A photobiological approach to biophilic design in extreme climates

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Highlights

- The biophilic design approach has potential benefits in extreme cold climates, especially for Nordic occupants.
- Lighting design should be developed to deal with the challenging state of living and working in northern latitudes.
- Non-image-forming effects of light have become the missing link between human needs and lighting design standards.
- Adaptive envelopes should be developed to optimize biophilic quality and fulfil the photobiological needs of Nordic people.

Abstract

This paper proposes the biophilic design approach as a plausible hypothesis for the challenging conditions related to living and working in extreme cold climates. Biophilic design has recently been developed to overcome the adverse effects of the built environment and to improve human well-being by redefining the human-nature relationship. Yet, biophilic design should be adapted to extreme cold climates in order to meet the biological needs of people in northern territories. This issue becomes more important when considering the availability of natural light due to the strong seasonal photoperiod and its effects on human well-being in such regions. The present paper critically reviews biophilic design patterns and identifies their main shortcomings. These shortcomings include the lack of (1) recommendations applicable to extreme cold climates (2) adaptation to the local photoperiods, and (3) a systemic framework integrated into the design process. The paper draws attention to the image-forming and non-image-forming effects of light as a basis of the human-nature design approach. In this regard, photobiological outcomes have been reviewed. Then, the paper discusses the existing lighting standards and guidelines in North America and how they have mainly been developed to fulfil the image-forming demands for light. Further efforts are needed to revise these standards with respect to the non-image-forming effects of light and the biophilic design requirements. Finally, adaptive building envelopes are presented as a hypothetical solution to optimize the biophilic qualities of buildings and address the biological needs of people living and working in extreme cold climates in northern territories.

Key words: Biophilic design; Northern territories; Light; Image-forming effects; Non-image-forming effects; Adaptive building envelope

1. Introduction

The biophilic design approach has potential benefits in extreme cold climates, especially for Nordic occupants. Biophilic design is among recent approaches to improve the interactions and positive relationships between human beings and nature in the built environment. The idea of biophilic design originated in the theory of biophilia. Etymologically, the word 'biophilia' comes from the Greek word meaning "love of life" [1]. The theory of biophilia was first propounded by Wilson [2]. This theory rests on people's inherent affinity towards life and lifelike processes and patterns. The development of the biophilia hypothesis is based on biological science and human needs. From a biological standpoint, humans are a part of nature and they synchronize to the environmental conditions [3, 4]. The theory of biophilia shares this view. It considers humans like other species who have steadily evolved to adapt to nature [5, 6]. The theory of biophilia emphasizes the psychological, emotional and spiritual dimensions of human well-being that result from innate human-nature relationships [7, 8]. These relationships exist throughout the world thereby suggesting that they go beyond any cultural and ethical differences [9]. In the field of the built environment, the nature-orientated design of architectural and urban spaces has thus been accentuated in the biophilic approach. Yet, no studies have been conducted to assess the use and adaptation of the biophilic approach to human needs in extreme climatic conditions.

The biophilic design approach intends to reconnect and promote the human-nature relationship and eventually express this innate relationship in human lives [8, 10]. Biophilic design claims that this relationship with nature is vital for human beings [10, 11]. It argues that architecture is capable of expressing individuals' physiological and psychological inclination to nature [8]. This architectural approach can ultimately create forms and spaces to inhabit that answer the design problem defined by different contexts [12, 13]. In this regard, biophilic design is an intelligible language of architectural spaces that is instinctive to human demands by presuming natural forms and patterns as vocabularies and compositional grammar [1]. A perfect biophilic design integrates nature into the built environment in a way that is restorative and inspirational without causing any disturbance to the function of the space [14]. Hence, designers can imagine buildings that are delightful, functionally productive and regenerative through a clear understanding of lifelike patterns and their interactions with human needs [15]. However, the use of the proposed biophilic design guidelines during the design process comes with many difficulties and obstacles.

The present paper discusses the body of knowledge in biophilic design and identifies its shortcomings for applications in extreme cold climates. Firstly, the paper discusses the difficulties and limitations of the suggested biophilic patterns in extreme environments by comparing a selection of climates. Secondly, shortcomings of lighting design are discussed in relation to the potential of photobiological science to build human- and nature-friendly spaces. Thirdly, the structural weakness of biophilic design to accomplish its mission is discussed. Finally, a hypothetical solution to overcome the identified gaps and shortcomings is proposed. Moreover, the study is conducted based on a critical review of knowledge in biophilic design, photobiology, and lighting design. In this regard, recent research, publications, standards and guidelines (in North America) related to biophilic design, biological effects of light and lighting design were considered. Several databases were searched including Web of Science, ScienceDirect, and SCImago. The publications were organized according to specific keywords related to photobiology, biophilic design and lighting design. Such keywords include biophilic design, biophilia, nature-friendly design, human needs, design process, image-forming and non-image forming effects, lighting design, lighting analysis, and metrics. Several review papers related to the keywords were also reviewed. The number of studies selected for review accounts for about 85 documents on biophilia, 120 documents on image-forming and non-image-forming effects, and 80 documents on lighting design. As explained in the following sections, several climate classifications were also reviewed to discuss climate conditions.

2. Biophilic design constraints in extreme climates

Biophilic design guidelines should be adapted to extreme cold climate conditions. Natural environments change annually from winter to summer conditions, as illustrated in Fig. 1. This situation typically intensifies from a temperate climate (Fig. 1, middle) to an extreme hot or extreme cold climate when moving to lower latitudes (towards the equator, Fig. 1, right) or higher latitudes (towards the Arctic, Fig. 1, left), respectively. However, the current biophilic design strategies were mainly developed for temperate climates. Climate classifications enable to clearly identify the importance and deficiencies of biophilic design patterns in extreme cold climates. Overall, four basic categories of climate classifications have been developed including (1) generic (2) genetic (3) climatic comfort (bioclimatic) and (4) energy and moisture budget classifications [16, 17]. In response to different latitudes and building applications, several guidelines have been devised based on such climate classifications. In terms of human comfort, bioclimatic classification schemes have been developed to analyze the weather and climatic conditions. These bioclimatic classifications mainly consider the physiological and psychological reactions of people to climatic parameters [17, 18]. One well-known classification is the ASHRAE climate zone. ASHRAE [19] provides a global climate zone classification system for the energy demand analyses in the built environment. It includes seventeen climate zones regrouped in eight main categories. The ASHRAE climate zone classification is based on four environmental factors namely heating degree days (HDD), cooling degree days (CDD), monthly mean temperature and monthly precipitation.

Figure 1. The built environment features emphasized by biophilic design strategies in relation to dynamic climatic conditions

Solar radiation and the photoperiod are identified as the main climate-causing factors [20] that trigger several biological and socio-cultural events [21, 22]. They influence inhabitants and man-made settlements economically, socio-culturally and physio-psychologically. However, climate classifications have mainly been focused on thermal aspects of solar radiation, neglecting the biological effects of seasonal photoperiods. In this regard, Fig. 2 shows the global illuminance patterns related to the sun. Considering the basic curve of a clear sky (shown in red in Fig. 2), the global illuminance increases logarithmically from about 450 lux during sunrise/sunset to around 110,000 lux when the sun reaches its zenith at a position located 90° above the horizon. It should be noted that daylight illuminance depends on geographical locations and that the sun reaches the zenith at a smaller angle for regions near the equator (between +/-23°). Fig.3 presents an overview of lighting features for three cities located in different climate zones and latitudes. Meanwhile, Fig. 4 shows an overview of thermal features in these cities. As can be seen, the photoperiod, shadow pattern, sun path, temperature, cloud cover, humidity comfort level and solar radiation significantly change from Los Angeles (Lat. 33,9°N) to Montreal (45,5°N) and Kuujjuaq (58,1°N). More specifically, in the extreme cold climate of Kuujjuaq (Fig. 3, right column), people experience longer days without complete darkness during the summer, a situation approaching 18 hours of daylight, from 3:30a.m. to 9:40p.m. in June. On the contrary, people are exposed to only a few hours of daylight during the winter: about 6.5 hours of daylight from 8:30a.m. to 2:30p.m. in December. In comparison, the day/night cycle is extended moderately in the temperate Los Angeles climate, from around 10 hours (around 7a.m. to 5p.m.) of daylight in December to nearly 14.5 hours (around 5a.m. to 8p.m.) of daylight in June (Fig. 3, left column). Thus, the solar radiation and the photoperiod are more challenging in the northern latitudes. In brief, dramatic seasonal photoperiod variations result in a lack of solar radiation and of light in the winter months combined with a few hours of darkness in the summer months. Overall, the climate features of northern territories include: (1) strong seasonal photoperiod variations; (2) low net radiation; (3) high surface albedo; and (4) mostly cloudy skies throughout the year, with snowfall precipitation in the winter. This situation results in a negative surface energy budget, very low seasonal average surface and air temperatures and ultimately, severe environmental conditions [20, 23].

Figure 2. Global illuminance patterns versus solar and lunar altitude (Retrieved from Thorington [24])

Figure 3. Lighting features of three North American cities located in different climates (meteorological data is derived from TMY-2 published by EnergyPlus and figures are derived by using weather spark [25] and online tools offered by Marsh [26])

Figure 4. Thermal features of three North American cities located in different climates (meteorological data is derived from TMY-2 published by EnergyPlus and figures are derived by using weather spark [25] and online tools offered by Marsh [26])

An extreme cold climate creates difficult conditions for living and working in the North. While the Inuit people (here called inhabitants [27]) adapt well to this extreme climate, non-adapted populations (here called occupants [27]) face many difficulties. Nordic occupants are forced to spend more than 90% of their time indoors with limited connections to the natural environment [28, 29]. Meanwhile, the vernacular and Inuit architecture is well adapted to such harsh natural conditions (for example see [30, 31]). However, the recently built modern settlements and buildings have most often been designed with little consideration for the harsh natural elements and the strong seasonal photoperiod. These buildings are mainly designed with a high thermal resistance envelope to satisfy the thermal comfort and indoor air quality demands [32, 33]. In the north of Quebec, the models imported from the south are not designed to provide northern occupants with desirable light and darkness throughout the year. This situation generates adverse effects on human well-being, both physiologically and psychologically. In this regard, previous studies reported several light-related complaints of sub-Arctic occupants such as desynchronized circadian clocks, sleep problems, lower physical activity, seasonal affective disorder (SAD), mood disturbances and higher UV light exposure [34-36]. Furthermore, the energy consumption of buildings increases because occupants are more disconnected from the exterior climatic conditions and cycles, and thus rely heavily on the interior environment to compensate. Therefore, there are higher demands for artificial lighting and mechanical heating systems with lead to negative environmental impact. Overall, this problematic situation exerts greater pressure on the economy due to excessive demands for energy production, the control of environmental risks and the additional pressure on the health-care system. The next section discusses lighting design strategies regarding these issues.

