Aalborg University Copenhagen

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Title: Sharing The Night: How can we design outdoor lighting and darkness which balances needs for humans animals and plants?

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Abstract:

The artificial light at night has been shown to negatively impact the environment, yet these issues remain underestimated. Finetuning of the lighting spectrum can be used to hinder the negative effects of light overuse. However, there is a dilemma rising between the needs of wildlife and humans. While the environmentally acceptable lighting is ecologically advantageous, humans might experience negative emotions due to its red appearance. This thesis approached this problem with use of mixed methods, consisting of qualitative and quantitative data collections. Tests were conducted in both controlled and outdoor environment. Qualitative data showed that use of red light causes people to expect their visual abilities to worsen, while quantitative dataset showed this was not true. Further, there was a pattern found regarding the importance of awareness about environmentally friendly lighting solutions. There might be thus a need for the general public to be informed better about the importance of environmentally appropriate lighting. This could further change market and demand, allowing such lighting to be implemented on greater scale.

PETR BOTEK
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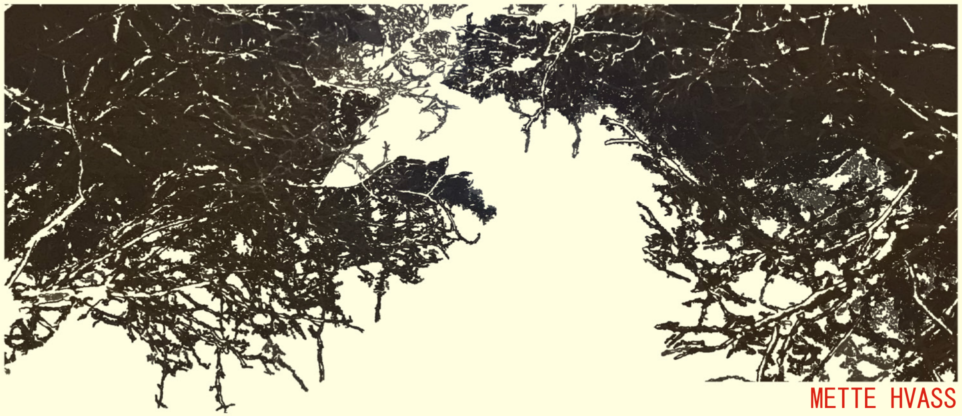
sharing the night



METTE HVASS

AAU CPH 2025

The artificial light at night has been shown to negatively impact the environment, yet these issues remain underestimated. Finetuning of the lighting spectrum can be used to hinder the negative effects of light overuse. However, there is a dilemma rising between the needs of wildlife and humans. While the environmentally acceptable lighting is ecologically advantageous, humans might experience negative emotions due to its red appearance. This thesis approached this problem with use of mixed methods, consisting of qualitative and quantitative data collections. Tests were conducted in both controlled and outdoor environment. Qualitative data showed that use of red light causes people to expect their visual abilities to worsen, while quantitative dataset showed this was not true. Further, there was a pattern found regarding the importance of awareness about environmentally friendly lighting solutions. There might be thus a need for the general public to be informed better about the importance of environmentally appropriate lighting. This could further change market and demand, allowing such lighting to be implemented on greater scale.

Thanks to Mette Hvass for the guidance and
Louis Poulsen for the borrowed lamp.

“I saw the days of the year stretching ahead like a series of bright, white boxes, and separating one box from another was sleep, like a black shade. Only for me, the long perspective of shades that set off one box from the next had suddenly snapped up, and I could see day after day after day glaring ahead of me like a white, broad, infinitely desolate avenue.”

_Sylvia Plath in The Bell Jar

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INTRODUCTION

Outdoor urban lighting design is a complex issue. It involves multiple aspects (perception of safety, lighting pollution, aesthetics, energy consumption, and others) that must be efficiently balanced to make sustainable decisions (Masullo, 2022). Artificial lighting systems account for about 19 % of global electricity usage (Zissis, 2016; Shahzad, 2016). In this regard, outdoor lighting or so-called public lighting systems (PLS) consume 3.23 % of the electricity produced in the world, as shown in Figure 01 (Sadeghian, 2024). The electricity for public lighting is produced by burning fossil fuels, making it an environmental pollutant and a direct contributor to climate change.

