations in insolation created by the Earth's tilt, there are also appreciable longitudinal variations due to the alternating configurations of continents and oceans across the Earth's surface, leading to wind and cloud patterns. Local climates develop as a consequence of distinctive complex regional interrelationships of solar radiation, temperature, cloud cover, and prevailing winds. Randomness in both diurnal and annual patterns of

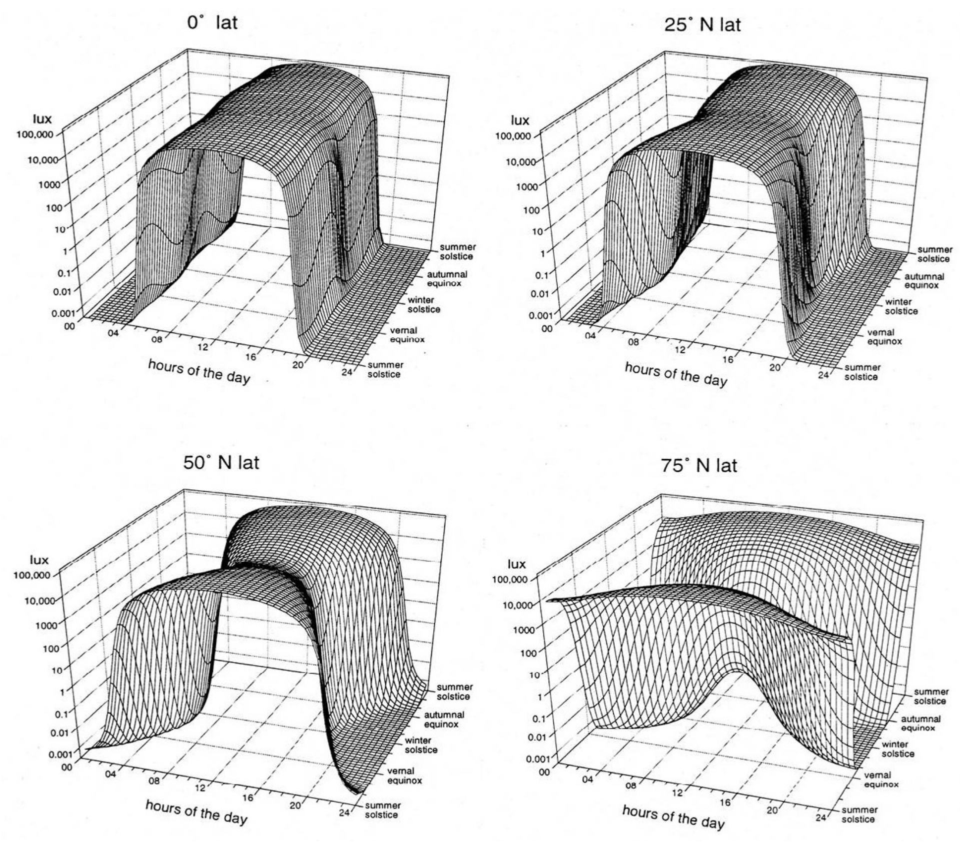


FIGURE 1. Daylight variations at four latitudes. Outdoor sunlight availability throughout a 24-hour period over a year. The 3D contour plots over 9 log units of illuminance, showing seasonal modulations dependent on latitude (shown for the equator and three equidistant latitudes to the north) (*15*).

insolation makes it impossible to predict the precise solar radiation intensity at a particular place on Earth at any one particular moment. Instantaneous solar radiation intensities do, however, form long-term statistical distributions for particular locations and these can, under certain conditions, be extrapolated reliably to other locations with different local climates (*11*).

For many solar energy applications, there is a threshold of solar radiation intensity that must be exceeded each day in order for an effect to ensue. This has important implications when assessing the outcomes—or indeed effective duration—of sunlight exposure. For solar thermal collectors, this threshold occurs when the solar heat gained equals the heat that is lost to the ambient environment. For a photovoltaic system, it may be the electrical output at which conversion from the direct current output to a usable alternating current is achieved with optimal inverter operating efficiency. Such threshold solar energy intensities correlate to the sky's clearness; the clearer the sky, the sooner a threshold intensity will be reached that day.

When an atmosphere is very turbid and cloudy, extensive scattering of radiation in the longer wavelengths causes the sky to appear increasingly white. Dust in the atmosphere scatters light just a few degrees off the direction of the Sun's rays moving toward the Earth's surface. By contrast, scattering from gas molecules occurs equally in all directions. Horizon brightening arises at low solar elevations, as more light is scattered from near the horizon than from higher parts of the sky (*12*). In fact, the intensity of solar radiation energy incident on a specific point on the surface of the Earth varies:

1. In intensity over time.
2. In the anisotropic distribution of diffuse radiation across the sky.
3. With local variations in ground reflectance.
4. Due to the slope and orientation of the receiving surface and as a consequence of shading by, or reflection from adjacent surfaces.

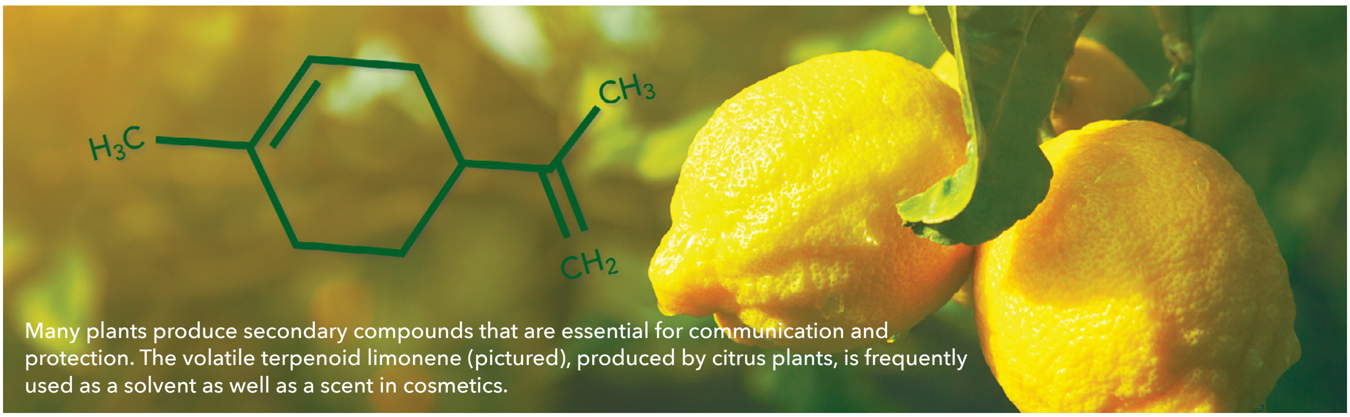
Solar radiation and daylight illuminance are related by the luminous efficacy of the solar radiation spectrum being experienced. Luminous efficacy is the ratio of the daylight illuminance to the corresponding irradiance of solar radiation. It is influenced by the spectral distribution of the incident solar radiation and varies with solar altitude, cloud cover, atmospheric pollutants, and the relative proportions of beam and diffuse solar radiation. All of these factors change during each day as well as seasonally, and are dependent on location.

Organic interactions of daylight

Daylight is that part of the solar radiation spectrum perceived by the human eye in the range of 380 nm to 780 nm. The physical and psychological characteristics of each person's visual system modify luminance perception. In bright, outdoor conditions, an eye's pupil physically constricts, the retina becomes desensitized to luminance, and photoreceptor pigments undergo chemical changes. Depending on the precise way in which the visual system adapts, the brightness of a particular luminance will be perceived differently. For example, a dim light such as a star may appear bright in the night sky, but this starlight is often imperceptible in bright sunshine. The luminous effect of daylight depends on a number of variables, including how a particular viewer's eye physiology interacts with the intensity and angular distribution of direct, diffuse, and ground-reflected solar energy components, as modified by the secularity and reflectance of receiving surfaces. Annual and diurnal variations of outdoor daylight are shown for four latitudes in Figure 1.

Disability glare caused by a very bright light source impairs vision due to a reduction in contrast that occurs when a retinal image is juxtaposed with scattered light. It arises when the optical components of the eye, such as the cornea, the lens, or the vitreous humor, have imperfect transparency or when diffuse light passes through the scleral wall of the iris. One example is afterimage retention or retinal burning from looking directly at a very bright light source, such as the Sun; it is determined by the individual's eye physiology, together with the intensity of the focused image of the Sun on the retina.

Plants fare better with direct sunlight. Through photosynthesis, plants convert water and sunlight (in the 400 nm to 700 nm range) into a variety of metabolites. These metabolites include energy-rich sugars, toxic compounds that help plants defend against predators and invasive organisms such as pathogenic bacteria and fungi, and compounds that help plants survive in extreme environmental conditions, thereby conveying an evolutionary fitness to the individual species. Certain metabolites that are produced, such as carbohydrates, lipids, proteins, and nucleic acids, are essential not only to the plant, but also to human health and nutrition.



Many plants produce secondary compounds that are essential for communication and protection. The volatile terpenoid limonene (pictured), produced by citrus plants, is frequently used as a solvent as well as a scent in cosmetics.

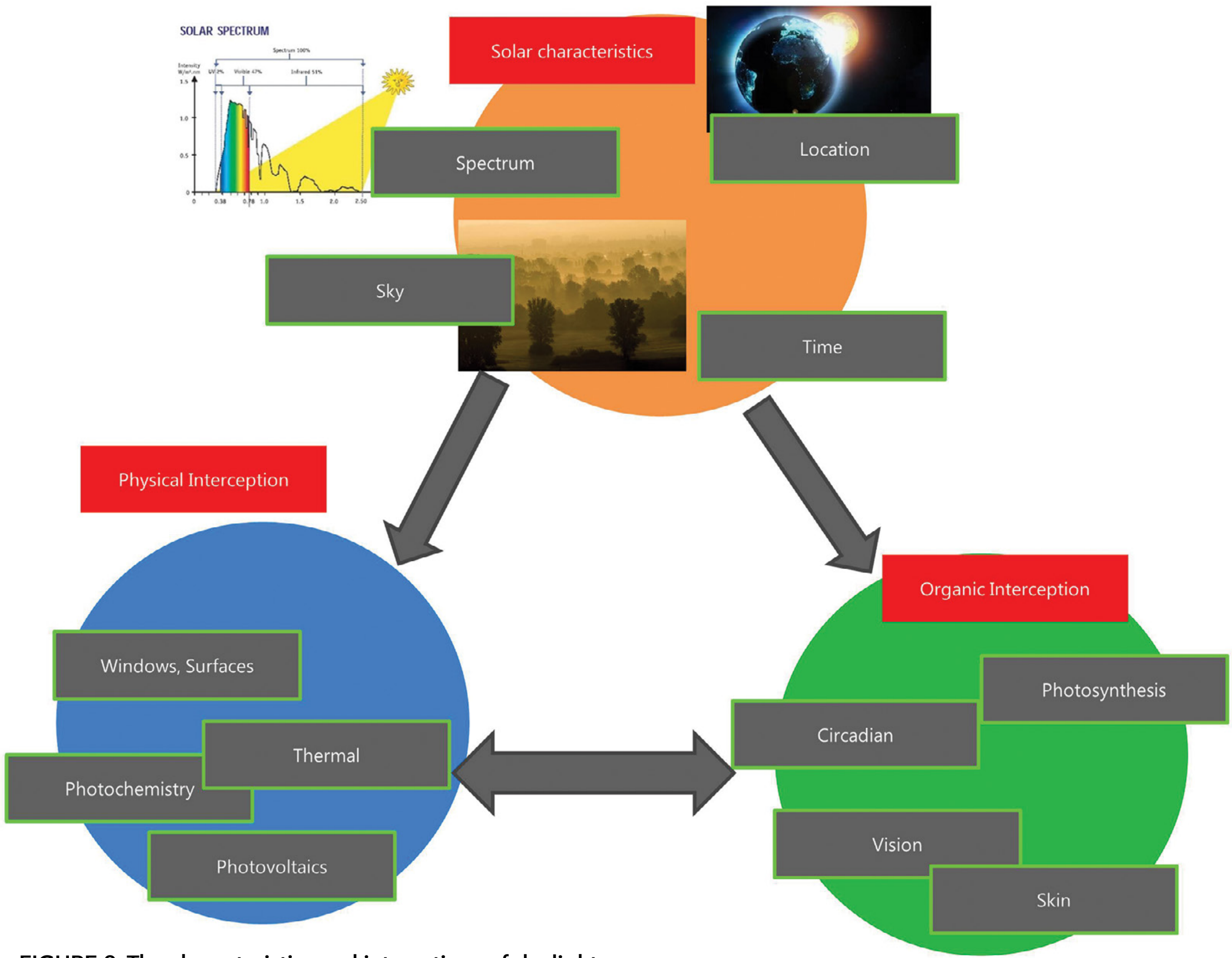


FIGURE 2. The characteristics and interactions of daylight.

Apart from its role in vision and photosynthesis, sunlight also provides important ultraviolet (UV) radiation. Skin exposure to UV light in the 280 nm to 320 nm wavelength range of the solar spectrum produces vitamin D and improves mood via production of the neurotransmitter serotonin (*13*). However, prolonged exposure to UV radiation causes freckling and sunburn, together with a higher risk of skin cancer (*14*).

Another nonvisual role of light is as a powerful cue for resetting the circadian pacemaker that regulates hormonal rhythms, alertness, and cognitive performance. The circadian "body clock" found in all plants and animals internally mirrors the external rhythm of night and day. The dominant daylight-driven circadian stimulus is a combination of light intensity, duration and timing of exposure, spectrum, and spatial distribution (*15*). Lower annual cumulative solar exposure in humans living at higher latitudes appears to be associated with negative health effects, such as a significant association with earlier onset of multiple sclerosis (*16*).

Retinal ganglion cells are directly connected to the internal biological clock in the suprachiasmatic nuclei of the human brain. These ganglion cells are particularly sensitive to light, especially to wavelengths within the blue range. Daylight includes varying blue-light content over the course of the day that acts as an environmental cue to maintain circadian rhythms. Chronobiological processes require sufficient illumination to ensure proper synchronizing of biological clocks; unfortunately, the levels of illumination normally provided by artificial light are chronobiologically equivalent to near darkness.

Architectural and engineered uses of daylight

Natural light has a spectral composition that provides the most preferable visual conditions for humans. Bringing daylight into buildings can provide illumination sufficient for working activities during most of the day, reduce use of artificial lighting and therefore electricity demand, positively impact visual performance, and allow for the diurnal movement of light and shade that can influence aesthetic appreciation of interior spaces.

The window is a critical physical part of a building structure, bringing light into the interior space and allowing occupants a view of the outdoors. The variation in transmittance of different parts of the solar spectrum through a glass window is determined by its chemical composition, molecular structure, and fabrication process (*12*). Daylight seen through a window has a particular apparent brightness and color that depends on how the intensity and spectrum of the received solar radiation interacts with the window's angular and spectral transmission characteristics (*17*). The illumination quality of daylight will be altered by the spectral transmission properties of the window glass and/or diffuse reflection by interior surfaces (*18*). The specularity of reflection by opaque materials ranges from mirror-like to totally diffuse. Humans more accurately assess interior spatial dimensions when surfaces are delineated by reflectances that provide strongly contrasting luminances. However, direct sunlight reflected by glossy surfaces can cause glare.

Daylight, though ubiquitous, is rarely understood holistically.

Illuminance, color-rendering indexes, and color temperatures indicate the perceived quality of a lit environment. Warm yellowish to reddish color temperatures are alleged to be more comfortable; empirical supporting data, however, remains weak (*19*).

Advanced daylighting systems use refraction and diffraction of direct sunlight as well as diffuse daylight to improve the delivery of daylight in buildings. Anidolic systems, based on nonimaging optics, can significantly enhance the penetration of daylight into deep office spaces (*20*). Reflective louvers or blinds, prismatic films, laser-cut panels, and holographic films can be installed or attached to windows to achieve the double function of solar shading and daylight redirection. Dynamically controlling the admission of solar heat gains and daylight in buildings can maintain thermal and visual comfort in workspaces, while simultaneously mitigating demand for heating, cooling, and lighting.

The solar radiation passing through windows offers another advantage by warming surfaces in buildings: It is familiar to experience these surfaces releasing heat by convection and long-wave radiation, thus providing warmth. Such "passive" solar heating does not usually come to mind as an application of solar energy. But this commonplace phenomenon is the consequence of the spectral characteristics of glass transmitting incident short-wavelength solar radiation (up to 3,000 nm), while trapping long-wavelength thermal radiation indoors—radiation which has been emitted from solar-heated interior surfaces (~10,000 nm). More commonly recognized applications of solar energy include technological systems that collect the Sun's energy to heat fluids or produce energy, which also take advantage of the transmission properties of glass. In solar thermal collectors, a fluid flowing through a metal absorber typically transfers solar heat for applications ranging from domestic hot water up to electrical power generation. Alternatively, solar energy can also be converted directly to electricity in solar photovoltaic modules, using particular combinations of materials that absorb solar radiation at wavelength energies corresponding to quantized electron energy gaps, in order to produce an electrical current.

Conclusions

Daylight, though ubiquitous, is rarely understood holistically. The interaction of daylight with organic and physical systems, as illustrated in Figure 2, has diverse consequences, from daylight through windows, to photosynthesis in plants, to vitamin D produced by exposure of our skin to the Sun.

In this publication, architects, vision scientists, botanists, physicians, physicists, engineers, and material scientists have contributed to an eclectic range of perspectives on daylight, each of which captures only part of the complex interplay of factors implicit in this apparently simple phenomenon. The insights from these very different contexts are brought together here to provide a cross-disciplinary narrative intended to enhance our understanding of this fascinating subject.

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Light as a source of information in ecosystems

Arthur Gessler[1], Harald Bugmann[2], Christof Bigler[2], Peter Edwards[3], Christina della Guistina[4], Christoph Kueffer[5], Jacques Roy[6], and Victor Resco de Dios[7]

The Sun is the primary energy source that drives the Earth's climate system. While some of the radiation emitted from the Sun is reflected back into space, a large portion is absorbed by the Earth's atmosphere and surface. Part of the longwave radiation re-emitted from the Earth is absorbed by radiatively active gases in the atmosphere—a phenomenon called the "greenhouse effect." This effect causes the Earth's surface temperature to be 33°K warmer than it would be without these gases. All parts of the Earth's climate system, including the hydrological cycle and atmospheric circulation, are driven by energy input from the Sun (*1*). Furthermore, sunlight is the central energy source for the biosphere, providing virtually all energy for life, from single cells to whole ecosystems. Except for a few peculiar ecosystems, such as the communities around hydrothermal vents on the ocean floor, all primary producers rely on sunlight for their energy supply. Plants and phototrophic bacteria (i.e., photoautotrophic organisms) convert light into chemical energy, which is distributed within the food web and supports all heterotrophic organisms including humans (*2*). Fossil fuel resources upon which current societies depend are essentially sunlight converted into biomass and accumulated over geological periods. The quantity of sunlight energy available to primary producers is thus of utmost importance—it drives virtually all biogeochemical cycles and food webs on Earth. It should be noted that only a small fraction of sunlight energy is actually converted into biomass, as many other factors (e.g., nutrient and water availability) are colimiting biological production on our planet.

Sunlight conveys not only energy, but information as well. In this respect, light quality (i.e., the presence of given wavelengths or ratios of particular wavelengths) and quantity are of pivotal significance to life (Figure 1). Light is an important cue modulating animal behavior, leading to convergent evolution, across many animal taxa, of complex light-sensing organs—including eyes—that allow for visual orientation within various light-wavelength bands. Similarly, a range of light sensors with absorption maxima at different wavelengths is important for the development and function of plants, such as triggering the time of bud

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break in spring or the shedding of leaves in autumn. In the organismal, ecosystem, landscape, and even global context, various attributes of sunlight provide important and essential information. For instance, light quantity and quality as well as their variation and alteration by organisms and communities within an ecosystem provide spatial information. Light quality (i.e., color) is central for many processes, including pollinator attraction, mating, and food location. Information is also contained in day length and the daily rhythmic variation of light quantity and quality, which both change with the seasons.

Plants are sessile organisms that need to endure and respond to day-to-day uncertainties.