Considering the challenges faced in northern climates, biophilic design has potential advantages. More specifically, the well-known guideline suggested by Kellert [6] consists in two basic dimensions of biophilic design. These dimensions are related to six design elements and over seventy design attributes. An updated version of this guideline includes three major experiences, namely: (1) direct experience of nature; (2) indirect experience of nature; and (3) experience of space and place [5]. This guideline also proposes twenty-four attributes of biophilic design. Another guideline, proposed by Heerwagen & Gregory [37], mentions seven attributes of nature-inspired biophilic design. These attributes include sensory richness, motion, serendipity, variations on a theme, resilience, sense of freeness and prospect and refuge [37]. Moreover, Browning et al. [38] identified fourteen patterns of biophilic designs, which they regrouped in three categories, namely: (1) nature in the space; (2) natural analogous; and (3) nature of the space. Overall, the proposed biophilic design strategies emphasize the nature-oriented design of specific features of the built environment, as depicted in Fig. 4. Such features include (1) visual and non-visual features; (2) airflow and thermal features; (3) acoustic features; (4) colors and materials; (5) shape and form; and (6) design implications and space syntax. It is claimed that biophilic design patterns are flexible and replicable in various climatic or cultural situations [38]. Yet, the usability, adjustability and productivity of biophilic design guidelines for such climates have not been assessed.

Biophilic design recommendations should be developed and adapted to the harsh nature of the north. More specifically, biophilic design guidelines mainly highlight the environmental aspects of buildings, such as interactions with plants, water, natural materials, views to natural landscapes, natural shapes and geometrical features of biological forms like fractals, scale invariance, natural light and light with qualities found in nature, fresh air, etc. [1]. Such biophilic patterns have potential benefits for extreme climates. However, the main questions related to the application of biophilia in extreme climates need to be addressed: How can a designer develop biophilic design recommendations for a severely cold or hot climate? How is it possible to take advantage of such extreme natural conditions in building design? Taking advantage of the biophilic design approach therefore calls for practical and appropriate strategies for the extreme climates of Nordic regions.

3. Major deficiencies of lighting design

Lighting design is one of the major elements to develop within biophilic design in order to deal with the challenging conditions related to living and working in extreme cold climates. People are exposed to the light provided by the design and control strategies of the built environment, which consequently affects their health. Hence, lighting design plays a key role in human-nature relationships and the theory of biophilia [6, 38]. Biophilic design patterns aim at maximizing the use of sunlight and skylight, directly and indirectly, and modifying the design of artificial lighting to be sufficiently nature-friendly [5, 38]. Meanwhile, visual and non-visual responses to nature and natural systems are other concerns of the biophilic approach that should be considered in lighting design [5, 38].

Growing attention has recently been given to the design of lighting in buildings to make them more restorative and adapted to nature-human relationships [14, 39]. The science of photobiology has thus far acknowledged the image-forming (IF) and non-image-forming (NIF) effects of environmental light on human beings. Photobiology is the science that studies the responses of humans, animals and plants to the local and systemic effects of optical radiation in the range of UV, visual (human visual system sensitive) and IR [40]. An IF visual response refers to the complex biological process that enables vision or image formation in human beings when light reaches the eyes [22, 41]. Incident light also stimulates several brain areas implicated in circadian rhythm regulation, alertness, well-being and moods; these are the body's NIF visual responses to light [22, 41]. In the built environment, inhabitants' photobiological responses are potentially affected by lighting systems and the opportunity of receiving daylighting. Yet, research on the built environment has mostly focused on the energy and visual comfort aspects of lighting systems. Therefore, other interactions of humans with light, in particular NIF effects, have been neglected. Moreover, the challenging light/dark cycle of northern regions has escaped the attention of researchers and designers. Generally, three major fields of lighting study in the built environment can be identified namely:

- **Energy aspect:** Over the past few decades, a considerable amount of research has been carried out to assess the energy aspects of lighting systems in terms of heat transfer and energy efficiency for example Yu and Su [42].
- **Sociocultural aspect:** A few studies discuss the socio-cultural aspects of light in the built environment. Humans organize the built environment according to four elements: "space," "time," "meaning" and "communication" [43]. People make their living spaces meaningful by transforming the spaces and its components into some recognizable signs or adding signs [44]. Considering architecture as a system of signs [44, 45], socio-cultural studies explore the meanings,

interpretations and ultimately communicational effects of light, as one element of space, in the built environment [45]. This area of light studies is still ongoing.

- **Human well-being aspect:** Light affects human beings through IF and NIF processing. However, the NIF effects of light on building occupants have escaped the attention of built environment researchers in comparison to the number of studies on its visual effects. More specifically, numerous studies have been conducted in the past few years to explore the interaction of light/daylight and the built environment with respect to visual comfort, analysis factors/metrics, analysis methods, simulations and measurements, impacts of windows and openings, shading and control strategies, and effects of materials [22, 41, 46, 47].

In North America, lighting design standards and recommendations have mostly been developed to address human visual comfort, energy efficiency and electrical safety issues [48, 49]. The NIF effects of light, which produce undeniable effects on human well-being [50, 51], have been neglected in lighting design standards. Furthermore, existing standards do not necessarily relate to the objectives of biophilic design. Thus, further research and development is necessary to establish guidelines in terms of NIF effects [48] and the biophilic quality of light in the built environment. The climatic conditions, particularly in Nordic regions, should also be addressed.

4. Contribution of photobiology to lighting design

Photobiological science should be integrated to lighting design standards to eventually produce comprehensive and appropriate guidelines for human needs in North America. To this end, employing the photobiological outcomes represents a recent effort to link lighting design with human health [52]. Fundamentally, optical radiation refers to a physical quantity transporting energy through radiation or literally electromagnetic waves [22, 53]. Optical radiation includes a series of spectra with different wavelengths, photon energy and power between the region of transition to X-rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm). Meanwhile, the term 'light' refers to different concepts, as suggested by the '*Commission internationale de l'éclairage (CIE)*' [54]. In some cases, it is used to describe the characteristic of all sensations and perceptions through vision. The term 'perceived light' is also used for such purposes. In other cases, it is used to represent radiation, which can stimulate the human visual system [54]. As depicted by Fig. 5, every bandwidth has a specific name, effect and energy. The bandwidth of approximately 360 to 830 nm corresponds to visual light (Fig. 5). To produce photobiological responses, the incident optical radiation must first be selectively absorbed by molecules of a living organism. Consequently, two types of reactions, namely photophysical and photochemical reactions, trigger a biological response [22].

Figure 5. Electromagnetic spectrum and corresponding photon energy and relative power at each wavelength from 100 to 850 nm and the approximate color associated with those wavelengths. The graphs are based on the data given by [22, 40, 49, 55]

4.1. IF effects in built environments

In the built environment, inhabitants' IF perception of light is acutely affected by lighting systems and spatial components. Light can be provided through different means in buildings. Several photometric functions have been developed to describe and evaluate the various light impulse parameters that influence human vision. These functions are extensively employed in lighting design. Table 1 provides a summary of the visual responses to different light parameters such as quantity, spectrum, and duration along with corresponding photometric metrics, units and equipment. Three broadly discussed light functions are the photopic and scotopic luminous efficiency and the relative spectral sensitivity. Accordingly, the photopic and scotopic luminous efficiency points to the action spectrum of vision for photopic and scotopic adaptations [22]. As shown in Fig. 6-A, V(λ) and V'(λ) represent the relative spectral sensitivity functions of photopic and scotopic luminous efficiency normalized at 555 and 505 nm for a standard observer with 2º and 20º visual fields, respectively [56-58]. Most of the lighting design studies have thus far focused on specific IF effects of light including [22, 53]:

- Luminance ratio and distribution
- Illuminance level, distribution and uniformity
- Glare
- Directionality of light
- Color rendering and color appearance of the light
- Material impacts on light visual perception
- Flicker
- Daylight metrics

There is a lack of knowledge concerning the interactions of IF effects of light and NIF combined with other biophilic principles such as offering a nature view. Moreover, the severe light/dark cycle of northern territories requires special attention in studies concerning IF effects in the built environment.

Therefore, it is arguably necessary to integrate IF with NIF effects in whole building design processes after which, climate-based spatiotemporal analysis methods will be developed for extreme climatic conditions. To this end, recognizing the biological mechanism of the visual system could provide designers with clues about how different parameters of light and space affect the IF and NIF perception of occupants. When light reaches the eyes, it initiates complex chemical and neural interactions between the eye and the brain that result in a visual response or image formation [22, 41]. This elaborated reaction of the eye-brain system, as one unit, enables humans to observe and ultimately perceive the surrounding world under very low to very high levels of light [22, 41]. The human visual system is sensitive to a specific bandwidth of light, so-called visual light, from 360 to 830 nm [49]. The neural part of the eye is the retina, which is responsible for the absorption of incident light and its transmutation into electrical signals that are convey to the brain visual system by the optic nerve in order to generate image formation [41, 49, 58]. The complex structure of the retina includes three layers, namely the photoreceptors, bipolar cells, and ganglion cells [22, 49, 57, 59]. There are four types of photoreceptors with different photopigments and spectrum peaks that can be categorized into two groups: (1) rods that peak at 491 nm and (2) cones namely L-cones (peak at 560 nm), M-cones (peak at 531 nm) and S-cones (peak at 420 nm) (see Fig. 6-B) [49, 57, 59, 60]. Cones and rods are basically responsible for day (bright light) and night (very dim light) vision, respectively [61]. Moreover, some specific ganglion cells, so-called intrinsically photosensitive retinal ganglion cells (ipRGC), have recently been identified as photoreceptors. The ipRGC initiate the NIF effects of light, in particular for the circadian system [62]. The next section discusses this issue in more detail.