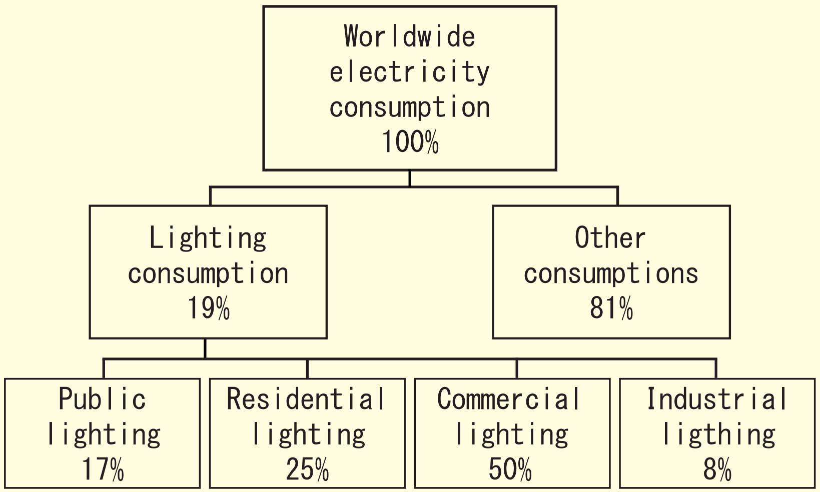


Figure 01_Share of public lighting from worldwide electricity consumption, adapted from Sadeghian (2024)

Lighting is usually communicated as a means of providing vision and visual clarity. However, it can also be seen as a way of countering the conditions of darkness. Sumartojo (2020) comments on the importance of darkness and how it enables us to reach beyond our usual ways of experiencing the world, adding a different dimension to our spatial perception and understanding our surrounding environment. Generally, the majority of conceptual understandings are yet made by humans, for humans. There are other actors existing in the lit spaces, being involuntarily influenced by human-made, long-term nature interventions. Even though most organisms have adapted in time to utilise daylight as a source of energy and/or information (Hirt, 2023), relatively new (within evolution scope) phenomena of artificial light at night (ALAN) affects both wildlife and humans in unprecedented ways (Emmers, 2018; Allen, 1880). Among the most acknowledged areas impacted by ALAN belong the locomotor activity and sleep patterns. Nonetheless, hormones, core body temperature in endotherms, metabolism, immune function, and several other physiological and behavioral processes critical for survival also have rhythms coordinated by light/dark exposure (Emmers, 2018)- regarding all forms of life, all living systems. Humans, being evolutionary diurnal animals, are spreading their daily activity time frame into night time with use of artificial light. A significant portion of all animals being nocturnal (28% of vertebrates and 64% of invertebrates worldwide) (Hölker, 2010), is affected by this. Thus, the negative effects of outdoor lighting presents a prominent issue within the lighting industry today and its implications on the environment.

ALAN gained prominence in the early 20th century when humans have come to expand their presence into night hours. Thanks to technological advancement, long distance and efficient transportation of electrical current became available and lighting powered by electricity became widely accessible. Reasonings behind this shift into nighttime activity are multiple, with prolonged working hours being the most prevalent argumentation today.

This led to great increases in numbers of lighting sources and overall illumination of public space, slowly closing the gap between visual properties of night and day. However, cycles of light and darkness do serve as important physiological cues. As generations change, gradual increase in urban outdoor lighting has managed to pervade the daily life of virtually every species of urbanized regions in the world, up to the point where it often may no longer be part of conscious experience (van Rijswijk, 2018). In humans, for example, exposure to extensive amounts of light in evening time and/or nighttime has been proven to disrupt circadian physiology, suppress melatonin secretion, impair sleep, and stress the visual system (Lunn, 2017). However, most inhabited areas of today are still in use 'after hours' and thus have to be artificially illuminated to support and essentially enable their intended daytime functionality. The ALAN provides many important functions in urban societies including aiding wayfinding, supporting feelings of safety and security, enabling outdoor activities, accenting historical and architectural heritage, and promoting economic development by enhancing social interactions (Casciani, 2020). All these anthropocentric advantages essentially span off from suppressing darkness.