In this chapter, we aim to highlight the importance of sunlight not only for delivering energy to the biosphere, but also for providing information that allows ecosystems to optimize their function and their reactions to environmental factors. We will focus on the importance of information carried by light at the largely unexplored ecosystem and biome levels. Evidence exists on the molecular, cellular, and individual levels that light information and how it is used is of central importance for understanding the processes and functions of life. We will also explore the temporal and spatial information conveyed by light and how it may increase the adaptability and plasticity of ecosystem responses, with a focus on plants and vegetation. The impact of human activity upon our planet is becoming ever more apparent, leading scientists to propose a new geological epoch: the "Anthropocene." Therefore, we also address the various ways that humans disturb or transform the information conveyed by light, and how the processing of light information in ecosystems has been and may be affected in the Anthropocene.

Information conveyed by light about recurring events

The direct effects of sunlight on energy transformation have been well described (*3*) on various organizational levels from the cell to the organ, as well as within food webs and ecosystems. However, the transfer and integration of information are not well understood, mainly at higher organizational levels—the ecosystem, the landscape, or the biome (*4*). While we know that the day–night rhythm has a strong influence on gene expression in plants via the so-called "circadian clock," we do not know to what extent these clock-triggered mechanisms affect the carbon and water balance of ecosystems.

Plants are sessile organisms that need to endure and respond to day-to-day uncertainties. Temperature, precipitation, herbivory, pathogens, and many other environmental factors affecting a plant's existence show only a limited degree of predictability. However, there is one environmental factor that varies deterministically as a function of time of year and geographical latitude: the photoperiod. Ecologists have long studied the mechanisms by which plants respond to and cope with unpredictable environmental changes. The adaptations and strategies they use to take advantage of predictable photoperiodic changes have been much less explored.

Plants can anticipate photoperiodic changes through an elaborate set of light sensors (*5*). They can anticipate dawn and dusk transitions, and can also more broadly "tell the time" and anticipate noon, midnight, and other times of day. Anticipation of the light regime is important because it allows the plant to prepare its metabolism in advance for the upcoming demands (e.g., to prepare for photosynthesis before dawn), to temporally couple or uncouple processes that are associated or incompatible, and, over the course of the year, to respond to changes in the seasons. The mechanism by which plants tell time is the circadian clock.

We have known for quite some time that not only gene expression, but also carbon and water fluxes at the leaf level, are regulated by the circadian clock (*6*). But we are only now beginning to understand the implications of this finding—and its evolutionary consequences—at the scale of the vegetation canopy and ecosystem. Diurnal variations in sunlight are the primary driver of photosynthesis, followed by variations in temperature. However, circadian regulation exerts a control of similar magnitude to that of temperature and leads to a time-dependent potential assimilation (the conversion of CO_2 to reduced organic carbon via photosynthesis) rate. This control means that, depending on the time of the day, maximum achievable rate of photosynthesis at a given set of environmental conditions such as light, temperature, and air humidity, will be different. The question then becomes, "Why it is necessary that the circadian clock increases or decreases the potential rate of photosynthesis depending on time of day?" That is, why is it that the potential assimilation rate is not consistently high over time? One could speculate that circadian regulation results in optimal resource use, such that most resources for photosynthesis are allocated at the time when they are most needed. However, recent research has shown that circadian regulation in photochemistry does not follow an optimized allocation scheme, but one that seeks to maximize carbon assimilation (*7*).

The control of stomatal conductance (i.e., the aperture of the stomata that allows CO_2 to diffuse into the leaf and water vapor to diffuse out) by the circadian clock is stronger than the control over assimilation, with recent research indicating that up to 70% of the diurnal rhythm in transpiration is driven by the circadian clock. This pattern of stomatal conductance that is consistent with a model based on maximizing carbon assimilation also leads to less conservative water use. For instance, circadian regulation is one of the major controls over nocturnal stomatal conductance, and leads to water wastage without any carbon gain. Recent work has shown how nocturnal conductance driven by the circadian clock is under genetic control; genotypes with higher conductance at predawn were able to assimilate more carbon in the initial morning hours (*8*).

Photosynthesis and stomatal conductance are not the only processes under control of the circadian clock—so is respiration (*9*). A major question concerning the circadian

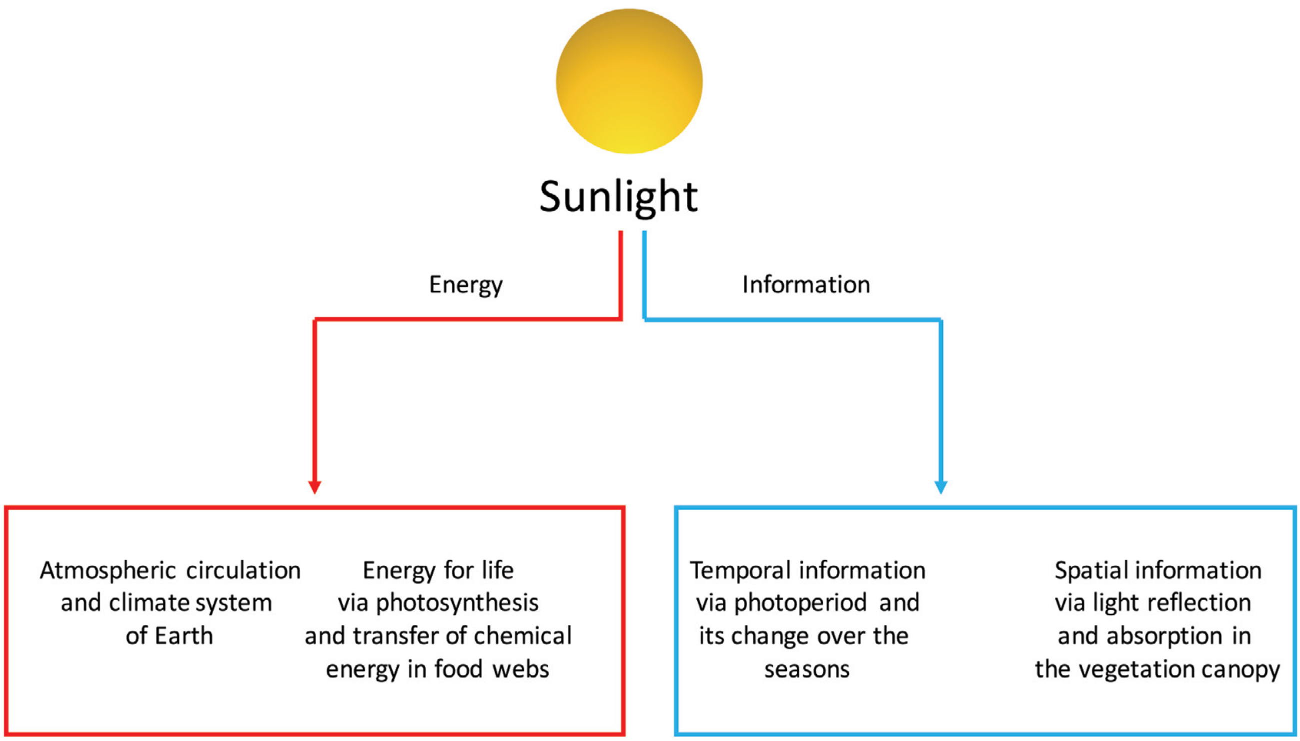

FIGURE 1. Energy and information conveyed by light. Energy from sunlight drives the Earth's atmospheric circulation and thus its climate system. It also supplies energy for almost all processes in living organisms. In addition, sunlight provides information; while this is well known on the molecular level and best explored in animals, much less is known about the information conveyed by light on the ecosystem level—especially how vegetation is affected on larger scales, up to the biome level. The photoperiod (i.e., the day–night cycle and its variation during the year) provides temporal information. Light absorption and reflection also provide spatial information and allow competitor recognition in plant canopies.

regulation of gas exchange is how widespread it is and under what conditions it is expressed. All plant species have the genes coding for the circadian clock, yet it is unclear whether circadian regulation of gas exchange is common to all plant species or whether the clock control over gas exchange is suppressed under certain conditions, such as in the understory (the vegetation layer(s) below the main forest canopy).

The processes regulating flux and function at the individual plant scale will not necessarily be the same as those found in the canopy or at the ecosystem scale, because not all processes relevant at one scale will be equally important at other scales (*10*). This is particularly true for plants, which are less centrally organized than animals. Research on the circadian regulation of photosynthesis and transpiration on the ecosystem scale in a field setting has received limited attention, mainly due to experimental limitations. The effect of the circadian clock is normally assessed under constant light and/or dark conditions, which is difficult if not impossible to achieve for whole ecosystems and under field settings. However, the few studies that have been published and that used either statistical filtering approaches or elaborated field infrastructure give some initial indications that circadian regulation may act as an adaptive memory to adjust ecosystem function based on environmental conditions from previous days (*11*, *12*). Still, we do not know if these clock-triggered mechanisms significantly affect the carbon and water balance of ecosystems, and if terrestrial biosphere models (which do not include these mechanisms) allow for a proper accounting of carbon sequestration and other functions of the terrestrial vegetation. Thus, global carbon and water cycles may be more complex than originally thought, if circadian memory acts not only on the molecular and individual plant level, but also on the ecosystem and biome scale. Thus, system responses may not be related only to the direct effects of environmental cues, but may also be driven by antecedent cues in the sense of an environmental memory. The diurnal and seasonal rhythmicity of daylight furnish a central source of information triggering this memory.

Circadian regulation is also responsible for part of the phenological change we observe through the seasons. Plants are often classified as either "photoperiod-sensitive" or "photoperiod-insensitive," depending upon whether

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leaf unfolding, flowering, or other life-cycle events depend on the photoperiod. Phenological events also depend on temperature and water availability, thus photoperiod is not the only important cue. As global warming advances, we are more often encountering an advancement of life-cycle events. However, such advancement has been slower than predicted based on temperature changes alone (*13*). Photoperiod signals, which do not change with warming, could thus provide a buffer against such phenological advancements.

Information conveyed by light from/about the local environment

Light provides information on the structure and quality of the environment and neighborhood within an ecosystem. This is important not only for animals and their spatial orientation, but also for sessile plants. Chlorophyll, the major light-absorbing pigment of plants, is activated predominantly by blue (400 nm–500 nm) and red (650 nm–700 nm) light, causing a depletion of these wavelengths further down in the vegetation canopy. Moreover, far-red light (700 nm–800 nm) is reflected by the leaves. This reflection also occurs downwards into the canopy, leading to an enrichment of far-red light. Thus, the ratio of red to far-red light will be reduced in dense canopies. Within complex, multilayer-canopy ecosystems such as forests and grasslands, the spatial distribution of light as well as its quality and wavelength composition allow for a 3D interpretation of available space and competitor location, and an optimization of shade-avoidance strategies (*14*). Due to the different absorption and reflectance properties of different objects, plants can differentiate between the shade of a nonliving object (e.g., a rock) and that of another plant: In the shade of a plant, far-red light is relatively enriched compared to the red light, whereas natural nonliving objects will not change the red-to-far-red ratio. Phytochrome is used by plants to measure the ratio of red to far-red light, and thus to detect whether the plant is in the shade of a competitor or not. In addition to red-light depletion, absorption of light by chlorophyll and other pigments also causes reduction of blue light in the shaded parts of dense canopies. Blue-light intensity and its change is detected through two classes of blue-light photoreceptors called "cryptochromes" and "phototropins" (*15*). These different photoreceptors regulate the concentration and allocation of various phytohormones, such as gibberellins, auxins, and brassinosteroids, which in turn affect growth patterns.

Because of their ability to sense light quality, plants can thus alter their growth strategy accordingly (so-called "photomorphogenesis"), for example by enhancing height growth to reduce competition for light. The red-to-far-red ratio also provides important information to plants about their location in the system. If sensed vertically, the red-to-far-red ratio of incoming radiation indicates how far it is to the top of the canopy (i.e., the lower the red-to-far-red ratio, the further the distance), albeit not in meters, but in terms of "competing leaf surface." By contrast, if sensed horizontally, plants can determine how far away the nearest plants are that might compete for light. Depending on

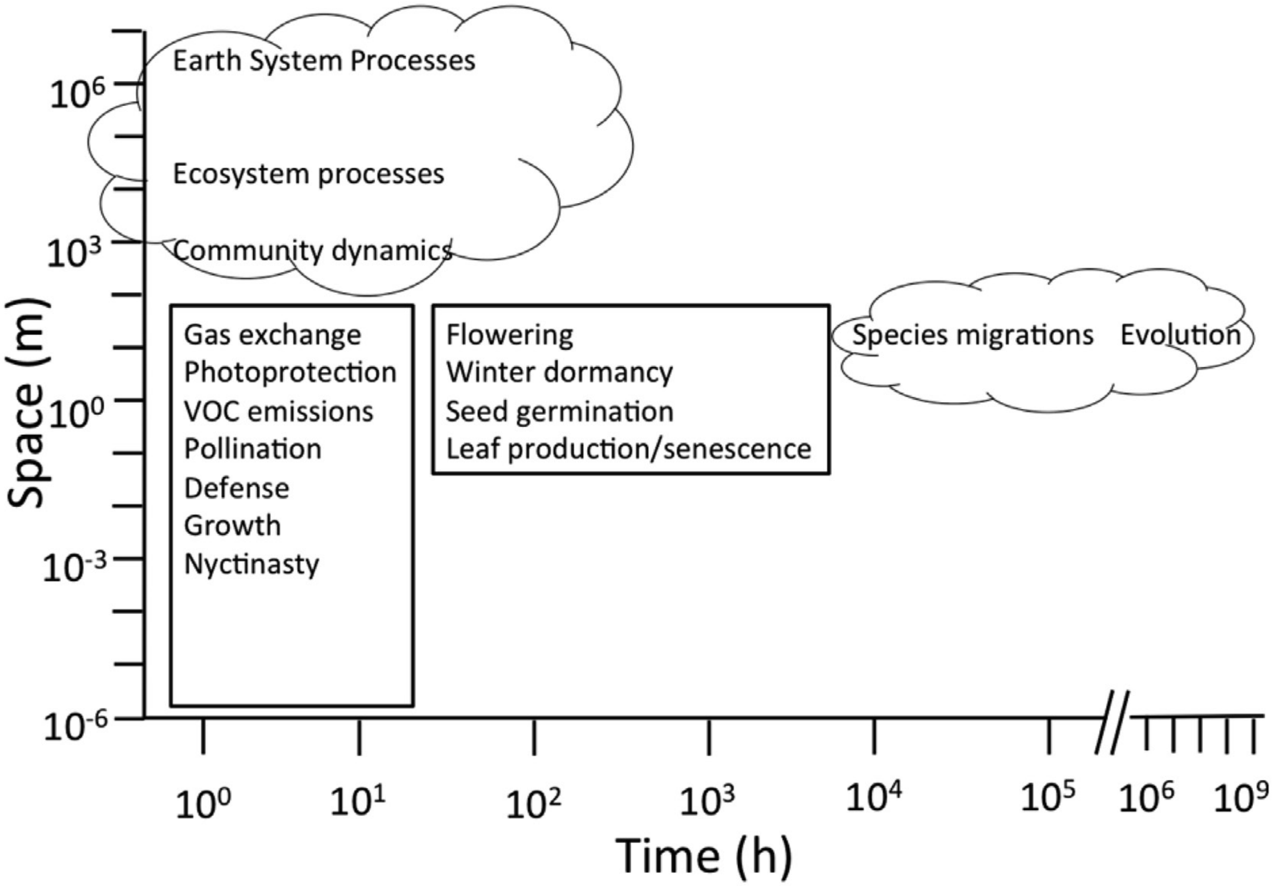

FIGURE 2. Circadian regulation of plant and ecosystem processes across scales. Circadian regulation acts on a series of processes, from organelles up to individuals, and on daily to seasonal scales (in boxes). The potential role of circadian regulation at larger temporal and spatial scales (in clouds) remains unknown. VOC, volatile organic compounds (emitted by the vegetation).

their life-history strategy, plants can adjust their growth accordingly, for example by growing away from their neighbors to avoid competition, or growing toward them so as to outcompete them.

Plants have developed different combinations of life-history traits such as growth and development rates, size and age at maturity, or lifespan in order to respond to changing environmental factors that may impact fitness. Organisms seek to maximize their fitness, which is determined by both reproductive success and survival. Because light is an important environmental factor, plant species have evolved strongly diverging morphological and ecophysiological traits to improve their fitness under differing and changing light conditions. Trees have evolved upright stems to get access to direct sunlight, with some species growing taller than others (e.g., giant sequoias in the Southwest of North America or some species of the *Dipterocarpaceae* family in Southeast Asia). Plant species such as some tall tropical forbs tend to grow extremely large leaves to collect sunlight. In contrast, the development of shade tolerance allows certain plant species to become established and survive under dense forest canopies or beneath multiple layers of herbs in grasslands. All of these traits affect the response of individual species to light, according to the information it provides on their position within the canopy and relative to their competitors.

Many open questions remain with respect to the orientation of plants within the complex canopies of forests and grasslands. For example, plants need to determine if they are shaded by parts of their own organism, such as leaves, or by competitors; and growth reactions need to be adjusted accordingly. Even though wavelength-specific reflectance and absorption patterns of different plant species may vary, conspecific competition cannot be distinguished from self-shading by sensing light quality alone. Light intensity and carbon assimilation may provide additional organism-integrating information, because the whole plant is a source-sink continuum for assimilates. If the majority of photosynthetically active plant parts are occupying space in the canopy where a net carbon gain is achieved, heterotrophic tissues such as trunks and roots will be supplied via phloem transport with assimilates, as will leaves that are growing at lower light intensities that do not allow positive net photosynthesis. In this case, and assuming a longer-term negative carbon balance, it may be advantageous to shed these leaves. However, if most leaves fall below a critical level of carbon gain, height growth may need to be promoted to get better access to light. Thus, light-energy foraging and light-quality sensing are closely interrelated and, in combination, determine the growth strategy of plants in ecosystems.

Sunlight not only provides energy for almost all processes in the biosphere, but is also an important source of information for living organisms and ecosystems.

The spatial information provided by light undergoes temporal shifts since light quality and quantity change during the day and across the growing season. Depending on latitude and several biotic (e.g., canopy density and structure) and abiotic factors (e.g., seasonal cloudiness), the light environment in an ecosystem may be spatially more complex but temporarily (seasonally) less variable (e.g., tropical rainforest), or spatially less complex but seasonally more variable (e.g., tundra). Moreover, the light climate within a canopy also depends on phenology, which again is often triggered by the photoperiod.

Phenological cues play a key role in the persistence of the herb layer in temperate forests, (e.g., those dominated by European beech)—where most herbaceous plants need to have accomplished their seasonal cycle prior to the development of the canopy, which casts too much shade on the forest floor for other plants to survive. These herbaceous plants take day length (photoperiod) as the trigger for the beginning of their development rather than weather patterns. They would lose precious time if they lagged behind weather patterns in their development. Although this strategy is risky (since tree phenology is strongly determined by weather cues), it is the only possibility for their survival, which hinges critically upon sensing light and shows the correlation between the temporal and spatial complexity of light as a source of information and energy.

Challenges related to light information in the Anthropocene

The term "Anthropocene" encompasses all major anthropogenic changes in ecosystems, biodiversity, and biogeography, among other factors, through climate change. Human impact on light as a source of information, which is important for ecosystem processes and function, can occur via direct effects such as the increasing abundance of artificial lighting, often referred to as light pollution. Moreover, rapid environmental change induced by mankind might interfere with circadian resonance, which normally serves to tune a plant's endogenous rhythms to match environmental cues. These impacts may compromise the evolved mechanisms of plants and vegetation and disrupt their ability to predict conditions in the (near) future based on hitherto "reliable" environmental cues (e.g., day–night rhythm or seasonal rhythm).

It is not only animals, which have often adapted their behavior to the day and night rhythm, but also plants and whole ecosystems that are affected by artificial lighting. While light intensity may be only locally (close to the light source) sufficient to induce photosynthesis at night, circadian clocks and photoperiodism are likely be more strongly affected at lower light intensities via phytochrome- and cryptochrome-sensing. Changes in the natural photoperiod as a consequence of artificial lighting are known to affect plant phenology in various ways, including changing the timing of flowering as well as leaf shedding of deciduous trees in autumn. As the photoperiod's natural, reliable cue is altered, it may no longer provide an adaptive advantage to enable the plant to cope with environmental conditions, but rather turn maladaptive. As an example, delayed leaf senescence in trees close to street lamps might increase the risk of early frost damage (*16*).