Figure 6. Normalized relative spectral sensitivity for **(A)** the functions of circadian C(λ) [59, 63], melanopic $V^z(\lambda)$ [57, 59], scotopic V’(λ) (CIE 1951), photopic V(λ) (CIE 1924) [22] **(B)**; and the human photoreceptors [59, 64]

Table 1. The IF effects of different parameters of optical radiation on human vision and corresponding photometric units and equipment [22, 41, 49, 65-67]

One of the highly important concepts in lighting design is color. Color is basically a human perceptual phenomenon that is visually experienced; it is not an intrinsic characteristic of light spectrum or objects. The term color is misleadingly used as a property of objects, since every band of light is denoted as a particular color (as displayed in Fig. 6) [22, 68]. In fact, color is recognized as the human color vision process of a light source spectral power distribution (SPD) which is modified by an object [22]. In the context of the trichromatic theory of color vision, the human vision system responds to a light SPD through three channels of red/green, yellow/blue, and luminance [22, 49, 68]. These channels are generated by L, M and S cone photoreceptors. Color matching functions (called as CMFs xyz) have been introduced to characterize and standardize the perception of color for research, design and evaluation purposes. CMFs xyz are used to calculate the tristimulus values for which CIE has published a chromaticity diagram [22, 41, 66].

4.2. NIF effects in built environments

Attention to the NIF effects of light in buildings and urban environments has recently increased. Ongoing efforts are being developed to bridge the gap between lighting design and photobiological knowledge of the NIF effects of light. Photobiological studies have revealed several important NIF effects of light on human beings [50, 51]. It is claimed that such effects can cause temporary or even permanent damage that can eventually result in death [69]. The NIF effects are stimulated by either artificial or natural light [50, 51]. The impacts of various parameters of light and the corresponding photometric metrics and units for the assessment of NIF effects are summarized in Table 2. Reviewing this body of knowledge in photobiology, as follows, provides designers with information regarding the NIF effects of light and offers a greater incentive for climate-adapted design.

4.2.1. *Circadian clocks*

The human circadian system refers to the master clock and other peripheral clocks of the human body [70]. Circadian clocks can be reset by and synchronized by environmental time cues or “zeitgebers” (i.e. time giver or synchronizer). The light/dark cycle generated by the local photoperiod is considered as the most effective synchronizing factor [21, 36]. From the perspective of biological mechanisms, eyes exclusive transmit IF and NIF information of incident light [22]. Studies show that the ipRGC, as one type of non-classical photoreceptors located in the retina, are responsible for absorbing and transmitting the NIF information related to light [62, 71]. The ipRGC are first known as melanopsin-expressing retinal ganglion cells (mRGCs) [57]. They contain a photopigment called melanopsin with a spectral sensitivity curve that peaks in the short wavelengths of visual light at about 480 nm, also called blue light (see Fig. 6-A) [72-74]. After absorbing blue light, the ipRGC send neural signals to the suprachiasmatic nucleus (SCN) through the retino-hypothalamic tract where the master body clock is located [4, 75]. The SCN initiates and controls many biological rhythms in human body such as the sleep/wake cycle, core body temperature (CBT), and heart rate variability [22] to name a few. It is remarkable that the endogenous master clock in the SCN, as well as other peripheral clocks, runs intrinsically close to, but not exactly, 24h or one day without the intervention of zeitgebers [4, 21, 62].

In the presence of an external light-dark cycle, the circadian system actively adjusts individuals’ diurnal behaviors and the temporal rhythm of biological functions to the local time and environment, in particular the photoperiod [76, 77]. The best way to characterize the circadian rhythm is to monitor the pineal melatonin secretion, core body temperature (CBT) or cortisol secretion cycle [21, 36, 77]. Melatonin is claimed to be a robust circadian marker due to its small variability. Melatonin is a darkness hormone that signals nighttime that will yield to drowsiness and sleepiness diurnal species such as human. Melatonin secretion occurs from around 7:00p.m. to about 07:00a.m. (so-called biological night) with a peak near 03:00a.m.-04:00a.m. for humans [22, 70]. Furthermore, the circadian rhythm and melatonin secretion have been reported to be highly sensitive to blue-light. Their spectral sensitivity functions peak at $C(\lambda)$~460 nm and $V^z(\lambda)$~480 nm, respectively (see Fig. 6-B) [57, 59, 63]. This can reset or delay/advance the phases of the circadian system and melatonin secretion by modifying several parameters of light [78] such as the quantity (dim/bright/light dose) [79], spectrum (blue wavelengths) [80], time (morning/afternoon/night) [75], duration (hourly) and history (weekly/monthly)[36] of the light that individuals are exposed to. Fig. 7 shows some patterns of the impacts of light parameters on different circadian rhythms, as proposed by previous researchers. More details on the impacts of different parameters of a light source on the circadian system are presented in Table 2. However, many difficulties arise in analyzing the circadian effects of a light source in the actual conditions of an existing building.

The development of a framework for the circadian assessment of lighting and daylighting systems in the built environment with actual photoperiod efforts is ongoing. Thus far, some functions along with their corresponding calculators have been developed such as ‘Melanopic lux’ $V^z(\lambda)$ [57, 81], Equivalent Melanopic Lux

(EML) [82],'Circadian Light' (CL_A), and 'Circadian Stimulus' (CS) [83, 84], which can be applied to different light sources. Studies in this area have been conducted in controlled laboratory settings. The applications and contributions of such studies in design fields are severely restricted due to the complex nature of the real world. A few published studies cover this gap by employing new metrics and developing new analysis methods. In this regard, the International WELL Building Institute [82] released a human-centered building standard in response to human well-being needs. WELL provides some recommendations for lighting design in terms of IF and NIF effects. WELL proposes the EML function to calculate the melanopic lux of a light source [81, 82]. WELL offers no specific analysis method. The time, duration, distribution and photopic history of the exposure to light has been neglected in this function. Meanwhile, it is argued that no scientific foundation supports the relationship between the NIF effects and 'melanopic lux' of light [85]. Moreover, Konis [48] developed a spatial assessment method to quantify and map the frequency of the circadian-effective daylight stimulus. This method was developed based on the EML function. Hence, it has the limitations of EML. The method also needs further empirical studies to confirm the assumptions of the relationship between exposure to various stimulus frequency levels and circadian impacts. Another study developed the photobiology-based lighting model [86, 87]. This model was developed to predict the magnitude and direction of the circadian effects by measuring the vertical illuminance at the eye level, light source spectrum, and timing. As a major limitation, this method has only been used to analyze the circadian effects of three types of skylights including D55, D65 and D75 [86, 87]. Furthermore, high dynamic range (HDR) imagery technique has recently been developed to analyze both IF and NIF effects of light [67]. The HDR image is mapped to the luminance distribution of a space by capturing multiple digital images of the scene [66, 67]. HDR imagery techniques can provide a spatial distribution of luminance based on RGB value of pixels [66]. In a similar way, the circadian effects of the scene can be calculated through HDR images [67]. It is also possible to determine the illuminance, CIE XYZ and CCT of the scene based on the RGB values of each pixel [67]. However, this method has several limitations. For example, it requires extensive calibration and post-processing steps. Meanwhile, the photometric information is highly dependent on matching the camera response and the photopic function [66, 67].

Overall, designers still have no effective and practical model to actively consider and evaluate the circadian effects of light in a space. Thus, further studies are required to consider and analyze the circadian effects in buildings with an actual photoperiod. Considering the challenging lighting conditions of the North, special efforts should be made for such climates. Meanwhile, lighting scenarios should be developed to adapt the requirements of human beings to daylight availability, outdoor views and circadian synchronization to light/dark cycles.

4.2.2. Alertness and performance

Investigations on individuals' alertness and performance under different light doses, quality and timing have been done as part of NIF aspects of light. It is claimed that alertness and performance are influenced through ipRGC light detection [74]. Exposure to light at night and under a high sleepiness state causes an increase in alertness and improves performance on some cognitive tasks [74, 76]. In terms of light spectrum, objective and subjective alertness levels also show an increase to either blue- or red-enriched light impulse [88]. Many studies have been conducted to explore the impacts of different parameters of light on alertness and performance, as stated in Table 2. However, studying these issues is an open-ended effort especially in response to lighting design adjustments in the buildings and the real-time photoperiod. No guideline has yet been offered to adapt light in the built environment for the purpose of alertness and performance increase.

4.2.3. Light-related health issues

Diseases and disorders due to insufficient or inappropriate light have become a serious concern especially in Nordic climate zones. Human- and nature-friendly lighting design of man-made spaces have been claimed to be capable of confronting these issues. However, the existing lighting standards for buildings require further development to be appropriate for humans and nature-friendly [48]. Some of the light-related diseases and disorders are sleep-wake disorder and insomnia, seasonal affective disorder (SAD), depression, eye diseases, skin diseases, weight gain, cardiovascular disease, cancer and eventually death [22, 69, 70, 75]. In the few past years, light therapy has been developed in order to cure and mitigate these light-related health problems [22].