Under natural conditions (i.e., in the absence of artificial light), diurnal and seasonal light-related triggers remain largely constant as climate factors are changing. Thus, the phenology of photoperiod-sensitive species may no longer be in resonance with current climatic conditions. The abovementioned buffer effect provided by temperature-insensitive photoperiod signals may therefore be diminished or may even turn negative, thus restricting the plastic response to direct environmental cues when the change in environmental conditions becomes more extreme. Our understanding of the role of light triggers in the adaptation of individual species (including adaptation by migration) and of whole ecosystems (e.g., synchronization among species, including plant–animal mutualism) is largely lacking, reducing our ability to predict impacts and devise response strategies. We do not yet know if the evolved ability of plants to predict future conditions based on aspects of the natural light regime is an advantage or a disadvantage with respect to global climate change and human-induced changes of the light regime. In general, it is assumed that prediction of conditions in the (near) future that takes advantage of "reliable" environmental cues (day–night and seasonal rhythms) optimizes resource use and provides acclimation and adaptation advantages. Circadian resonance has been repeatedly shown to be adaptive and to promote growth and survival (*17*). However, such binding to daylight rhythmicity, both on a diurnal and seasonal scale, may hamper species distribution and fast acclimation in the event of rapid environmental change. It may thus happen that the potential distribution range of a species—as defined by temperature and precipitation—moves north due to

climate change, but that the photoperiod cues at this new latitude do not match the evolutionary demands of that species. As the climate changes faster than ever, it is unlikely that plants will have sufficient time to adapt, especially trees and shrubs with long generation times.

Conclusions

Sunlight not only provides energy for almost all processes in the biosphere, but is also an important source of information for living organisms and ecosystems. In plants, light-quality sensing and light-energy harvesting are closely interlinked and determine the growth strategies within complex canopy environments. Yet, how various sources of information are coprocessed remains unknown. The information provided by the highly reliable photoperiod allows a plant to substantially increase photosynthesis, growth, and survival when the circadian clock period and the external light–dark cycle are matched. However, whether the circadian clock plays a role in modulating canopy and ecosystem water and carbon fluxes is still unknown. If ecosystem responses are also driven by antecedent environmental conditions via the circadian clock, Earth system models may be unable to fully capture the effect of global climate change on the Earth's biogeochemical cycles. Taking light and photoperiod as surrogates for other, less reliable environmental cues, such as temperature and precipitation, may prove to be an insurmountable evolutionary burden for some species, particularly when light and other environmental cues no longer match, preventing migration, for example. Neither species distribution models nor mechanistic dynamic global vegetation models normally take into account the impacts of natural light as a source of information. Thus, we need better mechanistic representations of the impacts of light information on ecosystem processes in order to include these in models that allow for the projection of future species distributions as well as ecosystem and biome function.

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IMAGE: OLAFUR ELIASSON, THE DOMADALUR DAYLIGHT SERIES (SOUTH), 2006

3

The effect of light on humans

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In this chapter, we review how light affects humans: first by describing the ways in which light impacts physiology and behavior, and then by discussing how different characteristics of light (timing, pattern, intensity, duration, and past light exposure) can influence alertness, cognitive performance, mood, sleep, and well-being, in addition to its major function in promoting vision. We conclude with recommendations for optimal lighting and a discussion of unresolved research questions.

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Primary physiological impacts of light

Daylight influences virtually every aspect of human physiology and acts via three main routes: (1) visual, (2) direct skin absorbance, and (3) nonvisual ocular actions on the circadian clock in the brain and on other neuronal pathways.

The primary use of light for humans is vision (i.e., seeing objects oriented in space and time, and detecting color, motion, and brightness). Exposure to light triggers the release of the neurotransmitter dopamine in the retina, which regulates light adaptation. Sufficient light is needed to produce high-quality images on the retina, which may play a role in the normal development of the eye, where the axial length and the refractive media are balanced so as to produce an image focused exactly on the retina (emmetropization) (*1*). The action of daylight on the skin to promote the synthesis of vitamin D is well known (see Chapter 5), as are the damaging effects of ultraviolet rays and effects on skin temperature and the perception of well-being. Light influences the circadian clock in a nonvisual fashion, governing daily rhythms of physiology and behavior by influencing nocturnal synthesis of the pineal hormone melatonin and diurnal release of the adrenal cortical hormone cortisol, for example, as well as the timing of sleep and wakefulness. Finally, light modulates mood partly through the release of the neurotransmitters dopamine and serotonin.

Photoreceptors and neuronal pathways

All ocular effects of light result from photons impinging on the retina. The incoming photon flux is determined by the intensity, spatial and temporal dynamics, duration, and spectral composition of the light, as well as the transmission and absorption characteristics of the eye and ocular media.

Photoreceptors in the retina

In mammalian eyes, photons are detected by specialized photoreceptor cells—rods and cones—that contain proteins with light-sensitive photopigments called opsins (Figure 1). When they absorb photons, the opsins change their electrical properties and conformation, eliciting a downstream biochemical cascade that communicates photon detection to the brain. Human retinas contain four opsins that enable vision: three in cones (long-, middle-, and short-wavelength–sensitive opsins with maximum sensitivity at 564 nm, 534 nm, and 420 nm, respectively), and one in rods (rhodopsin, maximum sensitivity at 507 nm). Both rods and cones transmit light information via the retinal ganglion cells to the lateral geniculate nuclei of the thalamus, and ultimately give rise to visual sensations when the impulses reach regions of the primary visual cortex in the occipital cortex. Further processing of visual stimuli occurs via projections from the primary to secondary visual cortices and higher-order brain regions. From the primary visual cortex, activity passes into two parallel processing streams—a ventral stream that analyzes objects and leads to the inferior temporal cortex, and a dorsal stream that analyzes spatial relations between objects and leads to the superior temporal and parietal cortices. In addition to classical photoreceptor cells located in the outer retina, the inner retina contains an additional photoreceptor cell type, the intrinsically photosensitive retinal ganglion cells (ipRGCs) (*2–4*), which contain the light-sensitive photopigment melanopsin (maximum sensitivity at 480 nm). There is growing evidence that ipRGCs contribute to vision by discriminating between brightness and light–dark transitions (*5*).

Nonvisual effects of light

IpRGCs are a subset of evolutionarily preserved mammalian retinal ganglion cells (Figure 1). They receive external input from the rods and cones that influence their light responses and are also directly photosensitive. The role of ipRGCs is not primarily for vision, but rather for nonvisual or so-called "non-image-forming functions." These functions can be defined as brain and body processes that vary with exposure to light and are mediated by the eyes, but are not directly involved in vision. The most fundamental ipRGC projection is a direct neuronal pathway to the "master clock" in the brain—located in the suprachiasmatic nuclei (SCN) (*6*)—that enables synchronization with the environmental light–dark cycle. Melanopsin-dependent projections also reach other specific brain areas, including the olivary pretectal nuclei that control the pupillary light reflex and many other functions (*7–9*). In primates, ipRGCs also project to neurons involved in vision, such as the lateral geniculate nucleus of the thalamus (*10*), suggesting a feedback mechanism from brightness perception and contrast discrimination back to the image-forming visual function (*5, 11*). Although many of the projections of ipRGCs have been identified, the exact mechanisms by which they modulate activity in their target neurons remain unknown. Experimentally, irradiance response curves of monochromatic light with different maximal wavelengths (so-called "action spectra") reveal the dominant role of melanopsin in driving physiological nonvisual light responses [e.g., suppression of nighttime melatonin (*12, 13*), circadian phase shifting (*14*), and pupillary light reflex (*15*)]. In addition to conventional mechanisms of transient neural adaptation, recent research suggests that additional epigenetic mechanisms exist, resulting in dynamic DNA methylation that regularly adjusts gene expression in the SCN and elsewhere (*16*).

Ophthalmological and neurobiological findings of the last decade have had an enormous impact on our understanding of the multiple effects of light and of sleep-wake behavior; our growing knowledge of the "biological" effects of light has also influenced the standards and practice of artificial lighting, as well as architectural design. Here we focus particularly on the nonvisual function of light, as it is less well understood than its function in vision.

The central and peripheral circadian system

The mammalian SCN contain approximately 20,000 neurons, the synchronized activity of which orchestrates endogenous rhythms of physiology and behavior with a period length averaging 24.2 hours in humans (*17*). To remain synchronized with the 24-hour solar day and the seasonal changes in day length, the SCN require daily exposure to an external *zeitgeber* (timing cue), which resets the endogenous clock to match the light–dark cycle. For most of human evolution, daylight was the primary *zeitgeber* for this synchronization. Only in the last century did electric light become a prominent factor interfering with natural entrainment.

The SCN in turn convey diurnal timing information to other brain regions. For example, both wake- and sleep-promoting neurons are directly or indirectly connected to the SCN (e.g., via the dorsomedial hypothalamus). In humans and other diurnal animals, signaling by the neurotransmitter glutamate activates wake-promoting neurons and their affiliated neurotransmitters, such as those in the basal forebrain, the lateral hypothalamus (orexin), the locus coeruleus (noradrenaline), the raphe nuclei (serotonin), and the pontine tegmental and tuberomamillary nuclei (histamine). In parallel, sleep-promoting neurons, such as those of the ventrolateral preoptic area of the anterior hypothalamus, are inhibited during wake-time and disinhibited during sleep (*18*). Rhythmic SCN information is also transmitted to the pineal gland via a multisynaptic pathway driving the circadian rhythm of melatonin production.

SCN information is also conveyed via neuronal, humoral, endocrine, and molecular pathways to peripheral organs and ultimately to all cells in the body via pathways that are not yet fully identified (Figure 2). Finally, each cell in the body contains a circadian oscillatory mechanism comparable to that of the SCN cells, characterized by a negative transcriptional–translational feedback loop involving dedicated clock genes and proteins. Together, these mechanisms result in the circadian oscillation of 10%–30% of all transcripts, proteins, and metabolites. These peripheral clock rhythms are usually synchronized with each other, with other organs, and with the SCN in the brain, to produce a regular 24-hour cycle (*19*).

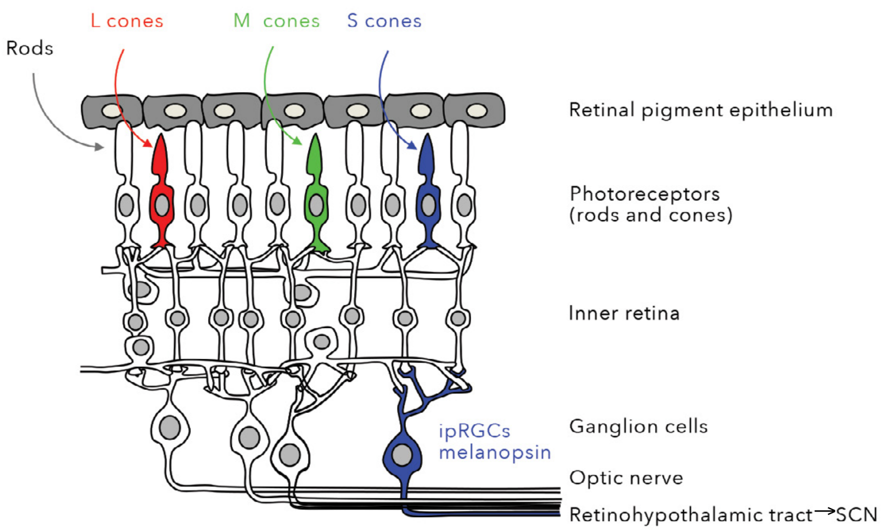

FIGURE 1. Schematic of the human retina. Classical photoreceptors, rods, cones, and newly discovered intrinsically photosensitive retinal ganglion cells (ipRGCs) are shown.

Physiological and behavioral processing of light by the brain

Acute and circadian impact of light on alertness

The state of alertness in humans depends on brain activation resulting from sensory input via the ascending reticular activating system and other wake-promoting neurons and their neurotransmitters and hormones (i.e., orexin, histamine, and cortisol). Light has the immediate effect of increasing subjective and objective alertness (*20*). Most of these effects depend on light intensity, timing, exposure duration, and spectral composition (short-wavelength blue light results in greater alertness than longer-wavelength light; see next section). The magnitude of light's effect on alertness also depends on the duration of prior wakefulness, physical activity, and light/dark history.

Subjective alertness can be assessed via questionnaires, while objective alertness can be measured by electroencephalogram recordings during wakefulness, or by other means (*20*). Initially it was thought that the effects of light on alertness were mediated by suppression of nocturnal melatonin production, but it has since been found that light can elicit an alerting response at all times of day, even when melatonin is undetectable (*21*, *22*). Mapping of the neural pathways activated by ipRGCs suggests that light directly affects brain areas involved in sleep–wake regulation. Functional magnetic resonance imaging studies have confirmed that monochromatic blue light acutely activates a number of brain areas (e.g., hippocampus, thalamus, amygdala, and locus coeruleus) associated with the observed alerting and cognitive effects of light in response to the activation of the primary and secondary visual areas of the occipital cortex and parieto-occipital junction (*23*).

Beyond its acute alerting effect, light is also a *zeitgeber* to the circadian system: It has the capacity to modify circadian timing (phase) and amplitude, depending on the time of day of exposure. Light in the early morning hours can advance—and evening light can delay—the circadian clock, and thus the rhythm of all downstream variables (e.g., alertness, performance, temperature, and melatonin levels) (*24*). As is the case with alertness, these capacities of light depend on intensity, light spectrum, and duration, and are also influenced by prior light history and interindividual differences (chronotype, age, genetic background, and lifestyle) (*20, 25–27*). Inadequate or conflicting entrainment signals can have serious physiological consequences. This is most obvious in night-shift workers, whose sleep–wake cycles (and thus also their light–dark exposure) follow shift-work timing and length, but usually without adequate synchronization of the circadian system. Side effects of circadian desynchrony in shift workers include gastrointestinal and cardiovascular problems, metabolic syndrome, cancer, and sleep and mood disturbances (*28–31*). Similarly, the short-term desynchrony induced by transmeridian travel—the well-known syndrome of jet lag—requires corrective light exposure for more rapid entrainment to the new time zone.

Impact of light on sleep

Light impacts sleep and sleepiness in humans in several ways. First, a beneficial impact of light on sleep comes from adequate bright light exposure during daytime, which can increase subjective sleep quality and duration the following night, most likely via augmentation of the circadian amplitude. Darkness at night (i.e., the absence of artificial light while asleep) is also important for healthy sleep. Dawn and dusk that signal the day–night transitions are thus important time cues for sleep and wakefulness. The dusk transition is often disturbed by blue-enriched electric light from artificial sources, as well as by electronic devices emitting short-wavelength blue light, such as television and computer screens. Besides delaying the timing of sleep, bright (and/or blue-enriched) light exposure in the evening also affects the structure of subsequent sleep, with reduced slow-wave activity at the beginning of the night and reduced rapid-eye movement (REM) sleep duration, as well as changes in REM sleep latency (*32*). These findings have practical, everyday implications. Bright light and/or light with a high proportion of short wavelengths (cold white) should be avoided in the evening and at night (except for certain kinds of night-shift work; see Chapter 5). This avoidance is crucial, for example, in teenagers who already show intrinsic preferences for later sleep–wake schedules than children and adults. Evening exposure to light-emitting electronic devices reinforces their late sleep times and makes compliance with the early school start difficult. Wearing blue light–blocking glasses, dimming room light and avoiding bright light and LED screen use, or using software designed to reduce light intensity and short-wavelength light emission of these devices, are strategies to increase sleepiness earlier in the evening, leading to earlier sleep onset and longer sleep duration (*33*).

Impact of light on mood and depression

Light has an impact on the regulation of neural circuits and on the function of neurotransmitters, for example, serotonin, which shows both daily and seasonal variations in its release. The turnover of serotonin in the brain is lowest in winter, and acutely stimulated by sunlight (*34*). In animal models, mistimed light exposure leads to anhedonic (i.e., depression-like) behavior and attenuated learning capacity (*35*). These effects are reversed by administration of antidepressants (i.e., selective serotonin reuptake inhibitors). Humans also display seasonal variations in psychology, physiology, and behavior, and a subset of individuals develop recurrent seasonal depressive symptoms, coined "Seasonal Affective Disorder" (SAD).

Seasonal Affective Disorder

Seasonal change in daylight availability was thought to trigger SAD, and the first light-therapy protocol was based on a model of photoperiodic response to light (*36*). Since then, many studies have shown that artificial-light therapy (and daylight) is highly effective as a treatment for SAD, with positive responses occurring within days (*37*). Light therapy is usually recommended for use throughout the winter (*38*). The mechanism behind light's antidepressant effect is still being debated, but the current understanding considers a dual mechanism. On the one hand, patients suffering from SAD fail to regulate serotonin turnover in winter, thereby becoming more vulnerable to depression. Depletion of tryptophan (a precursor of serotonin) in SAD patients following successful bright light therapy induces relapse, pointing to a serotonergic mechanism of the antidepressant effect of light. On the other hand, decreasing day length in autumn and winter may delay the circadian system relative to sleep in SAD patients. This drift is corrected by morning light treatment and leads to recovery. Another hypothesis considers that SAD develops from a combination of suboptimal daylight exposure together with too-intense or mistimed artificial lighting in the evening. Findings of a missense variant of the retinal melanopsin gene in patients suffering from SAD suggests alterations in light processing via ipRGCs (*39*).

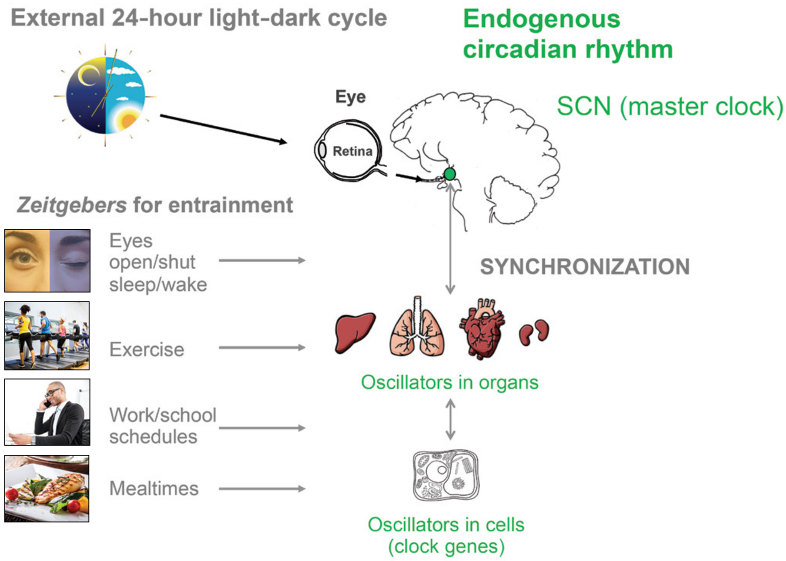

FIGURE 2. The circadian system. Light is the major *zeitgeber* that synchronizes the biological clock in the suprachiasmatic nuclei (SCN). Other *zeitgebers* such as meals, social interactions, and physical activity are also important for good entrainment.

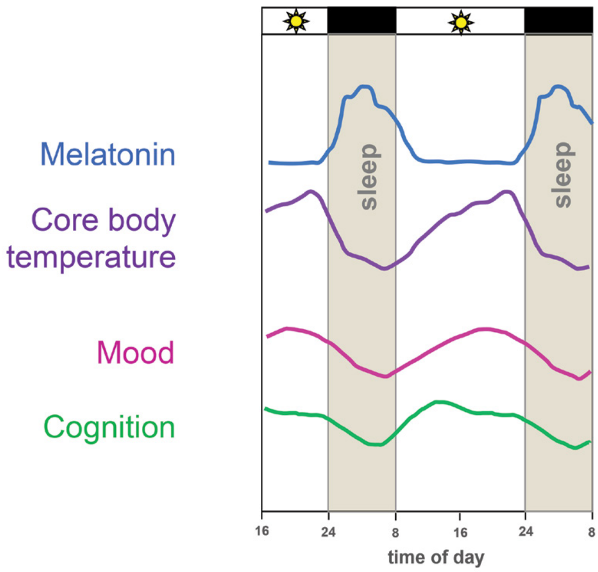

FIGURE 3. Examples of human circadian rhythms in physiology and behavior synchronized to the light-dark cycle. Data are double plotted using arbitrary scales; sleep periods (dark) are indicated.

Major depression

Although many patients with major depression exhibit some seasonal variation, the majority of them cannot be classified as suffering from SAD. Nonseasonal depression is often more severe than SAD, with the classic melancholic symptoms of anhedonia, insomnia, appetite and weight loss, and suicidal thoughts. Light therapy for nonseasonal depression has yielded positive results in a growing number of clinical trials, with the magnitude of response comparable to that of psychotherapy and antidepressant medication, whether used as monotherapy or as an adjunct. For this patient group, light therapy requires a number of weeks to work, and treatment duration optimally should continue until remission occurs (*40*).

Light therapy guidelines

Most clinical trials of light therapy have used light boxes. White light with an illuminance of 10,000 lux, a color temperature of 4,000 K, and an ultraviolet filter is recommended (*41*). The spectral power distribution must be considered, especially the amount of short-wavelength radiation. Even low-intensity blue light may, under certain circumstances, impose ophthalmological risks (blue-light hazard; see Chapter 5). Morning light is superior to light at other times. Prescribed daily time outdoors in the morning (daylight) is also efficacious, since even on overcast days in winter, outdoor illuminance exceeds 2,000 lux, as compared with indoor lighting (~300 lux) (*41, 42*).

Dawn and dusk that signal the day–night transitions are thus important time cues for sleep and wakefulness.

Metabolic and immunological functions

Circadian control of metabolism probably evolved in the earliest life forms (archaebacteria), with the goal of temporally separating nitrogen fixation from photosynthesis and controlling the cell cycle, DNA repair, and sequential processing of carbon-containing energy. In mammals, including humans, these sequential cycles involve the metabolism of glucose, the storage of metabolites as fat or glycogen, and the retrieval of stored energy during fasting periods at night. Mistimed metabolic processes or food intake mean that insulin and cortisol are not secreted at the correct times, increasing the likelihood of developing insulin resistance and type 2 diabetes (*43*). An important component of this pathology has recently been suggested as resulting from desynchrony between the central clock in the SCN and peripheral clocks in organs and tissues: Light shifts SCN timing, and food intake shifts the timing of peripheral clocks. All clocks thus can be mistimed with respect to each other and can undergo re-entrainment at different speeds, which has pathophysiological consequences (*44*, *45*). Correspondingly, large epidemiological studies have associated shift work with increased incidence of cancer and metabolic syndrome (*31*).

Light also controls immune function both directly and via the circadian clock (*46*). Many different immune parameters, such as cytokine levels, immune cell counts, and the response to immune challenge, demonstrate circadian modulation (*47*). Disruption of normal clock function via clock ablation or shift-work paradigms in rodents results in increased infection rates, morbidity, and mortality (*31*). Via a multisynaptic neuronal pathway, light also resets the timing of the nocturnal release of melatonin, which modulates both innate and adaptive immune systems (*48*).

Vision, visual comfort, and psychological aspects of light

The visual system is exceedingly well studied and will not be reiterated here (*49*). Obviously, many aspects of vision are important in ophthalmology and in the built environment (Chapter 4), not only in terms of aesthetics but also for visual comfort (Chapter 5). The conscious perception of objects in the visual fields depends on a number of factors associated with the physical properties of light (*50*, *51*). While visual perception is classically held to depend mainly on stimulus characteristics, recent evidence reveals that perception and decisions derived from these perceptions are biased by potential consequences of which the subject may be unaware. Thus, the potential effects of visually derived decisions may bias not only the response but also the way in which the sensory input is converted into vision (*52*).

Visual comfort

Visual comfort depends on our perception of light, which encompasses physiological sensations and functions as well as emotions. Thus, visual comfort is more than the "absence of discomfort" or glare (see also Chapter 4), and is determined by optimal light quality and quantity for specific tasks and individual needs. It also interacts with other stimuli such as temperature, noise, and air quality. Visual comfort is typically assessed by subjective evaluation of a lit environment, and in a few cases also by physiological measurements such as electromyography of eye muscles, pupil size, and cortical excitation. Together these studies reveal that visual comfort is highly variable and depends on:

- The light quality (e.g., brightness, intensity, spectrum, flicker frequency, contrast, luminous distribution, dynamics, angle of gaze, perception of room space, aesthetics, scenery, and window size).
- The characteristics and state of the individual (e.g., sex, age, medical history, visual ability, circadian phase, duration of prior wakefulness, prior light history, mood, and cultural conditions).
- Work-related conditions and living circumstances (e.g., work tasks, stress, socioeconomic status, and social relationships).

Psychological aspects of light

Light, depending on its characteristics, affects psychological and cognitive function in humans to varying degrees, directly or indirectly, by modulating alertness and thereby enhancing awareness and mental performance (*20, 23*). Higher illuminance immediately leads to better visual and cognitive performance than lower illuminance, both during the day and at night (*20*, *23*, *53*). These differences have been attributed in part to the alerting effects of light (see above), but also to task-specific brain activation and general attention, even when subjective alertness of the participants does not differ (*23*). However, a saturation threshold must exist, above which higher illuminance or longer light duration does not further affect mental processing in terms of cognition.

It is generally accepted that humans prefer lighting conditions with brighter light, including daylight, than a setting with pure artificial light (*54*). Higher illuminance enhances feelings of improved subjective well-being, vitality, and energy. Probably by different pathways, it also leads to good cognitive performance. By contrast, in the workplace, higher illuminance can also be accompanied by glare, which causes visual discomfort, or worse, impedes vision, creates visual distractions, and even headaches, all of which compromise mental processes. However, in indoor workplaces where windows provide ample daylight, higher levels of contrast and glare are normally tolerated without compromising work performance. During night work, while implementation of bright light enhances alertness, it may also lead to worsening of mood and motivation, especially in the second half of the night shift when homeostatic sleep pressure is high (*55*).

For the most part, experiments showing these results have been performed in laboratory settings using artificial light, giving conflicting results for different tasks or with different wavelengths of light, or both. One reason may be that light can have a differential effect on different cognitive domains. For example, light may induce faster reaction times in tasks associated with sustained attention (e.g., the Psychomotor Vigilance Task or the Sustained Attention to Response Task), but not in tasks associated with executive function, such as the N-back test or Stroop test. Some of these effects can last beyond light exposure (*56–58*). The spectral composition of light can lead to differences in emotional processing, such that brain activation to emotional stimuli is stronger under monochromatic blue light than under green light conditions (i.e., with higher involvement of melanopsin-mediated photoreception) (*59*).

In addition to its effects on cognition and performance, light can directly influence mood. Studies with healthy individuals have shown a mood-enhancing effect of bright light. For example, individuals with feelings of hopelessness had a greater desire to increase ambient lighting, and conversely, dimmer ambient lighting intensified feelings of hopelessness (*60*). Interestingly, a self-selected bright–dark scale can be used to monitor global mood in depression (*61*). Also, lighting has several emotional connotations (dependent on internal and external factors), and a light spectrum with longer wavelengths of light leads to a warmer perception of that environment than light with a blue-shifted spectrum (*62*). There seems to be a gender difference in emotional perception of light, with women generally preferring the warmer colors present in incandescent lighting over whiter, energy-saving lighting (with higher color temperatures) (*63*). Perspective of view, awareness of space, color of walls, scenery through the window, and uniformity of light as well as culture and aesthetics also affect the perception of light, visual comfort, mood, and well-being, indirectly leading to differences in productivity (see Chapters 4 and 5). Expectations and the need for security also have repercussions in terms of psychological responses to light. The factors necessarily differ in blind people (with or without melanopsin-dependent photoreception). Other environmental factors such as temperature, humidity, and stressors also need to be considered. The quality of light needed for specific domains of psychological functions remains unknown, and large interindividual differences are likely, as discussed in the next section.

Interindividual light exposure preferences and needs

Across all age groups and cultures, there is a strong preference for daylight over electric light (*64*). General work satisfaction is strongly determined by the presence of a window to the exterior in the workspace (*65*). Individuals seem to have preferences for illuminance levels and color temperatures of lighting. Here, seven mechanisms potentially underlying interindividual differences of light exposure preferences and needs have been identified:

1. There are intrinsic interindividual differences in the physiology of the eye (e.g., iris pigmentation, pupil dilatation capacity, quality of the optical media of the eye, and fluorescence of the retina, among others).
2. Differences in light exposure arise from the timing (and intensity) of light relative to an individual's circadian phase (internal time) (*66*). These differences are easily demonstrated in extreme early and late chronotypes, whose preferred sleep-onset and wake-up times differ by several hours and hence of timing of light exposure (*67*).
3. Genetic variations may also contribute to differences in an individual's sensitivity or responsiveness to light, as suggested from data collected in healthy individuals with a polymorphism in the clock gene, PER3 ($PER3^{5/5}$ vs. $PER3^{4/4}$). $PER3^{5/5}$ carriers exhibit significantly stronger subjective and objective alertness responses to light than $PER3^{4/4}$ carriers (*68*).
4. Interindividual differences in diet and metabolism may affect sensitivity or responsiveness to light. Also, the timing, amount, and type of food consumed may influence circadian and sleep timing that in turn modulates a person's light-exposure timing (*69*).
5. Interindividual differences in the history of light exposure (i.e., prior exposure to light) and duration of prior wakefulness can influence visual and nonvisual light responses (*70*).
6. There are cultural differences in light-exposure preference. For example, individuals in London expressed a preference for a more homogenous distribution of light and improved color rendering, while those in Seoul preferred lighting that reduced glare in daylit environments (*71*) (also see Chapter 4).
7. An individual's health status may determine how light is perceived and what type of light is preferred. Several neurological diseases (e.g., migraines) are associated with hypersensitivity to light (photophobia). Diseases affecting the retina or optic nerve (e.g., hereditary optic nerve diseases, diabetes, age-related macular degeneration, and glaucoma) often lead to increased demand for light for vision, but also cause blinding, poor dark adaptation, and greater contrast sensitivity. In addition, many eye diseases decrease light responsiveness (e.g., glaucoma and cataracts) by affecting both visual and nonvisual functions (*72*, *73*).

Mitigating negative effects of light on health

Which kind of lighting is good for health? The World Health Organization (WHO) defines health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." (*74*). In its most recent report, the International Commission on Illumination (CIE) presents a research agenda that includes their Five Principles of Healthy Lighting:

1. The daily light dose received by people in Western (industrialized) countries might be too low.
2. Healthy light is inextricably linked to healthy darkness.
3. Light for biological action should be rich in the regions of the spectrum to which the nonvisual system is most sensitive.
4. The important consideration in determining light dose is the light received at the eye, both directly from the light source and reflected off surrounding surfaces.
5. The timing of light exposure influences the effects of dose (*75*).

The current recommendations [as promoted by the European Union–funded SSL-erate Consortium project, Lighting For People

(*76*)] are: (1) to apply melanopsin-weighted illuminance [α-opic lux; (*77*)]; and (2) to use dynamic lighting (e.g., more blue and brighter light in the first half of the day and relatively more red light—with a low portion of short-wavelength light—and dimmer light in the last two hours before bedtime) instead of static polychromatic white electric lighting. In order to compare and predict the impact of lighting, a standardized method has been proposed for measuring lighting and light-emitting devices and the degree to which the five photoreceptor channels are activated (*77*). CIE is setting up a new Joint Technical Committee to translate this scientific consensus into the first international standard on quantifying irradiance with respect to stimulation of all ocular photoreceptors.

There is some information on light intensity (i.e., irradiance and photon flux; see Chapter 5) and spectrum (e.g., the brighter and bluer the content, the stronger the effect on the circadian system), but very little about light distribution, the impact of windows (i.e., rooms with windows provide daylight influx and a view), self-selected light exposure preferences, culture, or work content (see Chapter 4). Current applications focus on dynamic artificial lighting, possibly triggered by commercial possibilities or incentives, but much less on how to bring daylight into buildings. Studies on small numbers of individuals under laboratory conditions over a short time period do not permit an easy and direct translation of findings into generally applicable strategies for good lighting. To gain a more accurate, detailed understanding of light, prospective studies on larger and more diverse populations across years and in different seasons and latitudes are needed. In addition, to date no robust marker has been identified that reliably predicts the different effects of light on the individual during the day (since melatonin suppression can only be measured during the night), making it difficult to derive tailored recommendations concerning light intensity, spectrum, distribution, and dynamics that could be used by building planners.

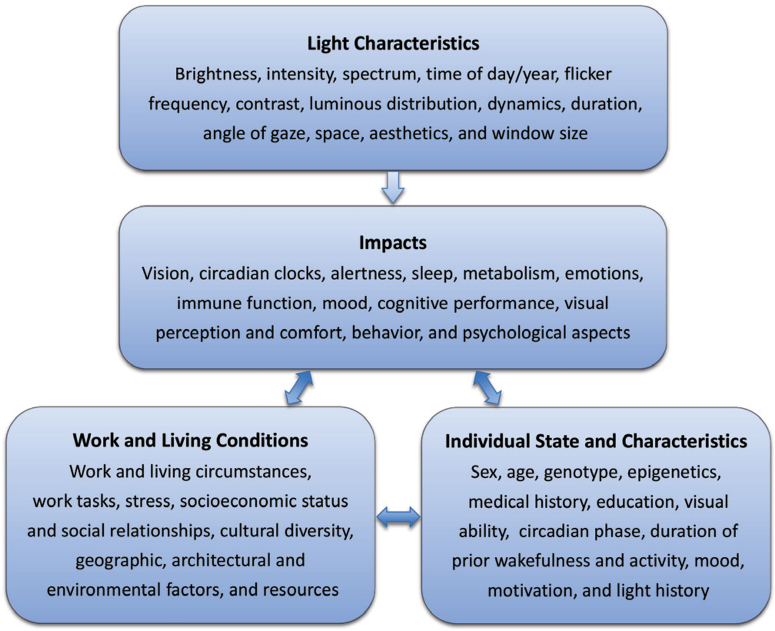

FIGURE 4. Summary of light impact on humans.

Consequences of light on health

In summary, light is necessary for vision and essential for health and well-being, because it synchronizes physiological processes to the environmental day–night cycle (Figure 3). Light affects many physiological and behavioral responses, ranging from hormonal rhythms and the pupillary response, to sleep, alertness, cognitive performance, and mood (*20*). However, we emphasise that these effects were quantified primarily under electric light conditions in controlled laboratory studies, which likely limits their general applicability. Ideally, equivalent studies using daylight are needed, although the technical difficulties and inherent variability will be a challenge. It seems intuitive that daylight should be preferred wherever possible over artificial light, yet we have little data to support this claim. In today's 24-hour lit environments, it is also important to ensure adequate darkness during the night to prevent any circadian phase shifts that interfere with restorative sleep, an essential aspect of good health. To better understand the effects of light on physiological and psychological processes, we need to consider the characteristics of that light as well as the individual's status, personality, living conditions, and culture, together with the complex interplay of the functional systems of the brain (Figure 4).

There are many ways to better implement daylight in our lives. We can improve access to daylight in buildings, and program artificial lighting to simulate outdoor light patterns (i.e., "dynamic lighting"). We can encourage people to spend more time outside by providing outdoor spaces and seating in cities with shelter from the weather, or by allocating flexible work schedules that allow people to go outside more regularly during daylight hours. These aspects require recognition of differences in cultures and climates across the globe, political awareness, public support, and education, as well as the publication and dissemination of this knowledge, particularly of the important nonvisual aspects of daylight. Meeting light needs is a fascinating challenge for society—we have only just begun to fully appreciate the importance of daylight for the health and well-being of humans.

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4

Daylight in the built environment

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Relatively recent cultural and technological changes, particularly in Westernized societies, have led to habitat and lifestyle shifts that have gradually estranged us from daylight. Although human beings are resilient and appear able to cope with extreme variations in environmental and living conditions, this process of separation can have negative impacts on health and well-being. Further research is essential in order to understand the impact of these changes and to initiate corrective measures, from changes in lifestyle and cultural attitudes to adjustments in the built environment and technology. This section explores these issues and the range of possible solutions.

Cultural and historical dimensions of daylight in the built environment

History of daylight in human habitats

The natural environment, abundantly bathed in daylight from sunrise to sunset, is the milieu in which the human species evolved. For millions of years, until the domestication of fire, the Sun was the only available light source. Perception of the solar disk's apparent journey through the sky has been a primordial experience of life on Earth. Daily exposure to its light and energy was essential for survival, while awareness of its changing positions was key to our understanding of time and space.

Only in the last few thousand years have human beings lived inside buildings. Prior to that, over millions of years of evolution, only caves and other natural shelters, as well as rudimentary man-made structures, provided a modicum of protection from the harshness of the natural environment, the ferocity of wild beasts, and the hostility of other humans.

As our mode of existence has become more sedentary, we have spent an increasingly larger percentage of our lives behind walls that screen us off from daylight, acting as either solar blockers or filters, depending on their

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opacity. Within recent history, estrangement from natural sources of light became even more pronounced following the invention of electricity and air conditioning. As the buildings they erected became taller and deeper, people found themselves further and further removed from the outer envelopes of those buildings, and now spend most of the day in artificially lit spaces, no longer aware of the Sun's position in the sky and unable to enjoy the health benefits of daylight. The levels of illumination normally provided by artificial light are, under certain circumstances and in terms of chronobiology, the equivalent of near darkness. Medical evidence shows that the predominantly indoor nature of our contemporary lifestyle has a detrimental effect on our well-being (see Chapter 3).

Spiritual implications

In the Western world, and especially in Christianity, the light of the Sun is strongly related to a notion of unique divinity. Sun worship is considered to be a possible origin of monotheism. The symbolic meaning of light is still alluded to in many terms that describe insight, understanding, knowledge, and intelligence, terms that are used in the religious ("illumination," "divine light," "heavenly") as well as agnostic, secular sense ("flash," "enlightenment," "brightness").

Urbanism and architecture, as forms of visual expression or visual language, are also full of light metaphors. In Western architecture, light (which for thousands of years almost exclusively meant daylight, hence light from heaven) has a very strong, positive connotation:

- Gothic cathedrals aspired to reach the sky, to catch the heavenly light and display its magical colors through stained-glass windows.
- In the Modern movement, daylight and fresh air were considered not only as hygienic necessities, but were celebrated as symbols of a new age; the cover of the book *Befreites Wohnen* (*Liberated Housing*) depicts the words "light," "air," and "opening" seemingly flying into a house through a window like living essences (*1*).
- At the other extreme, prisons have always been considered as dark places, metaphorically and physically; a principal characteristic of dungeons is their lack of light.
- The impact of iconic contemporary buildings like Peter Zumthor's thermal baths in Vals (Therme Vals, Switzerland, built in 1996) is strongly connected to their approach to light.

In Therme Vals, the iconography of the light falling down from the roof in artistically arranged rays generates a mystical atmosphere and transforms bathing into an almost sacred ceremony. The admiration that both experts and the general public feel for this building is based not only on its aesthetic quality, but also on the associations it awakens due to its resemblance to a religious space. The cultural codes used by the architect—light from heaven and light shining through colored glass—have an emotional impact, even if not all recipients are able to decipher or even to identify it.

In traditional Japanese architecture, however, daylight is treated with more reserve. Shinto and Buddhism do not focus on a single deity. The Sun is not the origin of Japanese spiritual and cultural identity, but is just one of the natural forces that influence human destiny, such as earthquakes or the power of the sea; it is feared and respected. In traditional Japanese houses, light is subtly filtered through different layers of transparent and semitransparent interfaces, and a unique aesthetic of twilight has been developed over the centuries (*2*).

Cultural considerations

The fact that modern habitats often screen off humans from daylight has important biological consequences—but it also raises cultural issues. In early human societies, the Sun had a central religious and hence cultural importance, relics of which can still be found in our modern world. Even in secular societies, most art forms, including painting, sculpture, literature, music, and architecture, are rooted in centuries of history during which cultural symbolism was focused almost exclusively on religious topics. Many of those themes, motifs, traditions, and conventions have survived in sometimes obvious, sometimes subtle forms. One quite obvious example of this connection between the Sun, religion, and everyday secular life is the fact that Sunday (the day of the Sun) is an official holiday (which also comes from the words "holy day"). Whether we reflect consciously on it or not, our past still shapes our present condition in the world. In particular, it influences both the production and perception of our cultural artifacts.