Table 2. The NIF effects of different parameters of optical radiation on humans and corresponding photometric units and equipment [22, 57, 59, 65, 67, 80, 82-84, 88]

Figure 7. (A) Melatonin phase shift and (B) melatonin suppression versus illuminance, melanopic lux and circadian stimulus (CS) for a single 6.5-hour exposure of white light at the cornea from a 4100K fluorescent lamp during biological night. Figures are modified and reproduced based on the data given by DiLaura et al. [22] and publicly released calculators for melanopic lux and circadian stimulus conversion by Lucas et al. [81] and Rea & Figueiro [85], respectively. (C) Regenerated figure of melatonin suppression level versus light dose (EML) based on Konis [48]. (E)) Regenerated figure of circadian phase response of the pacemaker to time of exposure to optical radiation given by DiLaura et al. [22]

5. Structural analysis of biophilic design

The current patterns of biophilic design present several strengths and weaknesses to efficiently fulfil design values and human needs. The main goal of biophilic design is to bridge the gap between people and nature in the built environment [5, 89]. As claimed by Gullone [9], Hartig et al. [39], and Ryan et al. [14], biophilic design restores and improves human health and well-being, both physiologically and psychologically. Hence, using a hierarchy of needs provides a clear image of how biophilic design satisfies and fulfils this goal. As depicted in Fig. 8, the suggested biophilic design attributes and patterns can be associated with Maslow's hierarchy of needs and interpreted for design. More specifically, Fig. 8-A & B illustrates Maslow's hierarchy of needs and provides a relevant interpretation for design and biophilia, respectively. The figure is designed according to the published works of Lang [90], Zhang & Dong [91] and Noltemeyer, et al. [92]. Maslow claimed that so-called deficiency needs (D-needs e.g. physiological and biological needs) should be satisfied in order to flourish self-actualization or growth needs (G-needs e.g. cognitive, aesthetics, self-actualization and transcendence needs) and reach the optimal level of functioning [91, 92]. Maslow also explained that an individual level of needs could be simultaneously satisfied or prioritized within a certain period [92]. The conceptual framework of Maslow's pyramid can be developed and adapted for design objectives, as depicted in Fig. 8-B [93]. Similarly, it can be claimed that poor designs may partially satisfy needs from different levels without meeting the basic and lower-level needs sufficiently [93]. On the contrary, good designs satisfactorily address the hierarchy of human needs [93].

Figure 8. (A) Maslow's hierarchy of needs and (B) interpretation relevant to biophilic design

Considering the hierarchy of needs and design values, the efficiency of biophilic design depends on its contributions towards the enrichment of design and the satisfaction of human needs. These issues are more important and challenging in the extreme cold climates of the North where people mostly stay inside buildings. It can be reasonably argued that the suggested biophilic design guidelines predominantly point out to the lower level of needs. In particular, biophilic design focuses on basic design requirements and on the improvement of human health and well-being. It has just a few indirect outcomes in mid-level needs such as usability and proficiency needs, or even higher-level needs by encouraging to biomorphic forms, complexity and mystery. In this regard, Browning et al. [38] suggest that biophilia is another component of environmental quality such as thermal comfort and daylighting, with the same necessity. In other words, biophilia is recognized as an environmental quality feature that considers human biological health and well-being in design, and that covers the deficiencies of human needs and building performance relationships [38]. This viewpoint has been widely supported and approved by reviewing existing studies of the physiological and psychological impacts of biophilic and nature-oriented design (for example see [8, 9, 14, 38, 39]).

As a main weakness, the given strategies mainly suffer from the lack of a systemic framework for the intervention and assessment of biophilic qualities from the early stages of the design process until after building execution. It is broadly recognized that the design process includes different stages such as "cognition, analysis, synthesis, design-making, implementation and evaluation" [94]. However, the given biophilic strategies propose no clear systemic intervention in any stage of the design process. This drawback has recently been noticed by some researchers. In this regard, the International Living Future Institute [95] released the 'biophilic design exploration guideline', which includes five steps to design and implement a project by biophilic exploration. In another study, Kayihan et al. [96] attempted to raise awareness of third-year undergraduate architecture students to biophilic theories. Yet, they did not propose any specific design process, intervention or evaluation mechanism for achieving biophilic design objectives. Thus, designers still meet serious challenges regarding how, when and to what extent biophilic recommendations could be applied in the design process. This limitation is basically attributable to the fact that the biophilic design approach only expresses advantages of nature in built environments.

As an environmental quality, biophilic design or quality does not necessarily relate to any evaluation system. In fact, biophilic qualities have not yet been defined as an index, indicator or rating system. Meanwhile, several validated indexes and evaluation systems have been developed for airflow, thermal, visual and acoustical comfort in built environments. Hence, neither designers, policy-makers, nor stakeholders have valid and reliable indicators to assess the biophilic qualities required for a space, a building and a city. Eventually, the proposed design patterns remain in the form of statements or manifests, remote from applications in built environments. Recent attempts have been made towards this issue such as the rating system offered by the International Living Future Institute [97], the assessment system proposed by the International WELL Building Institute [82], the biophilia matrix identification strategy suggested by McGee and Marshall-Baker [98], the biophilic quality index (BQI) [99] offered by Berto and Barbiero, or the analytic hierarchy process (AHP) examined by Sharifi and Sabernejad [89]. The proposed assessment methods and indexes are still far from being comprehensively, productively and efficiently involved in the design process or the post-occupancy evaluation of spaces. Meanwhile, more subjective and objective experiments and research are needed to confirm the validity and reliability of the methods and indexes offered.

6. A plausible hypothesis of adaptive envelopes

This paper calls special attention to building envelopes and adaptation strategies as a promising hypothesis to address the challenges of biophilic design for northern regions. Building envelopes are an in-between and transient space that link humans and their surrounding environment. Building envelopes stand as a promising avenue to address the human-nature relationship. Meanwhile, both nature and humans have been characterized as dynamic, adaptable and evolvable systems that change temporally (annually, seasonally or hourly) and spatially (geographical/latitudinal position), as depicted in Fig. 1. Hence, building envelopes should be designed as dynamic, adaptable and evolvable systems in response to the environmental conditions and human needs. In fact, building envelopes should be adapted to dynamic climate variations, particularly for the critical solar radiation and temperatures in extreme cold climates. Adaptive building envelopes could be developed to fulfil human needs and meet biophilic design criteria. In this regard, adaptive building envelopes have been identified as systems with intelligent, repeatable and reversible modification abilities for some of their functions, features or behavior over time, which adapt and modify the overall building performance according to dynamic environmental conditions [100]. The knowledge of adaptive envelopes and buildings is growing significantly. The idea of buildings that adapt to different contexts and actors in order to achieve satisfactory, reliable and sustainable responses has become the focus of worldwide discussions in recent years [94, 101]. Different adaptation strategies have thus far been proposed such as climate adaptive building shells [100], double skin façades [102], and climate responsive shells and forms [103, 104]. As shown in Fig. 9, several practices of such adaptive buildings and envelopes have been built around the world for example the Headquarters of the Swiss Federal Railways (Bern, Switzerland), Sharifi-Ha House

(Tehran, Iran), Arab World Institute (Paris, France), Kiefer Technic Showroom (Bad Gleichenberg, Austria), Al Bahar Towers (Abu Dhabi, UAE) and University of Arizona Cancer Center (Phoenix, AZ, USA). As these projects show, adaptive buildings and envelopes exist for different purposes and climates.

Adaptive envelopes should be developed to optimize biophilic qualities and to fulfil the photobiological needs of people in extreme cold climates. Previous studies asserted the economic and environmental effectiveness of adaptive buildings in terms of indoor air quality, visual comfort, acoustic performance, energy aspects and CO_2 emissions [105, 106]. No investigation has yet been conducted regarding the efficiency of such adaptive envelopes in extreme cold climates and the improvement of human NIF responses. Therefore, developing adaptive envelopes to reconcile occupants' photobiological needs with natural conditions hypothetically constitutes a promising solution to the serious lighting challenges in northern regions. Such adaptive envelopes are responsible for providing daylight and views to the surrounding environment, which comes with many difficulties to deal with in extreme climatic conditions. These adaptive envelopes should also detect outdoor environmental conditions and process the essential qualities and parameters related to photobiological and biophilic performances. Such envelope systems should optimize the utilization of natural environments based on lighting adaptation scenarios. The intended adaptive envelopes should eventually improve the well-being of occupants regarding the IF and NIF effects of light inside buildings. Adaptive building envelopes should be the subject of future studies. Currently, the authors of this paper are focusing on the development of such envelopes for buildings located in the north of Quebec, Canada, as part of the Sentinel North Strategy conducted by Laval University.

Figure 9. Examples of adaptive buildings and envelopes

7. Conclusion

This paper aims to propose biophilic design as a potential solution for the challenging climatic conditions of northern regions, especially regarding daylighting availability. The paper discusses the shortcomings of the suggested strategies in response to (1) their implementation in extreme climates; (2) local photoperiods and the photobiological needs of people; and (3) active and systemic interventions, contributions and evaluations in the design process and post-occupancy. Regarding the first shortcoming, the severe condition of the north demands more efforts to develop appropriate and practical biophilic design patterns and attributes. This should be combined with an efficient response to the respective environmental factors and parameters, in particular solar radiation and photoperiods. Therefore, developing and employing the biophilic design approach in this extreme cold climate will potentially yield significant human well-being and environmental benefits.

Furthermore, biophilic design emphasizes daylighting, natural patterns and cycles, view to nature and human-friendly lighting. Meanwhile, the light/dark cycle is identified as the most important environmental cue or zeitgebers that triggers many biological and socio-cultural events. The photoperiod shows a huge seasonal variation in the northern latitudes. Hence, the availability and accessibility to daylight come with difficulties in such regions. This paper draws attention to this situation and to the importance of light and local photoperiods for human well-being and health. The paper elaborates on this perspective in more detail by critically reviewing the knowledge of lighting design and photobiology. In this regard, it discusses the IF and NIF visual responses of humans to light. It also clarifies that the lighting design and control systems in buildings have undeniable biological effects on people, especially for those who live in sub-Arctic climates. Subsequently, the paper emphasizes the lack of knowledge in lighting design to fulfil the photobiological needs of people and meet the objectives of biophilic design. This issue points to the second deficiency of biophilic design guidelines in Nordic regions. More specifically, the NIF effects of light have become the missing link between human needs and lighting design standards. Researchers have recently made efforts to use the knowledge of photobiology to develop several metrics (such as Melanopic lux, EML CS and CL_A) and evaluate the NIF effects of light in built environments. Yet, this area of study demands further development in terms of evaluation systems, metrics, contributions to lighting design and the fulfilment of biophilic needs. Furthermore, accessibility to nature scenes, as a basic human need subjected by biophilic theory, has direct impacts on building lighting strategies and human IF and NIF perception of light. Hence, this issue should also be considered in the development of lighting standards and adapted for the harsh climate of northern territories.

Aiming to promote human-nature relationships, the last shortcoming of biophilic design calls for the development of a design process framework as well as an assessment system. The existing guidelines have offered no systemic framework by which designers can actively and consciously utilize biophilic recommendations in their design. Moreover, no assessment or rating system has been proposed to measure the quality or quantity of biophilia in the building. Therefore, the biophilic quality of the building is depended on the skills, experiences and intuition of designers towards translating and applying the recommendations into the design. Thus, future studies should focus on this aspect.