Among those artifacts, urbanism and architecture have a dominant presence in our lives: We spend most of our lifetime in a built environment. We shape it according to our notions and needs, and it shapes us by facilitating or hindering certain behaviors, and by creating a certain perspective on the world. Urbanism and architecture always express the cultural, social, political, and economic identity of the society that created them; they also influence it in a durable fashion.

The amount and quality of daylight we get is almost completely determined by our built environment. Like our cities and buildings, light is also shaped artificially; it is a social product, an expression of our cultural inheritance. Consequently, we need to consider our relationship to daylight not only in terms of biology but also through a cultural lens. In order to understand the importance of daylight, and to define criteria for its implementation in urbanism and architecture, we must understand all of its implications.

The cultural aspects of daylight encompass two important facts:

1. Since cultures around the world differ, the cultural identity and hence the culturally based needs of individuals will vary depending on their context. In this sense, these needs are relative, which means that appreciation of daylight to some extent is culturally determined.
2. As humans are fundamentally cultural beings, our cultural needs are essential even if they are not as primarily vital as our biological needs; within a defined context, the importance of those cultural needs is absolute in that they must be taken into consideration, especially when designing human habitats.

The acceptance of cultural artifacts strongly depends on the way they address the collective values of their public. In particular, urbanism and architecture, to be truly appreciated by users, must not only satisfy functional

Perspectives of an artist:
Objective light–Subjective light

Human cultural identities are rooted in specific geographical and historical situations. Consequently, they not only differ across the world, but also change over time.

Following the Industrial Revolution, the acceleration in technological innovation resulted in a perceived, subjective shift in spatial and temporal dimensions—the world began to feel smaller and time seemed to move more quickly. Concomitantly, accelerated, automated, and standardized working processes and daily routines led to an increasing number of different activities occurring simultaneously in the same physical and virtual spaces (*3*).

FIGURE 1. Different reactions to the same light. The person on the left is attempting to protect their eyes from the light's destructive power, while the woman in the center seems to be enjoying the light and has turned toward it, whereas the man in the foreground reacts as just an observer of the scene.

PHOTO: © S. APPELT, 2008

Human perception changes depending on the external inputs being experienced. Social and cultural values are constantly shifting, often going unnoticed because the changes are subtle and take place over a long time (*4*). The same can apply to changes in the characteristics of artificial light in our homes and workplaces, which over time have become more pervasive and ever brighter. With the introduction of digitized systems that have the capacity to provide more precise illumination, the management of light quality and application has become even more critical. Depending on intensity, spectral composition, and orientation, the impact of light can range from destructive to life-enhancing. Light is nonphysical, made tangible by the objects that it illuminates. Depending on the situation, the objects being viewed, and the mental state of the observer, the same light can be experienced as positive or negative. Additionally, the perception of the object being viewed as pleasant or unpleasant can be influenced by cultural, social, and temporal factors (*5*) (Figure 1).

The disparity of reactions to light exemplify its subjective, individual impact. Moreover, light can be used to achieve a clearly defined, objective, and precisely calculable goal.

"Objective light" can be described by the exact spectral composition, intensity, and duration it requires for specific functions. A laser beam, for example, can be used as "objective light" to cut hard material or for medical interventions. By contrast, "subjective light" can be described by the interplay of various aspects of "objective light" that might impact individual well-being, performance, circadian rhythms, health, social interaction, cultural experience, aesthetics, or functionality. In designing indoor or outdoor public and private spaces, light can therefore be considered as subjective and optimally applied, provided that the following aspects are considered: aesthetics, functionality, cultural values, social values, perception, ecology, sustainability, economic factors, safety, and well-being.

The sun can be seen as the light source with the largest range of impacts on individuals. Natural light is nonhomogeneous, providing varied intensity and imperfect illumination. It both dazzles and casts deep shadows. However, it has the ability to be evocative while also making the environment tangible. When using artificial light, the trend is toward optimization in terms of even distribution of illumination with subtle gradations, so that the eye is not exposed to strong contrasts. This need for optimization works in opposition to the sensuality of natural light. To preserve the spontaneity of natural light as well as the intangible atmosphere that natural light is able to create, it is advisable to evaluate when, where, and how natural light is combined with artificial light.

The reasons for a deficit in natural light in the lives of citizens today, particularly in Western societies, are diverse and closely related to sociopolitical, economic, ecological, and cultural developments that have occurred since the Industrial Revolution (*6*). Although it is possible to habituate to allegedly optimized light environments in which artificial light has been added, we wonder if this is necessary, given the ample availability of free daylight in most parts of the world. This is a particularly relevant question when considering the sustainability of resources and the potential loss of cultural values and individualism in a performance-focused and growth-oriented society.

needs but also offer the possibility of appropriation and identification. They must be in line with the cultural identity of their users, including their approach to daylight.

Daylight in the urban context

Daylight analysis has become an integral part of the architectural design process, particularly in recent decades. Increasingly sophisticated simulation models and analytical tools are being used not only to evaluate project alternatives, but also to generate optimal designs based on both daylight and artificial light. Less work has been done at the citywide level, although it can be argued that it is at the macro scale that comprehensive design measures concerning the optimization of daylight would be most effective.

The Therme Vals, Switzerland

Urban planning and development

Since the development of early human settlements, towns, and cities, the built environment has seen diminished access to daylight. The increasing proximity of buildings and their growth in both footprint and height has resulted in a gradual encroachment upon the natural environment and an increased amount of overshadowing.

Among high-rise developments, streets are in the shade for most of the day; from the sidewalks, only partial views of the sky can be seen. With growing rates of urbanization and the continuing increase in population densities, daylight in our habitats will continue to be reduced unless new approaches to urban design are adopted.

Daylight standards have always played an essential role in urbanism, having been established at the end of the 19th century with the worthy objective of enhancing the well-being of urban residents in overcrowded cities. The codes have evolved over time, with updated standards reflecting changing cultural priorities, particularly as a result of the gradual acceptance of artificial light as a substitute for natural daylight. However, these codes are still based on mostly outdated scientific data and need re-examination in the light of more recent research. More importantly, they need to be used creatively as generative principles leading to the development of new urban design concepts rather than as regulatory tools for control.

A most challenging field of contemporary urban research is the exploration of new urban typologies—including the orientation and configuration of built masses and interstitial public spaces—to ensure a satisfying interplay of light and shade at different times in the year, not only within buildings but also in streets and open spaces.

If comfortable levels of daylight and shade were to be regarded as primary objectives, not only at the scale of individual building design, but also at the larger scale of urban development (including the layout and design of land use and supportive infrastructure), a radical change in the design of cities would result.

Daylight and city pedestrians

Daylight and solar radiation impact the visual and thermal comfort of pedestrians in the city (*7*). In the built environment, solar radiation impinging on pedestrians includes direct sunlight as well as reflected light from outdoor surfaces. Solar radiation impacts city dwellers differently, with their perception of thermal radiation being dependent on their physical, physiological, and psychological characteristics, including their adaptability (*8*). In hot climates, high-albedo materials (that reflect a large fraction of incident light) reduce the air temperature, but increase radiant loads as well as the thermal sensation of pedestrians (*9*). By contrast, in cold, cloudy climates, the use of clear pavements improves the number of comfortable hours outdoors by increasing the amount of diffuse radiation reaching pedestrians, and consequently improving radiative exchange between the pedestrian and the outdoor environment. A pilot study in Sweden concluded that, due to the cold climatic conditions there, the Sun plays an important role in improving the thermal perception of Swedes both physically and psychologically (*10*). Current models used to determine outdoor thermal comfort [such as the Physiological Equivalent Temperature index, the COMFA (COMfort FormulA) outdoor energy budget, and the Predicted Mean Vote], compute radiation simply as an energy flux impacting the thermal sensation of pedestrians, but ignore the impact of glare or the visual perception of the spaces. The benefits of improving current methodologies and defining the most complete models to inform design for the built environment—models that take into account how solar radiation affects site design and individual thermal preferences—are clearly evident. Further investigations are still needed to fully elucidate the impact of daylight and solar radiation on the thermal and visual perception of pedestrians.

Daylit architecture: From human needs to daylight performance

When considering the application of daylight, what is the definition of "success"? For humans, we can postulate a rather general endpoint of health and well-being, although this is difficult to measure in a complex environment. Architecture and the built environment, together with natural spaces, provide the framework for our daily lives, but it is individual behavior that determines the amount of daylight actually received, and an individual's physiology that modulates the characteristics of that photic information (see Chapter 3). Cultural background determines our need for, approach to, and appreciation of daylight. In a world with so many people on the move, the cultural background of the users cannot automatically be assumed from their geographic location; in multicultural societies, different needs and approaches coexist and must be taken into consideration.

We must also embrace the emotional impact of daylight, broadening the range of performance predictors that are applied by including perceptual qualities.

Emotional responses to architecture

The optimal use of daylight in architecture for human health and well-being is a new challenge that goes beyond—and may even contradict—some of today's energy consumption standards. In particular, limitations imposed on window areas currently found in some energy standards are focused almost exclusively on technical data and aim to reduce the consumption of heating/cooling energy. They allow satisfactory solutions for most design tasks, but do not provide sufficient flexibility to encompass physiological, aesthetic, and cultural needs or special urban situations. Revised lighting standards now include non-image-forming (NIF) functions and metrics to quantify biological light exposure doses. Natural and artificial lighting should be complementary and synergistically incorporated into architectural designs so that time of day and the seasons can be seen and experienced within our living and working environments.

Illumination metrics

Current methods and metrics to evaluate daylight performance in buildings are based on the photometric responses of the human eye. The metrics used to quantify (day)light include measures of the amount of light such as illuminance [lux (lx)], daylight factor (DF), and daylight autonomy (DA); potential glare, including luminance (candela per square meter, cd/m^2) distribution in the field of view or derived values such as the daylight glare probability (DGP), daylight glare index (DGI), vertical illuminance, and unified glare rating (UGR); and perceived color of light expressed as the correlated color temperature (in kelvin). Some of these metrics, like DF, are static and theoretical metrics, while others are based on the climate at the specific location (climate-based daylight metrics, CBDM) and allow for more adequate location- and orientation-dependent daylight predictions. Due to the complexity of the calculations, computer simulations are generally used to calculate or predict these metrics. However, they are all based on luminous radiation as perceived by the human eye. Other important variables related to sound daylight design, such as view, cultural impact, environmental psychology, and physiological impact, are not handled by most of these metrics, resulting in an unavoidably incomplete picture.

We know that the spectral distribution of light, together with its temporal properties, are key drivers of NIF effects on physiology and human health (see Chapter 3). It is also important to include spectral considerations and temporal dynamics (beyond instantaneous evaluations and daylight illuminants) in research, through the use of new metrics and the development of new tools. We still do not know how much light exposure is needed each day, week, or season to fulfill our physiological needs, such as circadian entrainment or alertness maintenance. This question is becoming particularly urgent considering the increased time spent indoors in static lighting environments. Trade-offs will have to be found to minimize visual discomfort while ensuring sufficient light exposure. However, we currently lack the models and tools to properly make these decisions.

NIF response functions are diverse and therefore cannot be as clearly defined as the photometric response function. It is known that NIF effects are transduced by specific retinal photoreceptors and that the time of day, duration, and spectral composition of luminous radiation influence its efficacy (see Chapter 3). Proposed new metrics to account for NIF effects suggest the presence of spectral differentiation, forcing the designer to make use of more complex simulation tools that enable spectral simulation and can thus incorporate NIF functions into building design.

Apart from the development and implementation of new metrics into simulation tools, work also needs to be done to elucidate the specific effects of daylight on human health and performance, and to determine how building façades can be designed to be both energy efficient and support the well-being of occupants.

Dynamics and multidimensionality of daylight

Daylight is by its nature multidimensional. It reveals volumes and surfaces in a dynamic way—as the Sun arcs through the sky and is influenced by weather changes—and also provides visual interest through compositional effects that change over time. Importantly, daylight has physiological and behavioral effects on humans and many other creatures, enabling vision while also constraining it by generating discomfort at high intensity. As a result, natural lighting can and should be viewed from a multiplicity of perspectives when evaluating building design. These perspectives range from task-driven illumination, to visual and thermal comfort, to human-driven health and perception, presenting designers with multiple, highly variable, and bounded criteria that can sometimes conflict, but still need to be reconciled in order to create a satisfying living or working space (*11*).

Building occupants interact with their environment in many different ways: as users of a (work)space who perform tasks for which comfortable visual and temperature conditions are needed; as consumers of a space who seek to experience the aesthetics of its geometry and light dynamics; as inhabitants of a living space who require an environment conducive to health; and as beneficiaries of the planet's resources concerned about minimizing energy use. A recur-

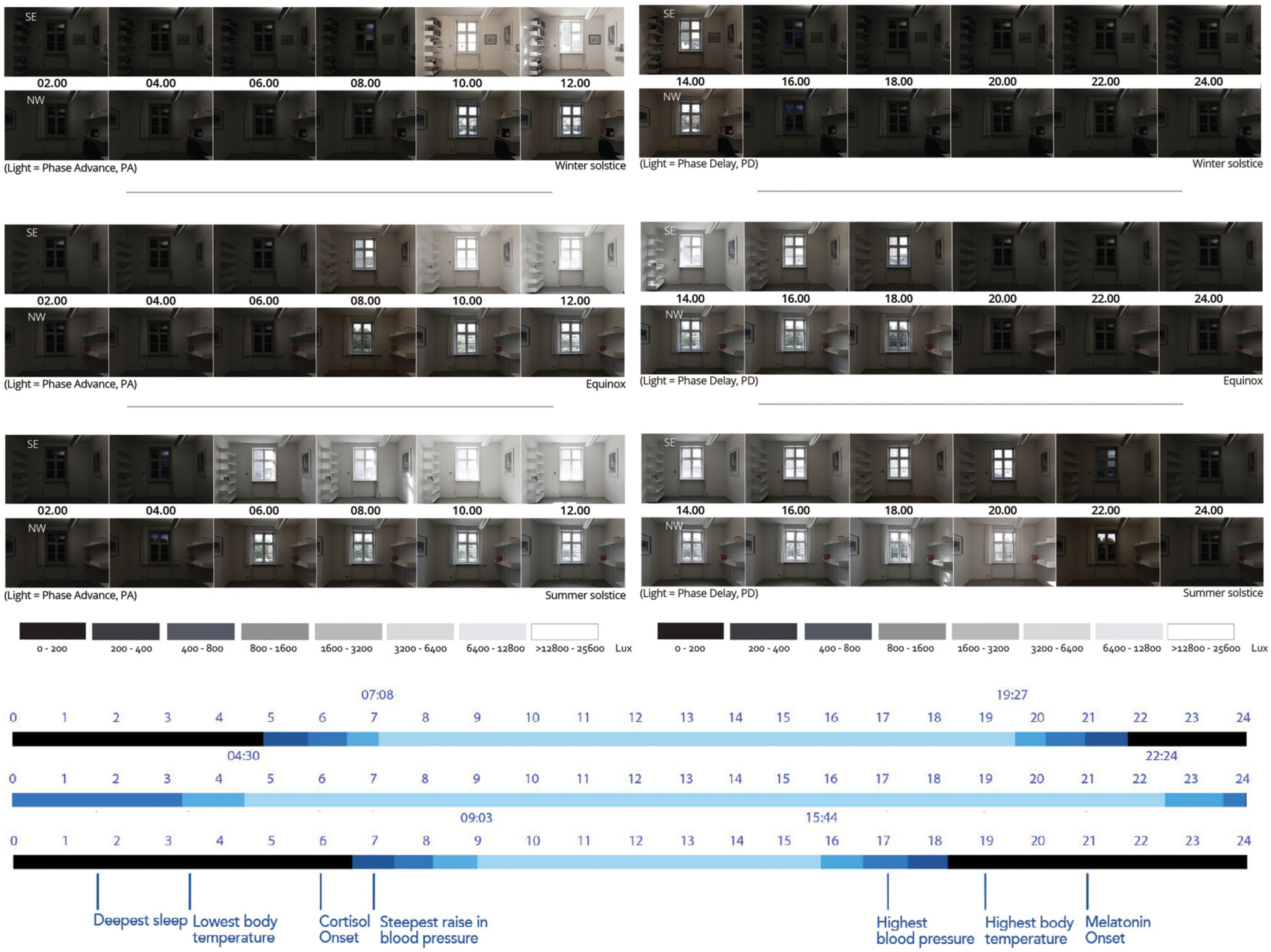

FIGURE 2. Differences in daylight during a 24-hour period in rooms facing southeast (upper) and southwest (lower) in Copenhagen, Denmark at latitude 56° north. At winter solstice (top), equinox (middle), and summer solstice (bottom), together with the circadian rhythm (below). The shades of blue indicate day (very light blue), civil twilight (light blue), nautical twilight (blue), astronomical twilight (dark blue), and night (black), at equinox (top), summer solstice (middle), and winter solstice (bottom), respectively. SE, southeast; NW, northwest. Illustration: Carlo Volf.

ring question that arises is how best to balance available resources (including solar radiation, energy, and natural or built surroundings) to fulfill the physiological and emotional needs of users.

The use of photometric properties to evaluate daylight has historically been dominant in both research and practice, while spectral properties, light exposure patterns or duration, and color and other perceptual aspects are only now, with the development of NIF-related simulation models (*12*), entering wider discussion (*13*).

We must also embrace the emotional impact of daylight, broadening the range of performance predictors that are applied by including perceptual qualities. Shadow, depth, light composition patterns, view to the outside, contrast, and texture, while highly valued by designers, are not currently integrated as performance indicators nor evaluated over time. This is despite the fact that the ephemerality of daylight composition may ultimately dominate all other aspects of design in terms of providing ambiance to a space, and thus generating an emotional bond with its occupants. The challenge is finding a way to measure such characteristics and develop tools to integrate them into the design process together with conventional, two-dimensional, threshold-driven metrics.

Better integration of natural and artificial lighting strategies, and of lighting- and energy-use analyses with these strategies, are overdue. Furthermore, holistic tools are still not broadly accepted research or practice. Apart from simply illuminating a space, natural lighting can influence thermal conditions and behavior, from gaze and eye movements to physical comfort. The interactions between all of these factors have yet to be properly explored (*11*). Spectrally and time-dependent, human-centric, field-of-view based immersive approaches for investigating daylight performance could be highly promising in addressing some of these challenges (*13*).

Building technology: Holistic design and emerging solutions

Improved building design

With respect to daylight, building design can be improved by considering the following factors:

Building orientation

The orientation of a building plays an important role in the transmission of daylight and the distribution of morning and evening sunlight during the day and throughout the year (Figure 2). In the northern hemisphere, a north-facing façade receives little direct sunlight in summer and none in winter. External surroundings, adjacent buildings, and trees all fundamentally modify the amount of daylight received. For example, the light from a green lawn is reflected onto the ceiling, while the light from a blue sky is cast on the floor. The upper floors of a building receive more direct sunlight and high-intensity sky-light, while lower floors reflect daylight with less intensity depending on the reflection, absorption, and transmission properties of surfaces adjacent to the building. Traditional architecture around the world has developed specific solutions to the challenges of local climates, often with limited technical opportunities and resources. One of these solutions is found in adapting the building envelope.

Building envelope

A building's envelope filters the outside world. With different seasons come different solar azimuthal angles and heights, creating different temperature and light experiences. A well-designed façade is able to balance these changes, not only at a given time of day or year, but during most of each day and most of the year. In this respect, finding the balance between too much and too little light is key; too much glass may create as many problems as too little, particularly when it comes to human health and well-being (*14*), and particularly if elements such as building orientation, footprint, and types of activities in the space are not taken into consideration. Sunlight is a very dynamic element: A window in direct sunlight may contribute more than 500 W/m^2 of energy on a warm day, or only 50 W/m^2 during cold and cloudy periods. Different switchable systems (e.g., solar control systems or layers of transparent and semitransparent interfaces) have been developed to adjust the amount of daylight and solar energy according to the actual needs of the users. The depth of the façade can also influence daylight: Overhangs and recessed windows can balance daylight received with the solar heat gain, letting in the winter sun while blocking the summer sun. The dynamic property of daylight can be applied in the design as a tool to create rooms of high aesthetic quality as well as stimulate the well-being of users.

Building footprint

The footprint of a building can also have a significant influence on daylight conditions within the structure. Daylight intensity decreases with the square of distance from the source: No matter what the size of a window, interior daylight levels more than 8 meters from the façade fall below 200 lx, corresponding to 2% of the outdoor daylight illuminance for an overcast sky. This means that deep buildings (with a large footprint) often contain areas of biological darkness (see Chapter 3), with daylight levels so low that an NIF system will fail to respond. The building footprint often follows cultural traditions. While thin, complex building shapes dominate in older cities, as in Europe, simpler, rectangular deep-floor buildings dominate in new cities, as in the United States, leading to more compact building forms, deeper volumes, and simpler façades without recesses or integrated balconies. While electricity cost considerations may explain some of these differences, they may also depend on factors such as geographical location, regional culture, behavioral norms, weather conditions, and architectural style, among others.

Human activity

Modern humans spend nearly 90% of their time indoors. However, it remains to be determined exactly how much daylight we need. Understanding the relationship between buildings and the activities that take place in them each day, and how this changes through the year, together with analysis of daylight quality and its spectral composition, are highly important when designing a healthy environment. Certain groups of people don't go outdoors much, such as the elderly and recovering hospital patients. During wintertime in northern latitudes, even healthy individuals spend less than an hour outside in daylight. Therefore, when considering human activity, building designers need to ascertain whether those occupying a building receive sufficient daylight. Making the most of the Sun, especially in winter, is an important step in improving building design.

Windows as filters

Inside a building, daylight is necessary for living and working, but glare and overheating must be avoided if possible. In temperate latitudes, heat from the Sun can provide energy savings in the winter, but should be minimized in summer. By glazing part of the building envelope (i.e., installing windows), the spectral properties and the amount of transmitted solar radiation can be modified to control light and solar energy transmission, avoid glare, and ensure a good distribution of daylight inside, while providing thermal insulation and a clear view to the outside.

Traditionally, window glass is considered to be a perfectly transparent material, enabling flawless visual contact with the outdoor environment, while the window framing is necessary for mounting the glass. We challenge this image and consider the window—understood here as any opening in the building envelope—as an angular, spectral, and temporal filter.

Angular

The very high normal transmittance (T_n) of glass ($T_n >$ 90% for one layer) is valid only for incident angles less than 50° and decreases dramatically for larger angles, resulting

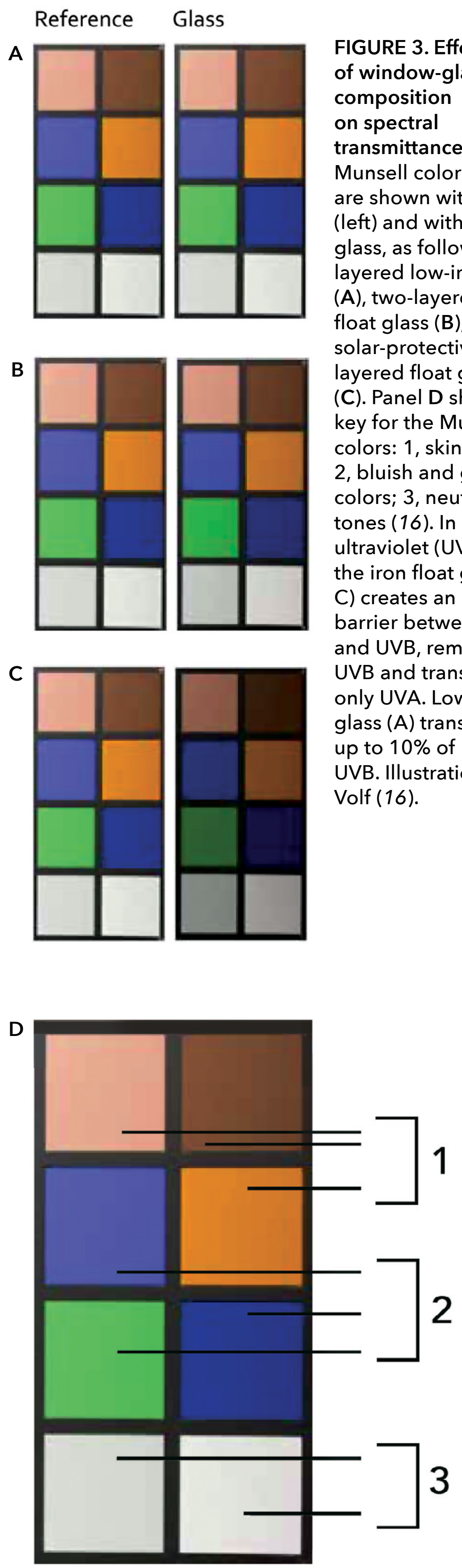

FIGURE 3. Effect of window-glass composition on spectral transmittance. Pairs of Munsell color panels are shown without (left) and with (right) glass, as follows: two-layered low-iron glass (**A**), two-layered iron float glass (**B**), and solar-protective three-layered float glass (**C**). Panel D shows a key for the Munsell colors: 1, skin colors; 2, bluish and greenish colors; 3, neutral tones (*16*). In natural ultraviolet (UV) light, the iron float glass (B, C) creates an effective barrier between UVA and UVB, removing UVB and transmitting only UVA. Low-iron glass (A) transmits up to 10% of natural UVB. Illustration: Carlo Volf (*16*).

in the hemispherical transmittance of vertical window glass being considerably lower than normal transmittance, and in sunlight falling at incidence angles of 50°–90° being almost fully reflected back to the environment, decreasing the occurrence of glare or damage to plants.

The framing and thickness of the wall limit daylight flux through the window. The glass-to-frame ratio is an important factor and should be as high as possible in projects where the window area is limited. Various types of shading devices inside, outside, or integrated into the window can help to adjust the actual amount of transmitted light and solar energy, and may contribute strongly to angular filtering, impacting not only the light flux passing through the window, but also the size and quality of the view.

Spectral

The spectral transmittance of window glass depends on its chemical composition, the thickness of the material, and any applied coatings (*15*) (Figure 3). It is not equal for all wavelengths, particularly in many advanced formulations of window glass. This variation causes changes in the color of objects viewed through the glass. For instance, some three-layer, low-energy glazes cause a significant color shift from red and blue toward green, potentially affecting the atmosphere of the room, since blue is associated with coolness, while red/yellow denotes warmth.

Temporal

Windows equipped with shading systems function as temporal filters. Retractable systems filter some light when covering the window, but provide unfiltered light the remainder of the time. Fixed systems filter light differently over time depending how they are controlled. Additionally, a reduction in light passing through the glass may occur at any time due to dirt, rain, snow, ice, or condensation.

Selecting window technologies and controls

The functionality provided by window systems—provision of daylight, aesthetics, cultural identity, protection from glare, solar gain management, and visual contact with the outside—can often be in opposition to each other. Consequently, the selection and design of window technologies and their controls will favor some functions, to the detriment of others.

One of the most widely used window technologies is the solar-control glass pane, which can be used in double- and triple-pane "insulated glass units," glass slats, or as a ventilated glass pane in two-layered, so-called "double-skin façades." While classic solar-control glass panes with static properties have spectrally selective transmittance, newer, switchable layers can change the visual and solar-control properties of glass pane in reaction to intrinsic or extrinsic triggers. Switchable glazing systems provide good visual contact with the exterior, but offer only limited glare protection due to their nonscattering properties.

The performance of a fenestration system can be properly assessed only if enough information is available about how the system is controlled. Manual control is far from optimal and is often determined by the emotional state of the occupants. External control devices are usually motorized and sometimes automatically controlled. One advanced control strategy is called "cut-off," where external opaque slats are tilted dynamically during the day to maximize visual contact with the exterior while blocking direct solar irradiation. User-adapted control algorithms that account for optimal lighting and visual comfort are currently under investigation.

The selection of a window technology and controls for a particular application will depend on those functions that the designer most wants to promote in the building. Quantification of the effect and efficacy of different technologies is difficult or impossible, requiring expensive expert consultation, particularly when considering aesthetic aspects, cultural connotations, and the well-being of the users. These subjective or "soft" factors are easier to ignore compared to more scientific, objective factors that are more often the default functions used in the selection of a window technology.

Novel developments in smart glazing

Switchable systems allow for control of visible transmittance and solar heat gains by the user or by user-adaptive intelligent algorithms. Electrochromic devices usually comprise transparent conductive electrodes, an electrochromic active layer, a lithium ion–conducting electrolyte, and a counter-electrode that might be electrochromic too (*17*). The oxidation state of the electrochromic thin films and the precise characteristics of the layer depend strongly on the conditions present during the deposition process (*18*). Challenges inherent in the development of high-performing electrochromic windows include obtaining a high switching contrast, short switching times, good color homogeneity, and a long-term durability. The latter may be achieved by using ion conductors that are composed of solid matter instead of soft or liquid compounds. Additionally, the internal interfaces between the electrochromic active layers and the ion conductor are of special importance. Novel nanocomposite materials in these interfaces will allow for faster switching times, a higher switching contrast, and better coloration efficiency. Additionally, novel plasmonic nanocomposite materials and nanocrystals open the possibility of selective switching transmittance in the near-infrared spectral region, in order to dynamically control solar heat gains while conserving the daylight flux (*19*).

Proper management of seasonally dependent solar heat gains can yield a considerable reduction in heating and cooling needs. In a recent proposal put forward by the École Polytechnique Fédérale de Lausanne, embedded micromirrors are used to change the angle of solar transmittance (*20*); adjustments are small enough not to perturb the clear view through the window, but large enough to avoid iridescence due to diffraction (i.e., the rainbow of colors caused by the prism-like effect of differential diffraction). Daylight is redirected into the depth of the interior space and glare is reduced, thus raising the level of visual comfort (*21*).

Thermal insulation is commonly achieved by using glazing that includes conductive coatings with low thermal emissivity (low-e); however, these coatings show a strong attenuation of the microwaves used by modern telecommunications. Through special laser treatment, such coatings can be made transparent to microwaves across a large frequency range (*22*). This type of novel coating was originally developed for trains, where the microwave attenuation by the metallic envelope is especially problematic. However, as wireless communication between persons and also between objects connected through the Internet of Things is continuously increasing, these microwave-transparent, low-e coatings might also become more important in the building sector.

Conclusions

The majority of people living in the contemporary world spend most of their time either inside or near buildings. This built environment is an answer to our practical, biological, environmental, cultural, sociological, and historical needs, and reflects our economic and technical capabilities. It also influences those needs and possibilities, and has a strong impact on our well-being and health. Thus, careful consideration of all the factors that determine the form and function of the built environment, and an interdisciplinary approach to understanding the complex interactions between those factors, is necessary in order to further improve and adapt it to our actual and future needs.

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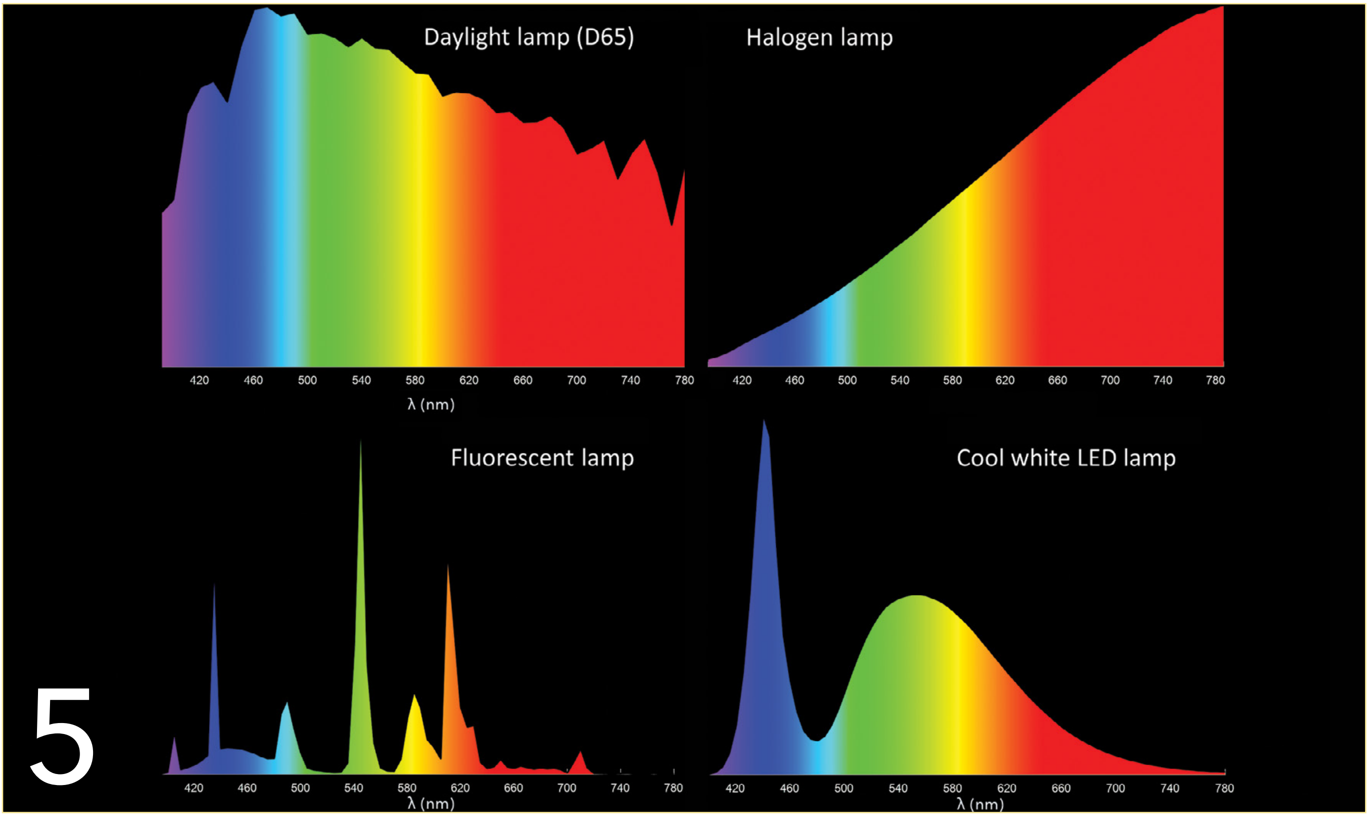

Reinventing daylight

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The Sun is acknowledged as the mother of all light sources: It enables life on earth as we know it. But what is it that makes natural light unique, and most technologically advanced light sources pale in comparison?

Properties of natural and artificial light

Comparison of daylight and electrically generated light

The quantity, quality, and dynamics of daylight and electrically generated light differ in the following ways:

1. Daylight, as we experience it when being outdoors, is typically more intense (on a sunny day the illuminance, E_{hor}, measured on a horizontal plane, is greater than 100,000 lux) than standard electrical light in offices (E_{hor} at a desk is ~500 lux) and homes (evening E_{hor} is ~5 lux–50 lux).

2. Daylight has an almost uniform spectrum containing all wavelengths. In contrast, light-emitting diode (LED) or fluorescent bulbs lack a continuous light spectrum (see Figure 1). This means that although we perceive these lights as white, it is not possible to make a good distinction between all colors illuminated by these bulbs. A more extreme example is that a blue object is perceived as gray under a red light source.

3. Daylight rays issued from the Sun appear to propagate practically parallel to each other because of the large distance between the Earth and the Sun, while most light rays from electrical sources diverge from each other because the distance between the lamp and the illuminated surface is small.

4. Daylight is polarized in a manner that changes throughout the day and the year depending on the position of the Sun relative to the Earth's surface. In general, electrical light sources do not produce polarized light.

5. Daylight intensity appears to be stable on a short timescale (under a second), while electrical light exhibits intensity and spectrum fluctuations induced by the distribution frequency of the electrical power grid (50 Hz–60 Hz), its harmonics, and in some cases high-frequency

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Due to its dynamic nature, daylight may not meet the lighting need for all spaces. For example, in the Hermès store in Brussels, daylight is controlled by a semitransparent white canvas stretched under the atrium, transforming an old parking lot into an art gallery where the diffused daylight perfectly illuminates the artwork.

PHOTO: MAGALI BODART

fluctuations of the electronic drivers (necessary to supply the correct electrical power to the lamp) (30 kHz–60 kHz). The resulting intensity fluctuations may be detectable as flicker, or may be residual (in flicker-free bulbs) and difficult to detect by the human eye (*1*).

6. Daylight shows pronounced temporal and spatial dynamics in both intensity and color over longer timescales (seconds to years) and is dependent on the observer's position on Earth, the date, the time, and the weather. In general, electrical lighting is static.

7. Daylight, or rather solar radiation, consists of a wider spectrum including ultraviolet (UV) and infrared (IR). Most electrical light sources are designed to maximize visible radiation (380 nm–780 nm) and therefore lack UV and IR radiation.

8. Daylight is freely available, while electrical lighting comes at a cost.

Daylight versus electrical light: Mimicking capabilities

Is daylight so unique that we cannot mimic its characteristics by electrically generated sources? Below we answer this question in the context of the ways in which these light sources differ.

1. Intensity. Depending on the time, date, and location on Earth, horizontal illuminance by the Sun reaches more than 100,000 lux. Although challenging, it is possible to reach comparable light levels with electrical light sources. Using an LED light source with an efficacy of 200 lumens (lm)/watt (W), approximately 10,000 W would theoretically be needed to horizontally illuminate a normal-size office (20 m2) and result in 100,000 lux on floor level.

2. Spectrum. The Sun is a black-body radiator, meaning that its absolute temperature determines the color of the emitted luminous flux. This type of light source generates a continuous light spectrum, enabling it to optimally render all available colors of objects. Thermal radiators like incandescent lamps can create the same phenomenon of a continuous light spectrum. Other lamps like fluorescent and LED bulbs, however, cannot.

3. Parallel beams. By applying optics, a diverging beam from a lamp can be transformed into a parallel light beam, a feature that distinguishes the Sun's rays from most artificial light sources.

4. Polarization. Electrical light sources do not produce polarized light. Exceptions are liquid-crystal displays (LCDs), which emit light with a strong and constant polarization.

5. Flicker. Most control systems necessary for electrical light sources like fluorescent tubes apply frequencies greater than 20 kHz, resulting in a flicker index of ~0.01 (on a scale from 0–1.0, where 0 means no perceived flicker), which is almost imperceptible to humans. The flicker caused by the electrical power grid might be more difficult to overcome.

6. Dynamics. Daylight dynamics encompass the amount of light as well as the color and directionality of the light. Through the development of very small dimmable light sources with a variable correlated color temperature (Tcp), as well as control systems that allow for preset programs and quick dimming, the ability to mimic any given daylight dynamic is within reach. These developments also open the way for the introduction of artificial windows that accurately mimic daylight dynamics (2).

7. UV and IR. Electrical light sources, by design, maximize radiation within the visible range, which does not include UV and IR. However, thermal radiators produce IR as well as light, so adding UV and IR to electrical light sources is not inconceivable. UV radiation, for example, is produced by low-pressure mercury discharge lamps (so-called "black lights") and transformed into light by the fluorescent powders within the tubes. Similar procedures exist for LED bulbs.

8. Freely available. When the process of transforming solar energy into electrical energy becomes highly efficient, it is possible that electrical light could be produced at little to no cost.

The above arguments indicate that most of the typical characteristics of daylight can already be mimicked by electrical light. Why then is daylight considered superior to electrical light? This question will be discussed in the following sections.

Biological context of daylight vs. electrical light

For most of our evolution, humans lived outdoors in the natural environment. Our photopic and scotopic vision (daytime and night vision, respectively) have not only adapted to natural light across the seasons, but our physiology is dependent on daylight, as documented in decades of research.

Light influences human well-being in four distinct ways: vision and visual comfort, chronobiology, psychological effects, and photochemistry in the skin. These four effects are explained in more detail below (see Chapter 3).