Finally, the paper identifies the promising hypothesis of adaptive building envelopes. More specifically, the adaptive envelope system should be developed to optimize the biophilic quality and photobiological performance of buildings in the North through lighting adaptation scenarios. In fact, building envelopes stand as a physical in-between and transient system that connect nature, humans, indoor and outdoor environments. They also provide a meeting ground for climate, biology, design and technology. Therefore, they should be developed to appropriately mediate the exterior conditions for human health and delight. Adaptive envelopes are hypothetically capable of offering mechanisms for the adaptation of buildings to human needs and natural conditions. This idea should be developed in future studies.

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Conflict of interest

Authors have no conflict of interests.

Appendix A

Photo courtesies of Fig. 9.

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Table 1

Table 1. The IF effects of different parameters of optical radiation on human vision and corresponding photometric units and equipment [22, 41, 49, 65-67]

Light parameter	Impact	Metric	Unit	Equipment
Quantity	• Photopic vision occurs at luminance higher than approximately 10 cd/m2. The visual system in this state of adaptation exhibits a spectral sensitivity to monochromatic optical radiation that is defined by the Standard Photopic Luminous Efficiency Function of Wavelength of the CIE. • Mesopic vision is intermediate between the photopic and scotopic states occurring at luminance below approximately 3 cd/m2 and above approximately 0.01 cd/m2 • Scotopic vision occurs at luminance less than approximately 0.01 cd/m2.	Illuminance	lux	Illuminance meter Luminance meter HDR image
		Luminance	Cd/m2	
Spectrum	• The canonical visible range is 360-830 nm • Photopic and scotopic visions peak at nearly 555 and 507 nm wavelengths, respectively. • UV and IR wavelengths have adverse effects on the vision system.	Wavelength	nanometer	Spectrometer Spectrophotometer Colorimeter Filtered radiometer Spectroradiometer
		Color temperature	Kelvin	
		Spectral power distribution	W/m2×sr×nm W/m2×nm	
Timing	• Vision system reacts to inclined light in any time (day/night)	Time	second	-----
Duration	• Vision system reacts very short (less than 1 s) to incident light. • Smooth movements faster than 40 degrees per second or erratic movement at slower speeds will lead to a dramatic deterioration in visual acuity.	Time	second	-----
Spatial distribution	• Distribution of light on the eye is important for visual comfort and performance. • It affects the image formation, ability to distinguish shapes, details and other spatial characteristics.	Measuring the luminous intensity distribution, luminance distribution, luminous flux or spatial color distribution	W W/m2 W/sr×m2	Goniophotometer CCD-based camera systems HDR image with calibrated digital camera
Adaptation	• The human visual system can process information over an enormous range of luminance, from a very dark night (10^{-6} cd/m2) to a sunlit beach (10^{+6} cd/m2) (approximately 12 log units), but not all at once. • Several important aspects should be noted such as the asymmetry in adaptation speed from low to high (seconds) and high to low (minutes) light levels, and the adaptation to colored scenes and multilevel adaptation mechanisms (Iris, eye lids, retinal adaptation etc.)	Time	second	-----

Color	• Color is a human perceptual phenomenon visually experienced and is not an intrinsic characteristic of light spectrum or objects. • Color perception depends on three components including optical radiation, objects and vision. • Materials change the reflection, transmission, scattering, and/or fluorescence of optical radiation. • Human color perception depends on retinal photoreceptors.	Color temperature Correlated Color Temperature (CCT) CIE Chromaticity chart (CIE xyz) Color Rendering Index (CRI)	Kelvin	Colorimeter

Table 2

Table 2. The NIF effects of different parameters of optical radiation on humans and corresponding photometric units and equipment [22, 57, 59, 65, 67, 80, 82-84, 88]

Light parameter	Impact	Metric	Unit	Equipment
Quantity (See Fig. 7)	• Human circadian pacemaker phase shifts in response to relatively low levels of a broadband spectrum white light source (approximately 100 lux [10 fc] at the cornea) • The phase-delay resetting response of the body clock saturates at ~600-1000 lux (~60-100 fc) at the cornea. • 50% of the maximum resetting response occurs with ~100 lux (~10 fc) at the cornea.	Illuminance	lux	Illuminance and Luminance meter Melanopic meter HDR image
		Luminance	Cd/m2	
		Melanopic	Melanopic lux EML CS, $\mathrm{CL_A}$	
Spectrum	• Circadian and melanopic sensitivity curve peaks in the short wavelength portion of the visible spectrum (blue light) at nearly 460 and 480 nm wavelengths. • Red light does not suppress melatonin. • Long-wavelength (red) light and short wavelength (blue) light increased alertness at night.	Wavelength	nanometer	Spectrometer Spectrophotometer Colorimeter or filtered radiometer Spectroradiometer
		Color temperature	Kelvin	
		Spectral power distribution	W/m2×sr×nm W/m2×nm	
Timing (See Fig. 7)	• The timing of any optical radiation exposure as well as natural photoperiod influences the direction and magnitude of body rhythm phase-resetting effects, in particular circadian entertainment. • Exposure in the morning can shift the circadian pacemaker timing earlier (i.e., advance the clock phase); exposure in the evening can shift the pacemaker timing later (that is, delay the clock phase). • Optical radiation exposure has a maximum pacemaker shifting effect when it occurs during the biological night. Exposure is less effective during the biological day. • Exposure to short wavelengths at night (or bright light) in conjunction with darkness (or less-bluish light) during the day facilitates adaptation to night work.	Time	second	-----

Duration	• The NIF effects depend on the duration and pattern of optical radiation exposure. • A daily three-hour exposure to 5000 lux (500 fc) at the cornea was as effective as a six-hour exposure for adaptation to an experimental night shift. • A one-hour exposure to 10,000 lux (1000 fc) from a polychromatic light source at the cornea has approximately 45 percent of the phase response curve (PRC) amplitude of a 6.7-hour exposure to the same optical radiation.	Time	second	-----
Spatial distribution	• The ipRGCs are distributed throughout the entire retina, being denser in the supero-temporal pole. • Unlike the visual system, NIF photoreception does not require precise spatial resolution of optical radiation because it concerns changes in ambient irradiance.	Measuring the luminous intensity distribution, luminance distribution, luminous flux or spatial color distribution	W W/m2 W/sr×m2	Goniophotometer CCD-based camera systems HDR image with calibrated digital camera
Adaptation	• The photic history (from the preceding hours, days and weeks) affects the sensitivity of the human body clock to optical radiation at night. • The higher the exposure to optical radiation during the day, the lower the human circadian system’s sensitivity becomes to optical radiation at night.	Time	second	-----

Figure 1

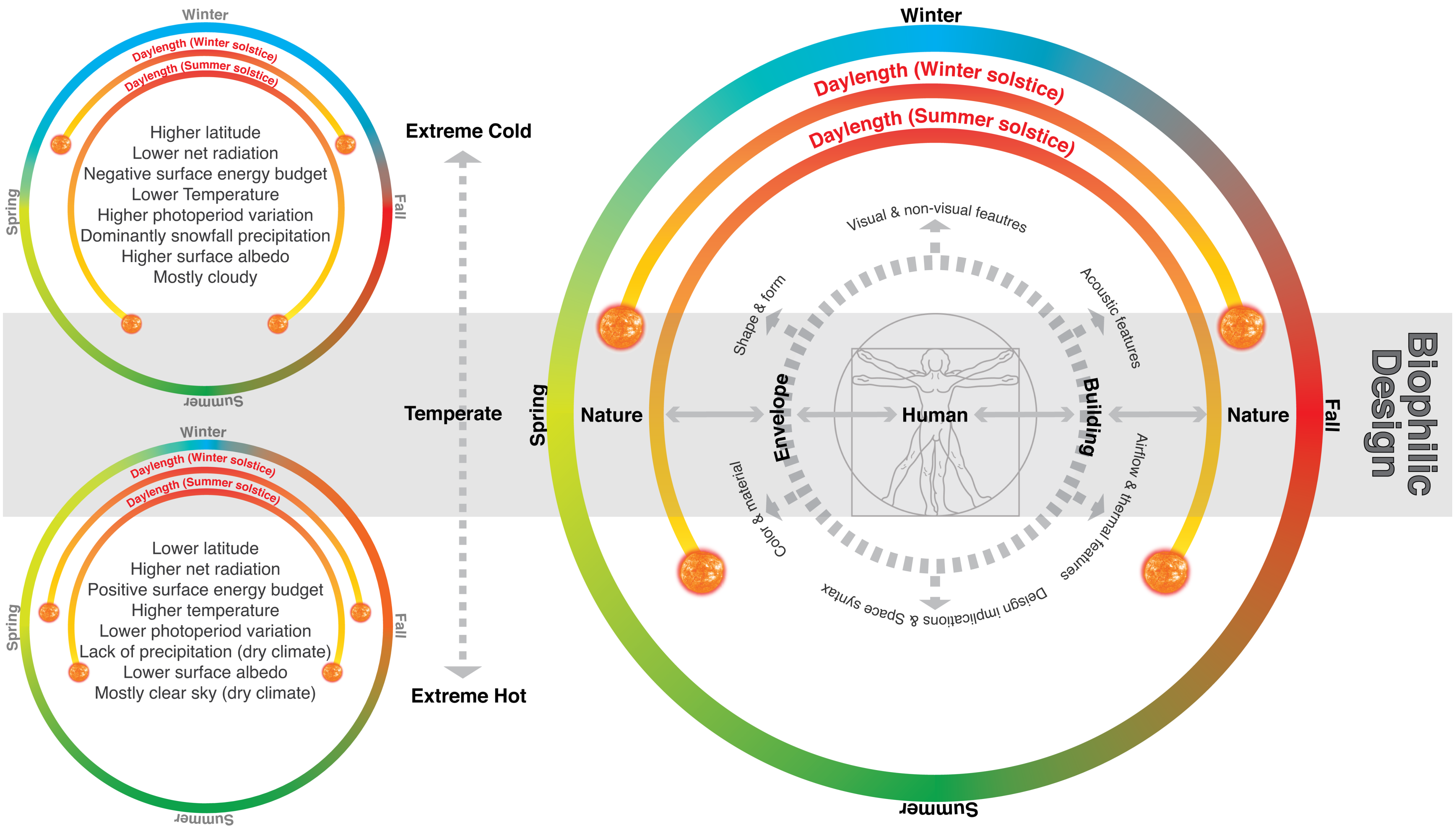


Figure 1. The built environment features emphasized by biophilic design strategies in relation to dynamic climatic conditions