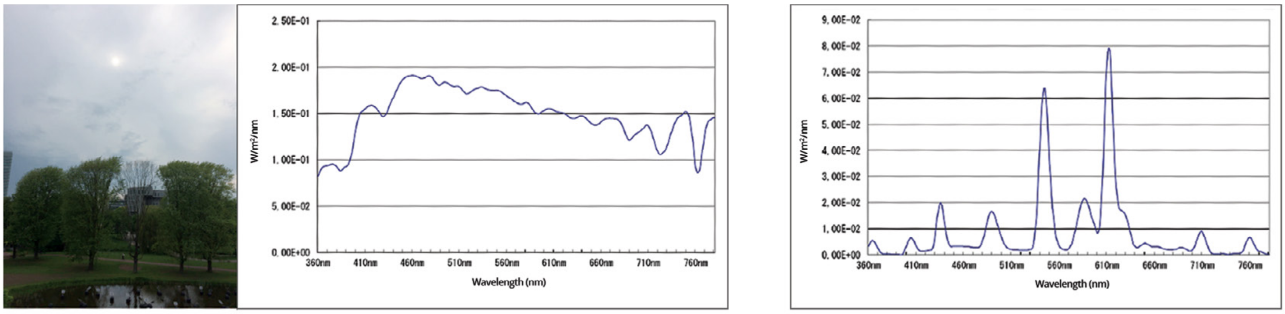

FIGURE 1. Example of spectral power distribution of daylight (left, May 11, 2017 at 5:30 p.m. in Eindhoven, The Netherlands) and of a fluorescent lamp [correlated color temperature (Tcp), 3000°K; color rendering index (CRI), 80]. Illustrations by Mariëlle Aarts.

Vision and visual comfort

Light enables vision, which permits us to extract information from the environment as the light reflected off objects strikes the retina of the eye. This ability depends on environmental conditions, the characteristics of the viewer's individual visual system, and that system's adaptation to prevailing light conditions.

Daylight facilitates the extraction of information because light intensities are high, making the discrimination of fine details easier. In addition, the spectrum of daylight covers the full visible range, with similar power at all wavelengths, facilitating color discrimination. Daylight lacks flicker, unlike electrically generated light, which can create temporal and spatial patterns that distract and strain the nervous system, resulting in fatigue, eyestrain, headaches (*1*) and, in rare cases, epileptic seizures (photosensitive epilepsy).

Chronobiology

Exposure to light entrains the circadian system, which in turn influences an individual's mood, sleep patterns, physiology, health, and cognitive abilities (see Chapter 3). In contrast to sunlight, electrically generated light has no intrinsic cycle, and the light production is entirely linked to human action. Moreover, in modern life electrically generated light is omnipresent during both day and night. It is important to note that low-intensity light exposure during the day enhances light sensitivity at night (*2*). Such sensitization effects based on light-exposure history imply that individuals who are mainly or exclusively exposed to low-intensity light are more vulnerable to the negative effects of electrical light at night.

Psychological effects

In the built environment, the availability of daylight also frequently affords a view of the outdoors. This provides observers with information on the time of day and the weather, as well as having a restorative psychological effect, especially if natural vegetation is part of the view (*3*).

The effect of light on the observer's mental state can vary according to his or her location on Earth (latitude), time of day, and time of year (see Chapters 1 and 3). In the northern hemisphere, there is a lack of light in the winter and an abundance in the summer. This is one possible explanation for a higher prevalence of seasonal affective disorder (SAD) in northern countries such as Denmark (*4*).

Photochemistry in the skin

Exposure to ultraviolet, visible, and infrared light triggers thermal and photochemical reactions in the skin, which at low dosages cause little cellular damage but have certain beneficial effects. Exposure to UVB radiation triggers vitamin D production, while UVA exposure converts epidermal nitrogen oxides (nitrosothiols, nitrites, and nitrates) into nitrous oxide (NO), which induces arterial vasodilation and thus lowers blood pressure (*5*).

Daylight contains both UVA and UVB radiation, and thus regular, even short-term exposure is sufficient for vitamin D and NO production. Electrically powered lamps emit little or no UV light. Also, most window glass (except low-iron glass) does not transmit UVB and markedly reduces UVA transmission. Consequently, exposure to only indoor lighting is insufficient to stimulate vitamin D synthesis, and it is questionable whether there is any conversion of epidermal nitrogen oxides to NO.

The abovementioned connections between daylight and humans may directly or indirectly impact their health. However, there is little documented scientific evidence of the relationship between daylight and health, despite extensive research on the question (*6*).

The cons of electrical light vs. daylight

Below we discuss, from a human perspective, some of the negative aspects of electrical light when compared to daylight.

Lack of intensity

A large body of evidence shows that increased daylight exposure raises levels of alertness, well-being, mood, quality of sleep, circadian entrainment, and cognitive performance (see Chapter 3), possibly over longer-lasting time periods than electrical light. However, the optimal quantity and quality of daylight required by each individual remain unknown and depend on at least three factors: the characteristics of the light (e.g., irradiance, spectrum, dynamics, and distribution) as determined by geographical location, climate, building orientation, and size of windows; the timing and duration of light exposure; and interindividual differences, such as age, mental, and physical status, culture, and tasks being performed.

Increased daylight exposure can be achieved by simply spending more time outdoors, independent of the weather or the season. Some innovative approaches are attempting to duplicate the nonvisual functions of light in order to improve health, such as mimicking the dynamics of daylight by providing increased illumination and greater exposure to short-wavelength (i.e., blue) light in the morning and early afternoon, and lower illumination and less short-wavelength light in the late afternoon and evening (*7*, *8*). In addition, there are commercially available control systems for mixed daylight/electrical lighting that automatically switch on when the sky is overcast, or in winter when the days are short (*9*). However, a common feature of all electrical lighting systems is the lack of sufficient scientific evidence to establish the optimal settings with regard to physiological and psychological functions as well as interindividual differences.

Daylight facilitates the extraction of information because light intensities are high, making the discrimination of fine details easier.

Light exposure can also lead to visual discomfort and glare, assessed using various glare indices (see Chapter 4). Visual discomfort in daylit spaces is usually better tolerated than under electrical lighting. Other factors may also cause visual discomfort (see Chapter 3), including flickering of electrical lamps (*10*, *11*). Flicker frequencies beyond visual perception (i.e., greater than 60 Hz) can still produce physiological responses that can be measured in an electroretinogram. It still remains to be answered whether chronic exposure to these flicker frequencies can be harmful.

In contrast to daylight, the spectral distribution of most electrical lamps is not continuous but has distinct peaks. This discontinuity may be the source of changes in color perception; other potential consequences have yet to be documented. One putative risk from modern solid state lighting is the so-called "blue-light hazard," thought to be caused by white or blue LEDs even at low light intensities (*12*). The blue-light hazard is considered to be caused by radiation exposure at wavelengths between 400 nm and 500 nm, which induces stress-related photochemical damage of the retina and its photoreceptors (*13*).

Timing and composition

An internal circadian clock governs nearly all aspects of human physiology (see Chapter 3), synchronizing the body to the 24-hour solar day.

Natural light is highly complex in timing, intensity, and spectral composition. The circadian clock has evolved to use this complexity in amazing ways. For example, it employs a special, nonvisual photoreceptor (melanopsin) to respond better to the blue light present at dawn and dusk, and it tracks seasonal changes through networks of neurons in specific brain regions.

The impact of light on biological function at night, for example in night-shift workers, is not clear. In 2007, the World Health Organization classified shift work that involved working at night as a Group 2A probable carcinogen (*14*). Research into this risk yielded evidence that chronic melatonin suppression at night, together with sleep deficit and circadian misalignment, may at least in part contribute to the pathogenesis and growth of breast, prostate, and ovarian cancers (*15–18*).

Such circadian misalignment issues arise partly because the circadian clock cannot shift quickly enough to compensate for the time change (giving rise to jetlag after travel, for example), thereby presumably rendering the body's physiology suboptimal for the actual environment. Mistimed metabolic processes mean that insulin and cortisol are not secreted at the proper time for meals, increasing the likelihood of developing insulin insensitivity and diabetes. Correct release of the nighttime hormone melatonin, which is suppressed by light, may also play a role (*16*). However, light at night need not necessarily suppress melatonin release, especially in cases when the blue portion of the light is reduced or removed (*19–21*).

Recent research shows that the problem of shift work may be even more complex. In fact, the central clock in the brain shifts time faster than peripheral clocks, and peripheral clocks are themselves shifted by feeding cues. At the same time, environmental light can directly activate the hypothalamic–pituitary–adrenal axis, a major avenue used by the central clock to control peripheral ones (*22*). Thus, mistimed lighting can result in clock desynchrony even among the different clocks within the body. In rodent models, prolonged mistimed light can fundamentally and permanently alter the neural network of the master clock by changing its period and amplitude, especially if the misalignment occurs at a young age (*23*). The physiological consequences of these modifications remain unknown.

Finally, different wavelengths of light can directly and acutely activate brain circuits for sleepiness (red and green light) and arousal (blue light), and this activation passes via the suprachiasmatic nuclei (SCN) master clock (see Chapter 3). Artificial light during the day, due to its spectral uniformity, obliterates these different cues; it is currently unclear how irregular light timing might impair the SCN's ability to carry out its functions properly.

Perception of the outdoors

An interesting characteristic of any window is that, to the indoor observer, the light projected through the window is effectively flipped both horizontally and vertically: The sky is projected down onto the floor, while the ground and other areas below the horizon are projected up onto the ceiling. Similarly, the light reflected from outside surroundings to the left are projected to the right indoors, and vice versa. The window provides a direct visual connection to the outside world, while also acting as a filter that dramatically changes the characteristics of the daylight. The window brings into a building a reminder of life and movement outside that seems to be essential for our well-being, a function that remains difficult or even impossible to replace through artificial means.

Economic impact of the use of daylight

Apart from the energy savings achieved through better use of daylight in building design, researchers have also reported daylight's positive impacts on health, mood, productivity, and learning (*24*). However, these benefits have been difficult to quantify. Additionally, the energy and operating costs of a building are small compared to the cost of employees' salaries, making it difficult to justify large expenses to achieve small reductions in costs, and also placing emphasis on keeping the indoor climate comfortable for employees while at work.

From an energy perspective, daylight provides both light and heat. Even so, the outdoor climate and indoor temperature are seldom in balance, requiring the consumption of energy to provide a comfortable indoor climate. Astute use of the benefits of daylight can therefore be profitable for companies if it increases productivity and decreases absenteeism, offsetting any investment in optimizing daylight in the building. If the impact of daylight can be expressed in terms of financial benefits (related to, for example, sustainability or health), windows will be considered as an asset and not simply an expense.

Tools for building light evaluation

With the increase in computational power and the emergence of faster rendering techniques, lighting simulations are now omnipresent in our lives: in movies with 3D effects, in augmented reality games on our smartphones, but also more traditionally in the rendering of architectural projects (new or retrofitted). In the latter, practitioners use rendering techniques mainly for architectural design (rapid visualization allowing real-time interactions), visualizations (artistic views), and simulations (based on physical principles, but requiring longer computing time). Apart from generating accurate renderings, simulations also can be used to derive dynamic metrics for lighting, visual comfort, and energy performance. The interpretation of these metrics can highlight the choices between different lighting solutions or demonstrate compliance with a lighting regulation.

The most widely used simulation tool to evaluate daylighting performance is the Radiance software suite, which is also used as a rendering engine for other simulation software packages. This engine performs backward ray tracing, uses three channels to render images, and computes metrics for red, green, and blue (RGB) light. One reason for its popularity is because computer screens display images using RGB light and can therefore reproduce the radiance and luminance values in the simulation as they are perceived by the human eye on a computer screen.

Although simulations produced by Radiance are close to ideal, several issues arise when considering the spectral composition of the light itself. In daylight simulations, the source of the radiation itself is of crucial importance, as it serves as a boundary condition necessary for solving the light propagation equation. As such, its intensity and spectral composition are equally important and must be converted into RGB radiance values. However, with most sky models (such as the Perez All-Weather model), only the luminance distribution is used, disregarding the spectral composition.

Furthermore, the transmission properties of the glazing and fenestration system—together with the reflective properties of the walls, ceiling, and floor—are provided as RGB values for a given illuminant (with a given spectral composition). This leads to difficulties in combining daylight and electrical light in simulations, as they may require separate renderings depending on the color of the light sources. Finally, non-image-forming (NIF) effects of light can be reasonably well evaluated using RGB values, but, as mentioned earlier, validated colored sky models are currently unavailable.

A diverse range of research institutes are currently working on generating an accurately colored sky model. Apart from the color of the source, the color transmission properties of the window elements (e.g., tinted glass or colored blinds) are also being assessed using goniophotometers (i.e., scientific instruments that are able to measure the luminous intensity emitted by or reflected from an object at different angles). Indeed, as the spectral composition of light changes as it passes through the fenestration system, the color perceived within the room is impacted, as are the NIF effects.

In the future, it is hoped that tools to evaluate NIF-optimized daylight and electrical lighting solutions can be developed. These tools may contribute positively to human well-being, as well as improving building energy efficiency by providing light (and energy) only in those spectral ranges that are needed.

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6

Uses of daylight

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Daylight is a ubiquitous energy source for a variety of technical applications, including photovoltaics (*1*). In this chapter, however, we highlight two areas where daylight offers new, promising applications: artificial photosynthesis and solar disinfection. In the final section, we discuss the challenges of light storage.

Artificial photosynthesis: Driving chemistry with daylight

The transformation of sunlight into chemically stored energy is the foundation for life on Earth. The conversion of daylight energy into electric power by photovoltaics has reached a high level of development, having been commercialized and widely applied. Furthermore, the technologies enabling the direct conversion of light energy into chemical energy, such as solar fuels, are currently being developed (*2*). Our understanding of the structural and functional characteristics of the biological systems underlying photosynthesis has increased tremendously in recent decades. This knowledge can be applied to the technical challenges encountered in attempting to transform light into chemical energy, potentially making the process simpler, more robust, scalable, and adaptable. That said, artificial photosynthesis will likely use a different operating mechanism—after all, trains and cars do not walk on legs, and airplanes fly very differently than birds.

The dream of using visible light in chemical reactions is more than 100 years old. Italian chemist Giacomo Ciamician (*3*, *4*) of the University of Bologna developed many chemical reactions that required sunlight. He widely promoted his idea of converting daylight energy into fuels and chemical products via chemical and technical processes as being much more economical compared with the use of fossil carbon energy resources (Figure 1). However, technical developments during this time continued to focus on the use of these resources. Only recently, triggered by dwindling carbon resources and climate concerns, have technologies driven by daylight energy received public and political attention once more.

The conversion and storage of energy from daylight starts with the absorption of solar radiation by molecules, which causes their elevation to an excited state, often accompanied by some type of charge separation. The separated charge represents electrical or redox potential, as found in a battery, and is the basis of most photovoltaic devices. Release of the redox potential provides electrical current.

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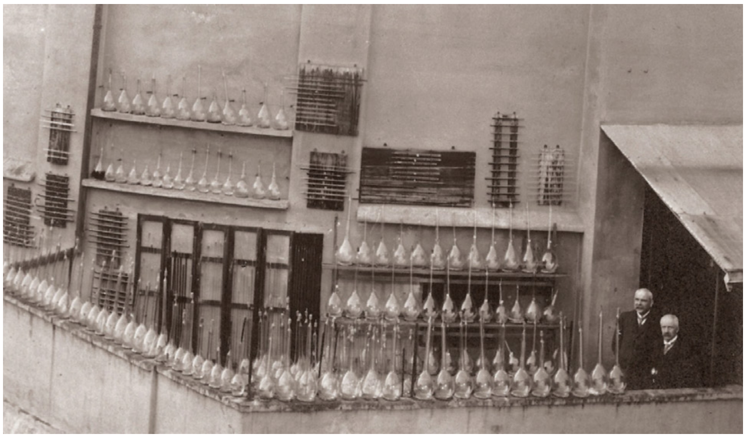

FIGURE 1. Giacomo Ciamician (right) and his colleague, Paul Silber, on the balcony of the chemistry institute of the University of Bologna, Italy at the beginning of the last century, shown with experiments demonstrating their vision (now over 100 years old) of using daylight energy for chemical reactions.

PHOTO: UNIVERSITY OF BOLOGNA

Artificial photosynthesis—the conversion of solar energy into chemical products that are higher in energy than the starting materials—requires a more complex process. Three principle concepts involved in this type of chemical conversion are described below.

Power-to-chemistry technology

Electrical power can be generated by photovoltaics, wind, or hydropower, which all originate from solar energy (Figure 2). The electricity generated is then used for the electrolysis of water, which produces hydrogen gas as a fuel or a reactant, for example, for the reduction of carbon dioxide to methane or carbon monoxide. This type of "power-to-chemistry" technology is an area of active research and is a possible solution for long-term and large-scale storage of solar energy. Key challenges, among others, include achieving higher-efficiency electrolysis of water, replacing current precious-metal electrodes (e.g., silver–palladium) in capacitors with cheaper and more abundant materials (e.g., copper and nickel), and combining electrolysis with other chemical reactions [e.g., the reduction of carbon dioxide to generate synthesis gas, or syngas, a fuel gas consisting of carbon monoxide (CO) and hydrogen (H_2)] for subsequent chemical reactions, such as the Fischer–Tropsch process, to yield liquid hydrocarbons. Other more general needs include the development of cheaper, longer-lasting photovoltaic cells with greater solar-to-electrical energy conversion efficiency, and the scaling up of the power-to-chemistry process to large, industrial applications.

Photoredox catalysis

The direct conversion of visible light energy into chemical products without intermediate electricity generation is possible using dyes and photocatalysts that absorb the light and convert the excitation energy into separated charges at the molecular level. These separated charges can then be used in chemical redox reactions to enable endothermic reactions or reactions that would otherwise require higher temperatures. Prototypes of direct fuel generation by processes such as photocatalytic water splitting into oxygen (O_2) and H_2 are still rare and are challenging to scale up to industrial levels. Photoelectrodes can be directly inserted in aqueous electrolytes to convert water into H_2 and O_2 (*5*). Such photoelectrochemical cells can be placed in decentralized installations to collect solar energy directly and generate H_2 as a fuel (Figure 3).

One important advantage of photoredox catalysis as a method for organic synthesis is the special nature of light as a chemical reagent. Visible light is freely available and easy to obtain from either a natural or an artificial light source. It is nontoxic, interacts specifically with the colored photocatalysts, and does not leave a trace even when used in excess. These characteristics make it an ideal reagent for synthetic transformations. In a research setting, defined emission from light-emitting diodes (LEDs) or energy-saving light bulbs is generally used instead of daylight irradiation to ensure reproducible reaction conditions.

Although chemical photoredox catalysis is being actively investigated in academia, and its first applications are now appearing in the chemical and pharmaceutical industries, there are still many challenges to overcome. The photophysical steps involved (such as light absorption and charge separation) are typically fast, proceeding on the pico- to nanosecond timescale. This speed means that the charge-separated states essential to the chemical reaction may recombine before the reaction occurs, resulting in the absorbed light energy being lost as heat. To avoid this loss, both the photocatalyst and the reaction conditions must be optimized to ensure the most efficient process possible. However, the molecular-level mechanistic details of the reaction are not always known, making the rational design of new systems or of improvements to current processes difficult.

Future perspectives for artificial photosynthesis

Within the next decade, technologies for the storage of solar energy either as synthetic fuel or as starting materials for chemical production are expected to reach maturity and be available for large-scale applications. Several different technologies may be used in parallel depending on the specific requirements of each. These technologies could include conversion of solar energy into electricity that is then used for hydrolysis, in combination with chemical transformation or solar energy concentrated by mirrors into high-temperature reactors to generate electricity from steam, or even direct synthesis of syngas from water and carbon dioxide (CO_2).

The generation of synthetic fuels by direct photoredox catalysis is less likely to be ready for industrial-scale applications in the near future, since current energy efficiency and catalyst stability are limited, and scaling up would

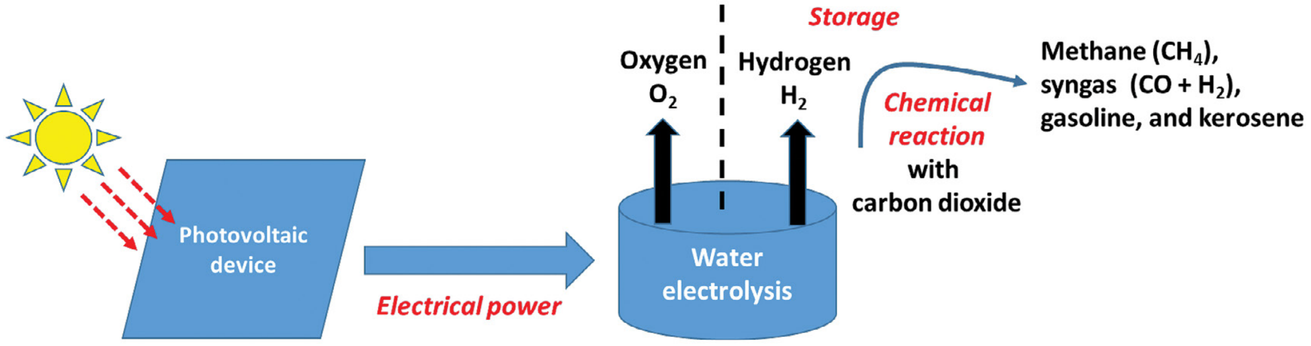

FIGURE 2. Schematic of the conversion of solar energy into stored, chemical energy. Electrical power from photovoltaics is used to power electrolysis of water to create hydrogen, which can be stored or used to generate power through a chemical conversion process to produce methane, synthesis gas (syngas), gasoline, or kerosene.