Figure 2

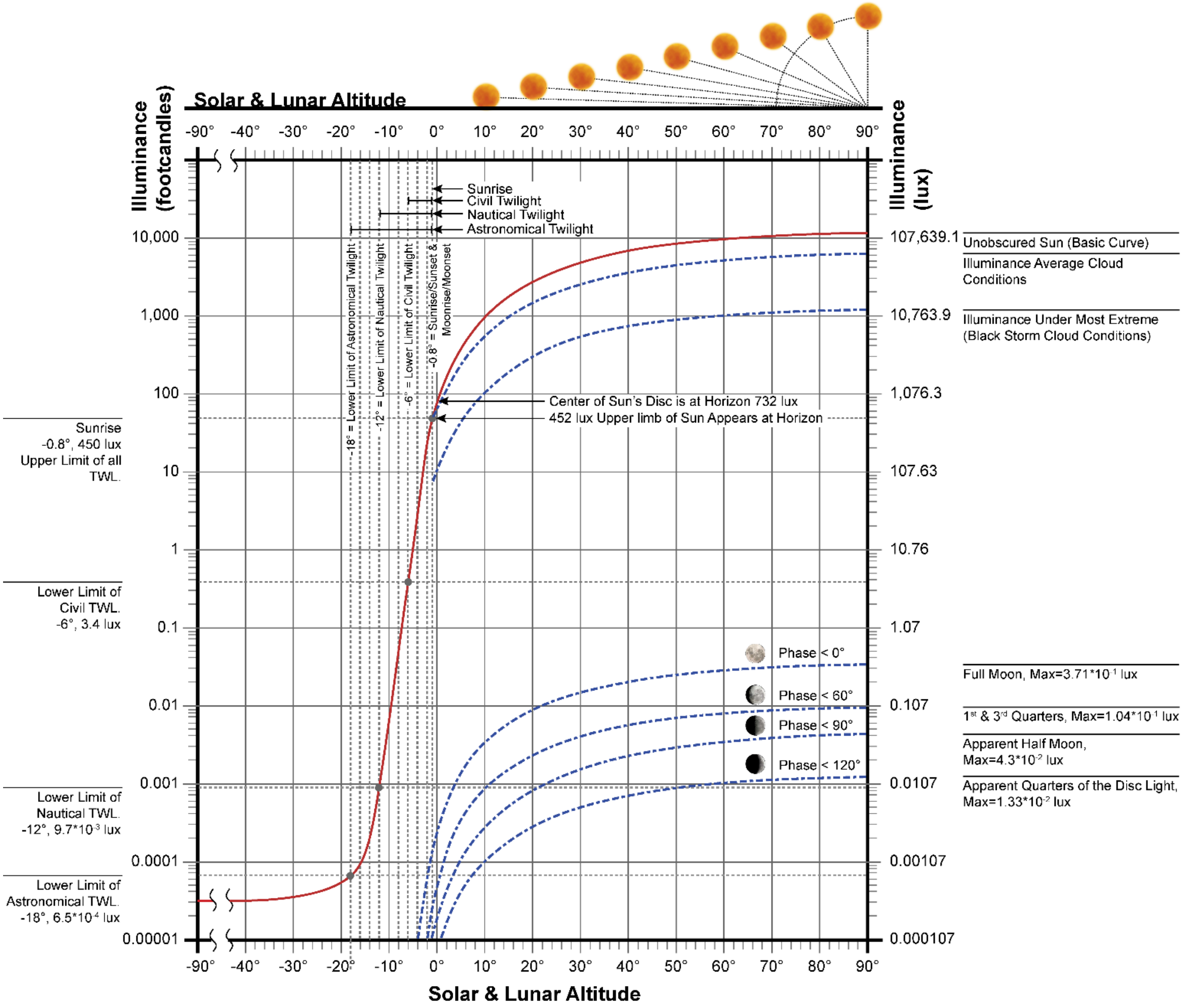


Figure 2. Global illuminance patterns versus solar and lunar altitude (Retrieved from Thorington [24])

Figure 3

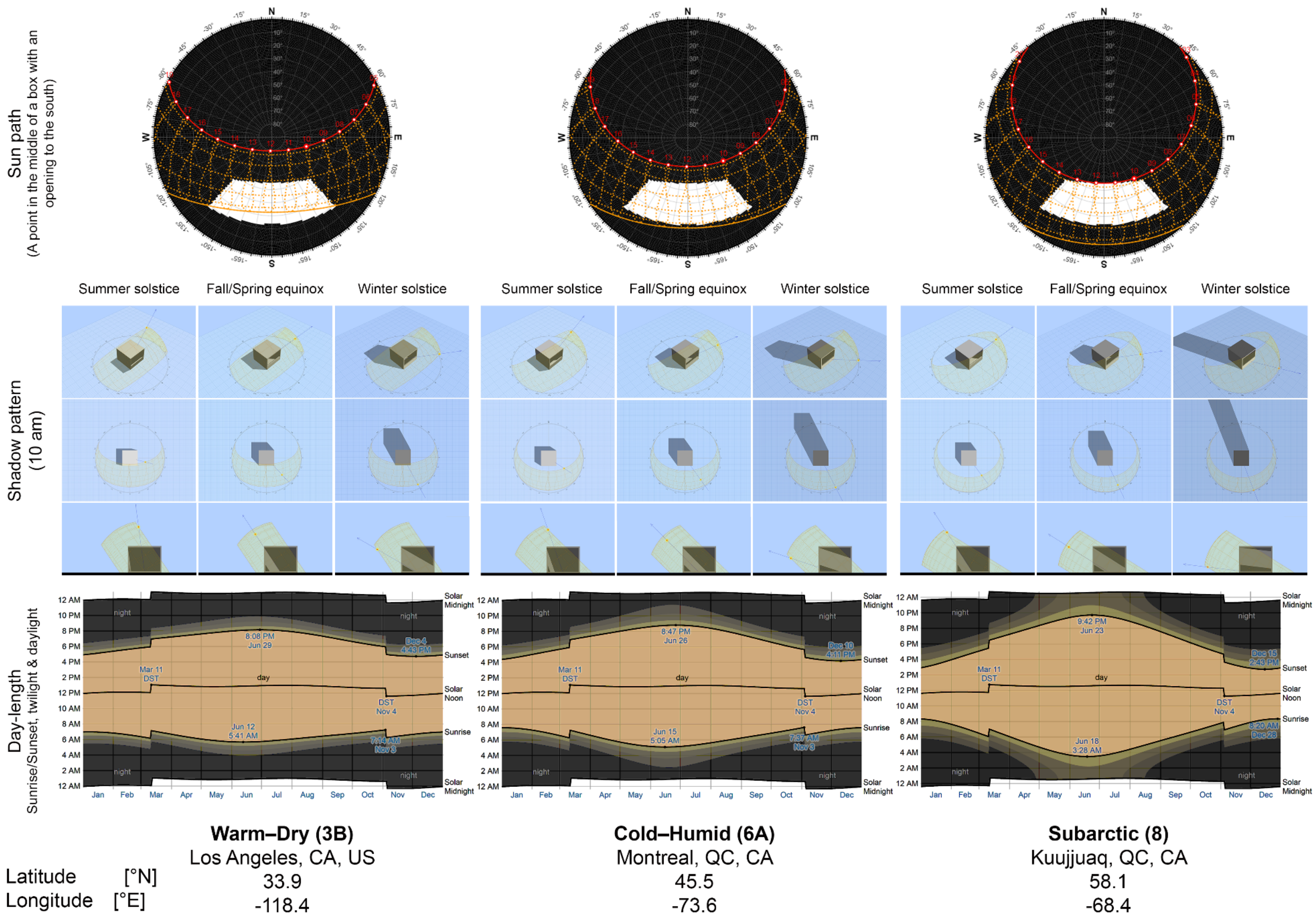


Figure 3. Lighting features of three North American cities located in different climates (meteorological data is derived from TMY-2 published by EnergyPlus and figures are derived by using weather spark [25] and online tools offered by Marsh [26])

Figure 4

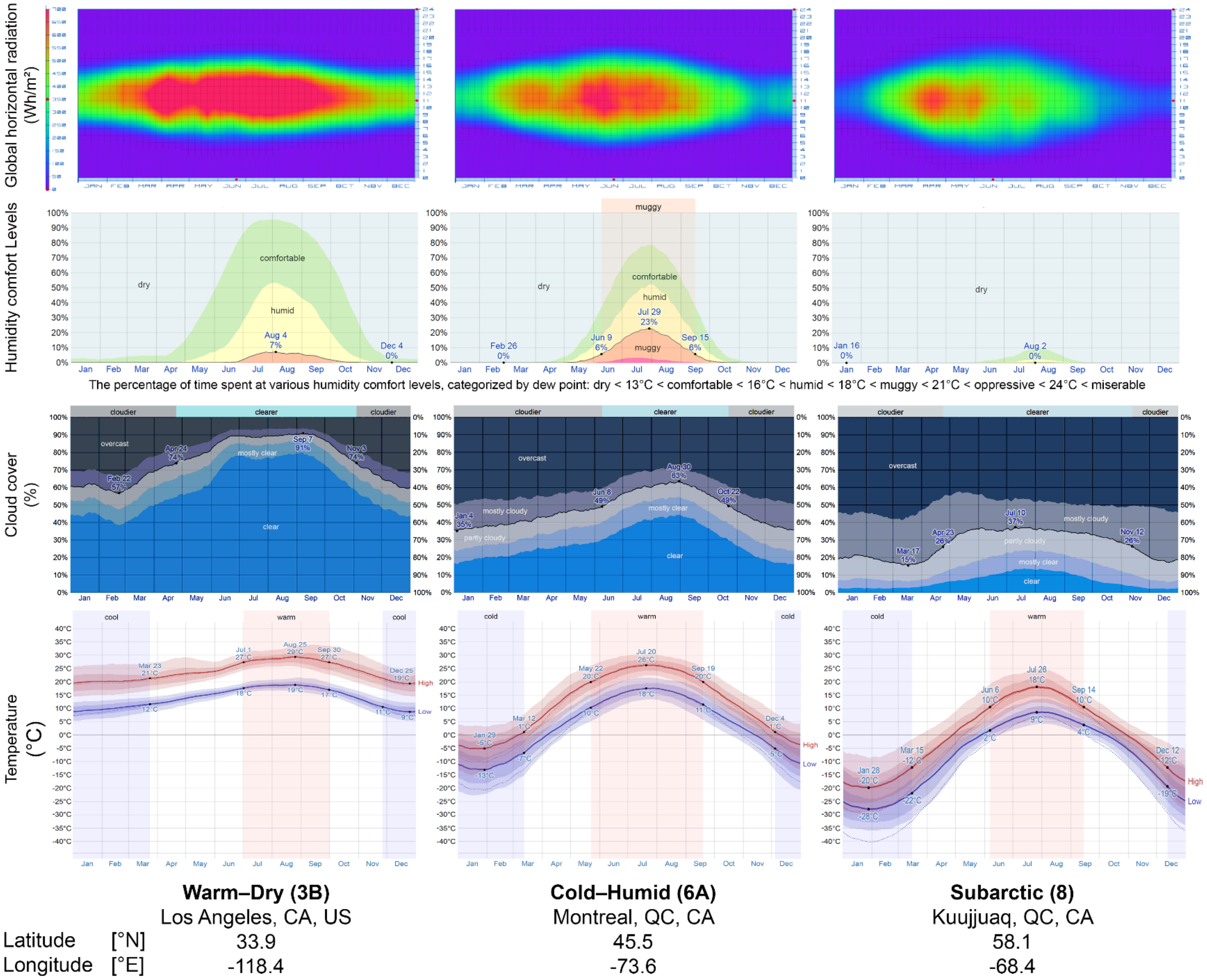


Figure 4. Thermal features of three North American cities located in different climates (meteorological data is derived from TMY-2 published by EnergyPlus and figures are derived by using weather spark [25] and online tools offered by Marsh [26])

Figure 5

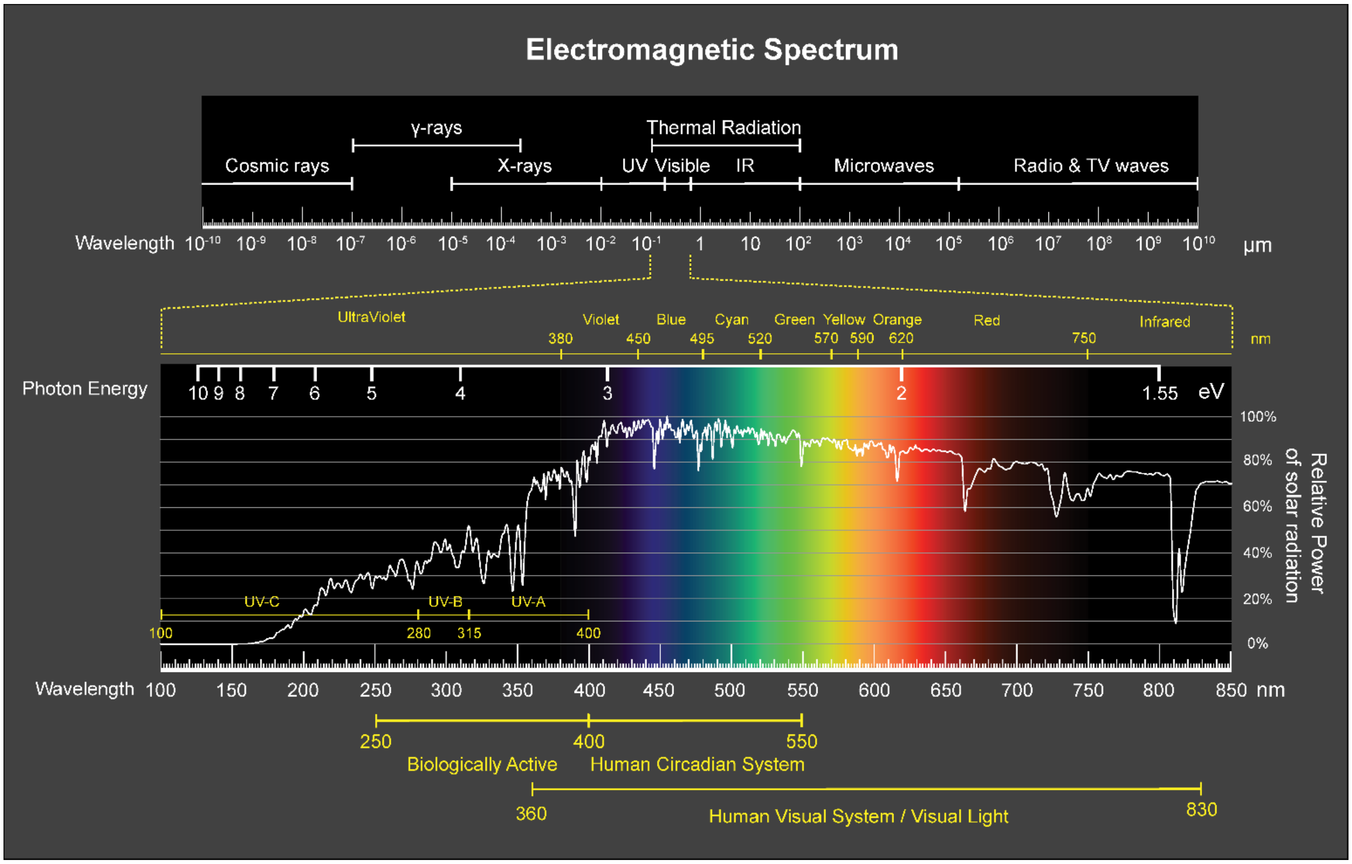


Figure 5. Electromagnetic spectrum and corresponding photon energy and relative power at each wavelength from 100 to 850 nm and the approximate color associated with those wavelengths. The graphs are based on the data given by [22, 40, 49, 55]

Figure 6

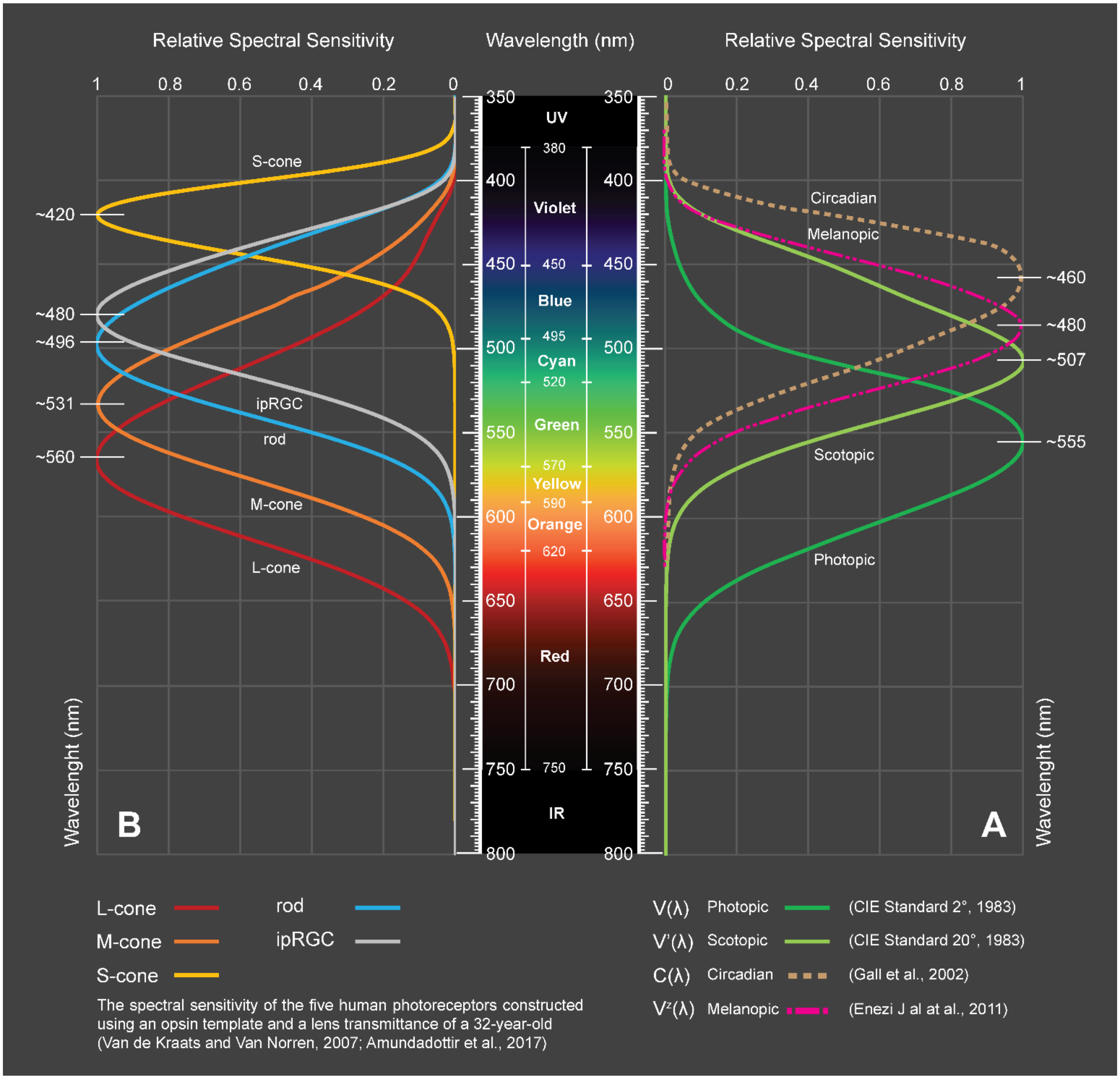


Figure 6. Normalized relative spectral sensitivity for **(A)** the functions of circadian $C(\lambda)$ [59, 63], melanopic $V^z(\lambda)$ [57, 59], scotopic $V'(\lambda)$ (CIE 1951), photopic $V(\lambda)$ (CIE 1924) [22] **(B)**; and the human photoreceptors [59, 64]