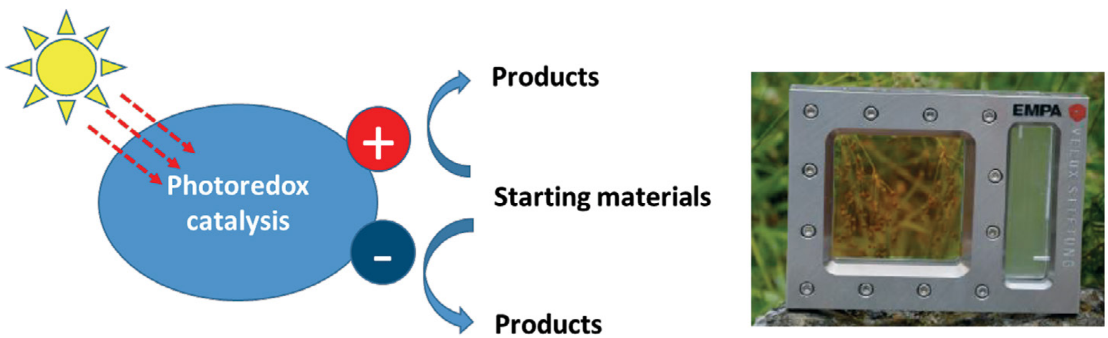

FIGURE 3. Left: Schematic showing the direct conversion of light into chemical products by photoredox catalysis. Right: Photoelectrochemical cell for solar hydrogen production.

be technologically challenging. However, within the synthetic chemistry industry, particularly in fine chemical and pharmaceutical production, photoredox catalysis may offer a valid and economic alternative to existing methods. In addition, direct use of energy from daylight in the synthesis of chemical products holds the promise for specific applications such as self-disinfecting or self-repairing surfaces, and the self-regulated generation of molecules with specific color, odor, or bioactivity properties.

Solar disinfection

While artificial photosynthesis converts light into energy-rich molecules, another use of light energy has been rediscovered only recently: disinfection.

Drinking water

The first scientific report showing that bacterial growth can be inhibited by sunlight dates back to 1877. Over the next two decades, inactivation of a number of microbial pathogens by sunlight was clearly demonstrated, and the use of sunlight and artificial light for sterilizing drinking water and disinfecting wastewater was put forward (*6*, *7*). However, it wasn't until 1980, in work on the solar treatment of oral rehydration solutions by Acra and colleagues, that sunlight was conclusively shown to safely disinfect water (*8*). Subsequent methodological developments and numerous clinical- and health-impact studies confirmed that exposure of drinking water to direct sunlight for 6 hours inactivates most, if not all, relevant waterborne pathogenic microbes and viruses (*9*, *10*). In 2005, this method, referred to as SODIS (solar disinfection) (*11*), was recognized and recommended by the World Health Organization (WHO) and UNICEF as being safe for disinfecting drinking water at the household level (Figure 4). Today, SODIS is used daily by more than 5 million people in rural Africa, Asia, and South America (*12*).

Although SODIS was shown to be effective, the exact disinfection mechanism has received little attention. Based on studies showing that ultraviolet-C (UVC) light could directly damage nucleic acids (*13, 14*), it was assumed that the mechanism of cellular inactivation of microbes and viruses was through UVA/UVB damage to DNA. However, recent work has demonstrated convincingly that the deactivating agent is actually direct and indirect oxidative damage to proteins (*15*). Visible light and UVA/UVB stimulate the formation of reactive species (most likely reactive oxygen species) in the electron transport chain located at the cytoplasmic membrane (*16*). These reactive species first attack membrane-bound proteins and later cytoplasmic proteins, leading to a loss of protein activity, denaturation, and subsequent aggregation. Oxidative damage to DNA

FIGURE 4. Application of SODIS bottles in Togo for drinking-water disinfection.

PHOTO: EAWAG

appears to occur only in a much later phase and is of secondary importance. In contrast to DNA damage, for which a number of well-known repair mechanisms exist, damaged proteins are difficult to repair and are simply replaced by newly synthesized molecules. Available data suggests that recovery from protein damage is difficult and that SODIS is a more efficient means for cell inactivation and killing than previously thought (*17*).

Medical applications

Unrestricted bacterial growth and infections are still a major cause of death in developing countries, often because adequate treatment is unavailable. Antimicrobial agents are needed to treat acute infections as well as to prevent future disease.

Since the discovery of penicillin by Alexander Fleming in 1928, antibiotics have been an effective treatment against bacterial infections. However, antibiotic resistance has been a cause for increasing concern (*18*). Additionally, high treatment costs often prevent their application in developing countries. One technique to avoid the transmission of infectious diseases is the application of photosensitizers (substances that absorb light and transfer the energy to adjacent reactants) in combination with UV light to decrease the pathogen load. This approach can be applied to reserves of whole blood (*19*) to reduce the risk of transfusion-transmitted diseases. The same technique has recently been applied in ophthalmology for the treatment of infectious keratitis (*20*) and in oncology for the treatment of cancer (*21*). The advantages of eliminating pathogens or tumor cells with UV light are that (1) it is economical and (2) thus far, it has proven immune to microbial resistance.

Although UV light or other short-wavelength radiation can be used as a stand-alone approach for surface disinfection, the disinfection of the human body is more complex, as death or permanent damage of cells (such as DNA mutation) should be avoided. The use of longer-wavelength radiation not absorbed by DNA is one option, together with the application of a photosensitizer that can increase light absorption and spatially delimit the treatment zone (*22*).

The design and fabrication of more specific and reliable photosensitizers is ongoing, including molecules that are designed to bind exclusively to pathogens (*23*) or tumor cells (*24*) in order to increase the specificity of the treatment (Figure 5). Despite advances, a current limitation of photodynamic treatment is its strong dependency on oxygen, which limits the treatment of deeper skin layers or of internal organs.

The Sun emits a continuous spectrum of wavelengths from approximately 290 nm to 3,200 nm. Light in the UV portion of that spectrum (< 400 nm) could potentially be used for disinfection, especially for the treatment of ocular and skin infections. In combination with a suitable photosensitizer, UV light has the potential for rapid, economical management of superficial infections. Also, a combination of UV light and a photosensitizer as an antimicrobial treatment can reduce the use of antibiotics and other antimicrobial drugs whose effect on the environment is unknown (*25*).

Storage of daylight

Photovoltaic solar energy stored in batteries can be used to power electric lights at night, which allows for local, autonomous provision of lighting. It is likely that LEDs will be developed to successfully mimic the spectral distribution of daylight, enabling the creation of artificial "daylit" areas deep inside buildings that can compete with a range of optical-fiber, mirrored, or luminescent devices that redirect daylight into building interiors (*26*). However, no attempt has yet been made to define or artificially create the aspects of daylight that elicit all of its overt, tacit physiological and psychological responses. Certainly, artificial lighting cannot currently provide the physical views of external environments that accompany daylight—and are often intrinsic to its appreciation. Even if it becomes possible to fully emulate daylight in a single, economically viable device, its spatial and architectural integration into a building would be a further challenge. Speculatively, such a device could comprise a set of spectrally selective optical-fiber microresonators that each receive and retain different wavelengths of daylight for subsequent emission. Light could be trapped by total internal reflection in a micrometer-sized, dielectric structure with a circular symmetry, in a manner analogous to the echo of barely audible speech in a whispering gallery (*27*). Microresonators have also been incorporated in liquid crystal devices similar to those used in switchable windows. Practical daylight storage devices would likely incorporate various transmittance and luminescent materials to provide light distributions similar to daylight. Daylight storage remains a challenging topic requiring further investigation.

In summary, the growing popularity and increased use of daylight in direct electricity production via photovoltaic cells has resulted in less attention being paid to other fields of application. Here we have emphasized pathways to the synthesis of "solar fuels" like H_2, and outlined future developments that could lead to the production of complex molecules via artificial photosynthesis. Daylight also generates reactive oxygen species that are excellent reagents for low-cost disinfection of drinking water. Furthermore, the production of daylight-induced oxidants can disinfect surfaces for medical applications and support specific treatment processes.

FIGURE 5. Corneal tissue soaked with riboflavin (a photosensitizer) under UVA irradiation as a treatment for infectious keratitis. The induced photochemical reactions result in the generation of reactive oxygen species with antimicrobial activity. This treatment modality is a promising alternative to antibiotics for infections involving multiresistant bacterial strains.

PHOTO: SABINE KLING, UNIVERSITY OF ZURICH

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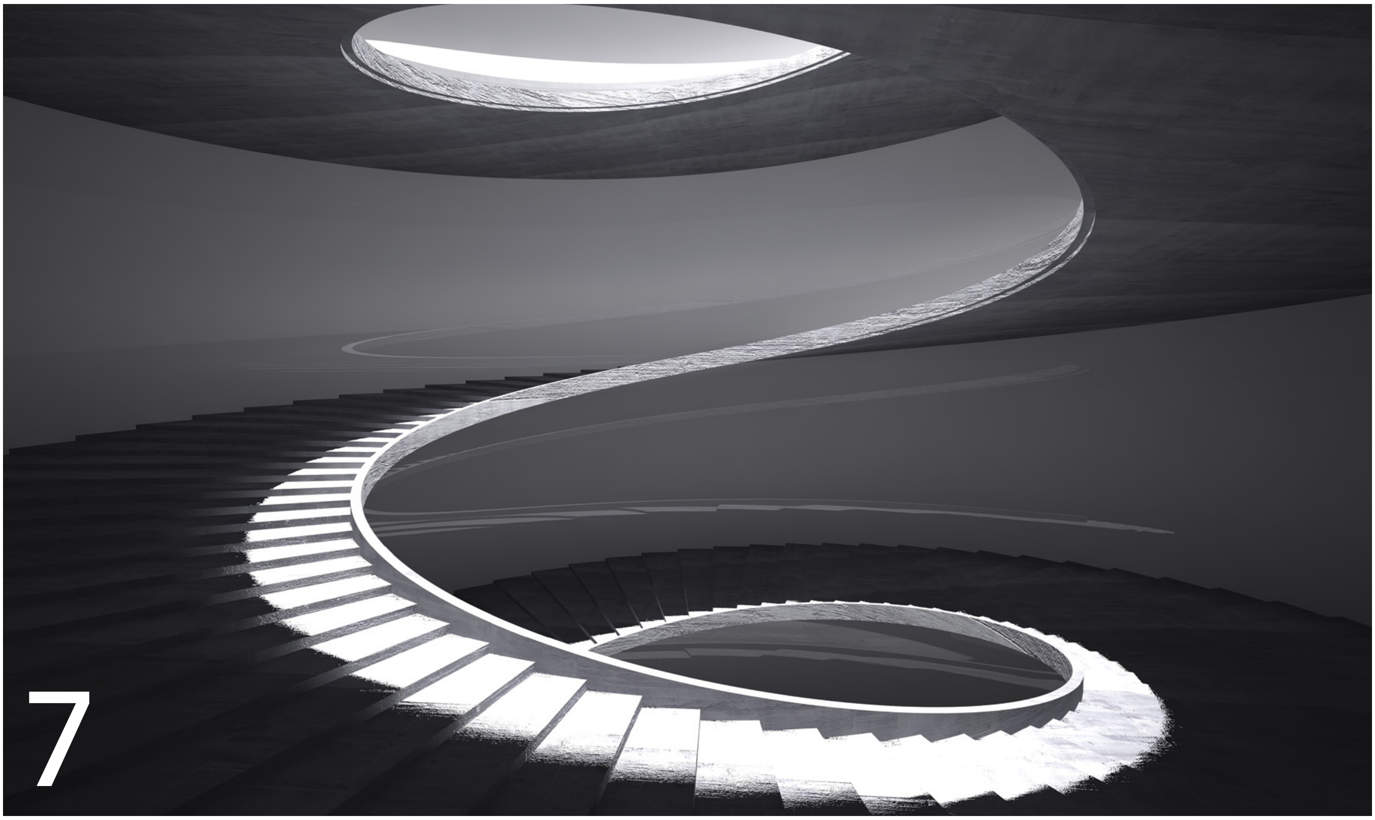

7

Closing thoughts

Brian Norton[1] and
Jean-Louis Scartezzini[2]

Daylight is fundamental to the existence and evolution of nearly all life. It is critical—directly and indirectly—to essential processes in most plants and animals, including humans. People also harness daylight to provide heat and electricity, and in architectural design they seek to use daylight to provide visual and thermal comfort in built forms that express cultural identities. The study of daylight has been approached from many radically different perspectives, as illustrated in this publication. From the medical, botanical, and physical to the aesthetic and architectural, the "what," "why," and "how" aspects of daylight are understood through different scientific and historical contexts. In this chapter we discuss some instances where distinct disciplinary insights into daylight are converging to offer promising new discoveries.

A place for plants

Plants both alter and adapt to local light conditions. Human society has been built around domesticated or wild-harvested plants that act as "light factories" to harness the Sun's energy to produce nutrients, medicines, fibers, construction materials, and fuel. Today, declining biodiversity, together with the loss of cultural knowledge of plant uses, poses a threat to our future on Earth. Gaining a fuller understanding of why this biocultural diversity is important to human civilization may foster a more sustainable, healthy, and resilient human society.

Data-origin dilemmas

A significant challenge in daylight research is finding a way to bring together insights from data measured at widely differing spatial and time scales, originating from a wide variety of instruments and sources. These sources might range from satellite data about light reflected from the Earth's surface to hyperlocal measurements of solar radiation, and from data on the energy balance recorded from individual plants to population-level collections of circadian rhythm information. Cutting-edge tools and protocols are required to adequately assess light quantity and quality, as well as to appreciate the specific temporal, spectral, and intensity differences between daylight and artificial light, and the physiological responses to each source. Integrating all of these data sources would enable a systematic comparison of detailed simulations and laboratory findings with studies of natural environments.

User-centric approaches

Since forgoing a hunter–gatherer existence for an increasingly sedentary lifestyle, many humans now spend an increasingly larger part of their lives inside buildings. Less exposure to daylight with greater use of artificial lighting has

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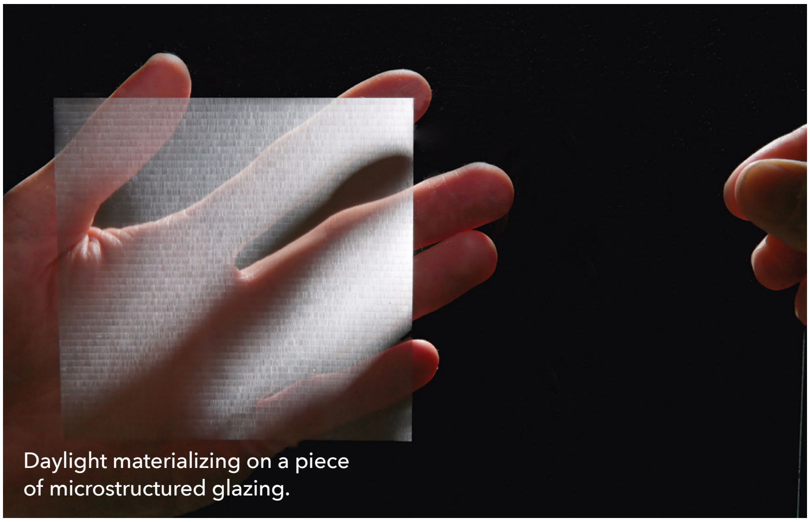
been necessitated by economic drivers for deep-plan buildings, but also by the need to express cultural, social, and political identities. The aesthetic needs arising from specific cultural contexts should spur innovative ways to use daylight and create built environments that users can both accept and appreciate.


Daylight materializing on a piece of microstructured glazing.

Being easily measurable, user comfort and energy consumption are often the dominant criteria used when selecting window technologies in most buildings. However, the efficacy of a window technology and the role of occupants in its control are influenced strongly by subjective aesthetic factors and cultural notions, and also by the occupants' physical and emotional well-being. Additional research is required to incorporate these more subtle factors into window design and selection. Furthermore, interactions between diverse variables, such as the influence of natural light on thermal conditions, human behavior, labor productivity, gaze, and eye movement, remain to be further explored. Finally, light color has been claimed to strongly influence indoor comfort (*1*). However, current data suggesting that warm-yellowish-to-reddish correlated color temperature produces beneficial psychological effects is weak, indicating that more research is required (*2*).

Storage of daylight

Technologies are currently being developed for the storage of daylight energy as synthetic fuels or starting materials for chemical production. Some examples include solar energy converted into electric power and used for the electrolysis of water; solar power technologies that use mirrors to focus sunlight, converting it to heat to drive a turbine to generate electricity; and direct photoredox catalysis used to generate synthetic fuels [although the latter process is hampered by basic inefficiencies and issues with catalyst stability (*3*)]. Research efforts are also underway to investigate the storage of daylight energy in single-medium systems such as spectrally selective optical-fiber microresonators (*4*).

Daylight as an antiseptic

Ultraviolet (UV) light and other types of short-wavelength radiation are being considered as disinfectants with the potential to be fast, economical treatments for superficial ocular and skin infections. Since short-wavelength UV can cause DNA breaks that may lead to cancers such as melanoma, less-damaging, longer-wavelength UV is being tested for human use. Photosensitizers are also under investigation as a means to increase light absorption in a small treatment zone to mitigate cell death and permanent DNA damage. The design and fabrication of more specific and reliable photosensitizers requires ongoing research (*5*).

Daylight as a time cue

The photoperiod and seasonal temporal rhythms, driven by variations in the intensity of distinct solar wavelengths, together with temperature and shifting lengths of day and night, all act on different organisms in a myriad of intertwined ways. How these dynamics influence the health and well-being of all organisms, but particularly humans, is the subject of intense research on the nature and flow of internal information collected by photoreceptors. On a fundamental level, scientists would like to elucidate those properties of daylight that define specific physiologies important for health, and to better explain the specific mechanisms of light action that might affect it. It is unknown to what extent and under what conditions different nonphotic *zeitgebers* compete or interact with the nonvisual effects of light, and how enduring and beneficial these effects are. For instance, much work remains to be done on how to balance the threat of skin cancer with the potential negative side effects of insufficient daylight and circadian malentrainment.

Conclusions

Daylight is important in everyday life. Human activity impacts the availability of daylight, from the shade created by tall buildings, to the introduction of aerosols into the atmosphere that diminish and scatter sunlight, to our influence on the global climate. Novel urban planning and building-design approaches must respond to these threats by assessing the impact of the built environment on both the future of the biosphere and of humankind. Long-term transdisciplinary research that includes vision researchers, neuroscientists, physicians, physicists, engineers, architects, and lighting designers is essential to (literally) open society's eyes to the psychobiological importance of light for health and well-being. More broadly, bringing attention to the full impact of human activity upon our world will hopefully encourage mitigation of some of our more harmful behaviors.

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EPILOG

The importance of daylight for our daily life and health as well as for nature cannot be overrated. Daylight also constitutes common ground for scientific discourse since it features in so many different disciplines. The Velux Stiftung therefore initiated the Daylight Academy, where scientists meet and exchange their expertise to create interdisciplinary knowledge, groundbreaking ideas, and international cooperation. The first outcome of collaboration facilitated by the Daylight Academy is this booklet.

This was only possible thanks to the outstanding work of the authors and chapter editors, who are members of the Daylight Academy. They are convinced that such a publication is exigent and timely to show a broader audience the importance of interdisciplinary daylight research. We would like to express our highest appreciation for these contributions.

Lykke Ogstrup Lunde,
President

Lukas von Orelli,
Director

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