Figure 7

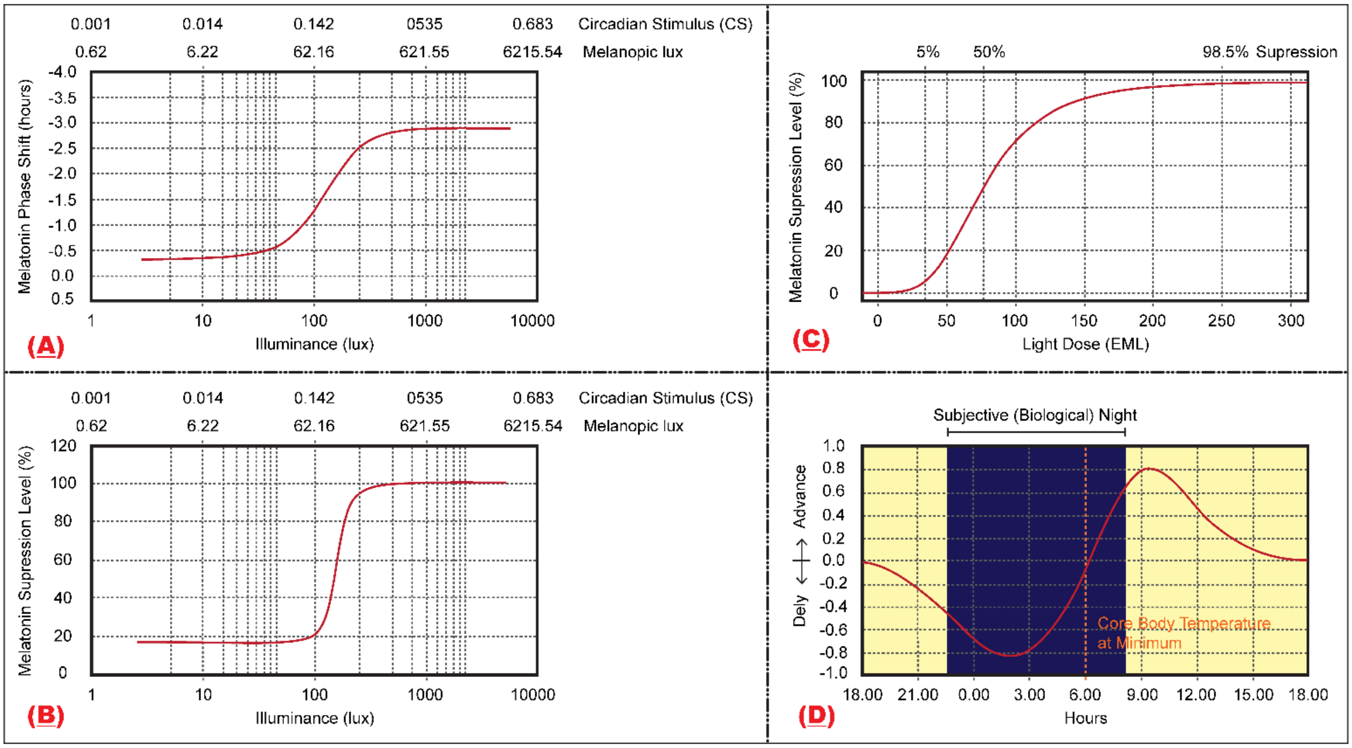
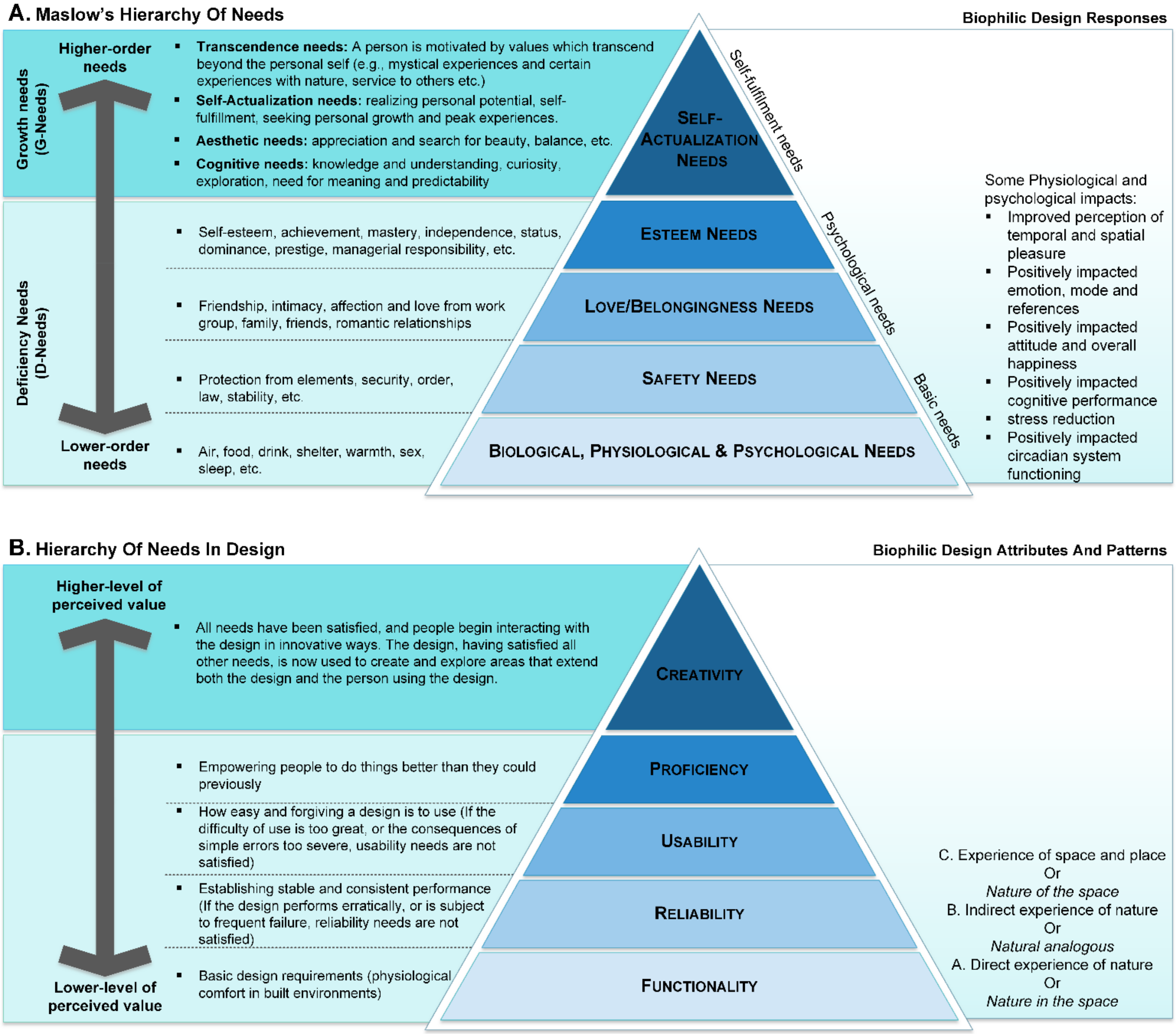


Figure 7. (A) Melatonin phase shift and (B) melatonin suppression versus illuminance, melanopic lux and circadian stimulus (CS) for a single 6.5-hour exposure of white light at the cornea from a 4100K fluorescent lamp during biological night. Figures are modified and reproduced based on the data given by DiLaura et al. [22] and publicly released calculators for melanopic lux and circadian stimulus conversion by Lucas et al. [81] and Rea & Figueiro [85], respectively. (C) Regenerated figure of melatonin suppression level versus light dose (EML) based on Konis [48]. (E)) Regenerated figure of circadian phase response of the pacemaker to time of exposure to optical radiation given by DiLaura et al. [22]

Figure 8



- **Transcendence needs:** A person is motivated by values which transcend beyond the personal self (e.g., mystical experiences and certain experiences with nature, service to others etc.)
- **Self-Actualization needs:** realizing personal potential, self-fulfillment, seeking personal growth and peak experiences.
- **Aesthetic needs:** appreciation and search for beauty, balance, etc.
- **Cognitive needs:** knowledge and understanding, curiosity, exploration, need for meaning and predictability

- Self-esteem, achievement, mastery, independence, status, dominance, prestige, managerial responsibility, etc.
- Friendship, intimacy, affection and love from work group, family, friends, romantic relationships
- Protection from elements, security, order, law, stability, etc.
- Air, food, drink, shelter, warmth, sex, sleep, etc.

Some Physiological and psychological impacts:

- Improved perception of temporal and spatial pleasure
- Positively impacted emotion, mode and references
- Positively impacted attitude and overall happiness
- Positively impacted cognitive performance
- stress reduction
- Positively impacted circadian system functioning

- All needs have been satisfied, and people begin interacting with the design in innovative ways. The design, having satisfied all other needs, is now used to create and explore areas that extend both the design and the person using the design.

- Empowering people to do things better than they could previously
- How easy and forgiving a design is to use (If the difficulty of use is too great, or the consequences of simple errors too severe, usability needs are not satisfied)
- Establishing stable and consistent performance (If the design performs erratically, or is subject to frequent failure, reliability needs are not satisfied)
- Basic design requirements (physiological comfort in built environments)

C. Experience of space and place
Or
Nature of the space
B. Indirect experience of nature
Or
Natural analogous
A. Direct experience of nature
Or
Nature in the space

Figure 8. (A) Maslow's hierarchy of needs and (B) interpretation relevant to biophilic design

Figure 9

						
Case	Headquarters of The Swiss Federal Railways	Sharifi-Ha House	Arab World Institute	Kiefer Technic Showroom	Al Bahar Towers	University of Arizona Cancer Center
Location	Bern, Switzerland	Tehran, Iran	Paris, France	Bad Gleichenberg, Austria	Abu Dhabi, UAE	Phoenix, AZ, USA
Function	Office	Residential	Cultural	Office	Residential tower	Medical/ Educational
Climate	Cold	Cold	Temperate	Temperate	Hot & humid	Hot

Figure 9. Examples of adaptive buildings and envelopes (photo courtesies are given in Appendix A)