The very meaning of the abbreviation "ALAN" pinpoints how unnatural (artificial) lighting at night is. This poses self-inflicted adverse effects on humans, but also many other stakeholders, who are affected by this without any substantial recognition. ALAN is shown to be very influential already, while its use is growing globally in time. Expectedly, the pattern of expanding daytime seems to be following the economical growth, originating in the global west, and spanning through economical metropolises of today (Widmer, 2022). In European countries, light pollution is increasing at a rate of 2 % to 10 % each year (see Figure 02). Recent global surveys of night sky brightness have concluded that 23% of land surfaces between 75° N and 60° S, including 88% of Europe and 47% of the United States, experience "light pollution" in the form of an increase in night sky brightness at least 8% above the natural level (Falchi, 2016) and that this artificial illumination is gradually invading biodiversity hotspots (Guetté, 2018).

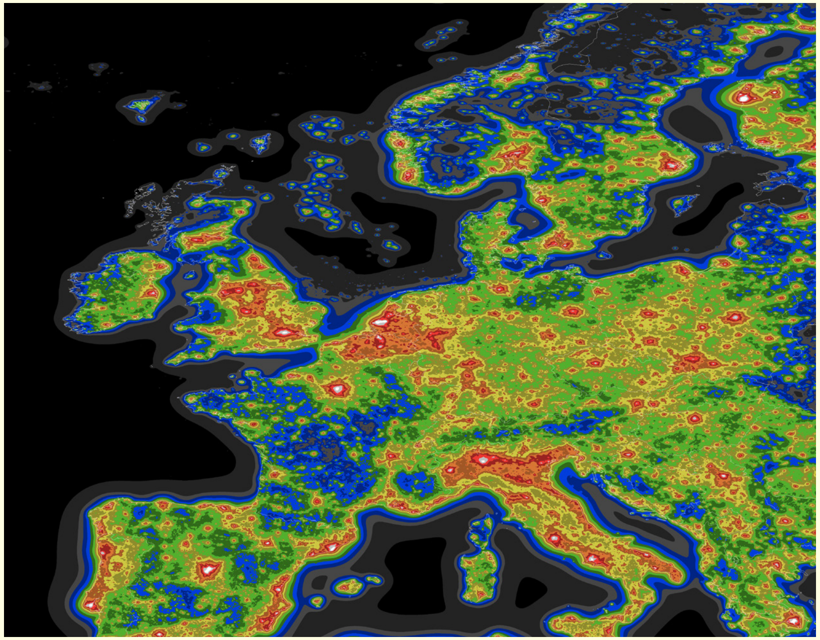


Figure 02_Light pollution map of Europe (Lorenz, 2024)

As mentioned above, artificial light has been used to illuminate the night-time environment for over a century. During this period, numerous alternative lighting technologies have arisen, each emitting light with unique spectral characteristics (Elvidge, 2010). One of the important players within technological progress has been the invention and subsequent evolution of light emitting diodes (LEDs). Most commercial white-coloured LED street lamps emit more of their light in the blue region of the visible spectrum than do other ALAN types (see Figure 03). This progression into the general prevalence of blue spectrum is important, as exposure to blue light at night has been recognized to cause increased health risk in humans, as well as other organisms and the ecosystem stability. Contrary to knowledge of these negative effects, the reduction of illumination energy requirements that LED technology enables, has also been responsible for the steady increase of illuminated areas at a rate averaging 2.2% per year (Kyba, 2017).

An impactful parameter of lighting within the wide range of PLS effects is its spectral qualities. As Rea (2009) points out, for example, an important fact to account for is metal halide light sources (“cold white”) result in increased brightness perceptions compared to the illumination of high-pressure sodium lamps (“yellowish white”) when same in illuminance value. This is caused by a change of spectral sensitivity of the sensory cells of the eye after the activation of scotopic vision. The rods have a different wavelength sensitivity, causing blue objects to appear brighter and red objects to appear darker. This phenomenon is called the Purkinje shift (Jacobs, 2015). Accounting for Purkinje shift is rather divisive in the implementation process, as it makes lighting more visible with higher blue content and thus possibly more energy saving friendly. On the other hand, it has been proven to be more disruptive to circadian rhythmicity and have a more severe effect on other living organisms compared to warmer lighting.

This has been, mostly within academia, recognized as an issue and is being analysed and solutions are being researched (Pérez Vega, 2022; Méndez, 2024; Burt, 2023). Multiple approaches on how to tackle this abrupt night illumination shift are generally being divided into either further technological progress (smart lighting), or learning from natural rhythms and translating them into design and technology (migration corridors).

Different actors of living systems-plants, animals, humans, each have different motivations to utilize light and different ways of perceiving this light in their daily rhythms. The cycles are, however, for all actors similarly directed by the spectral composition of the light itself, which formulates the research question.

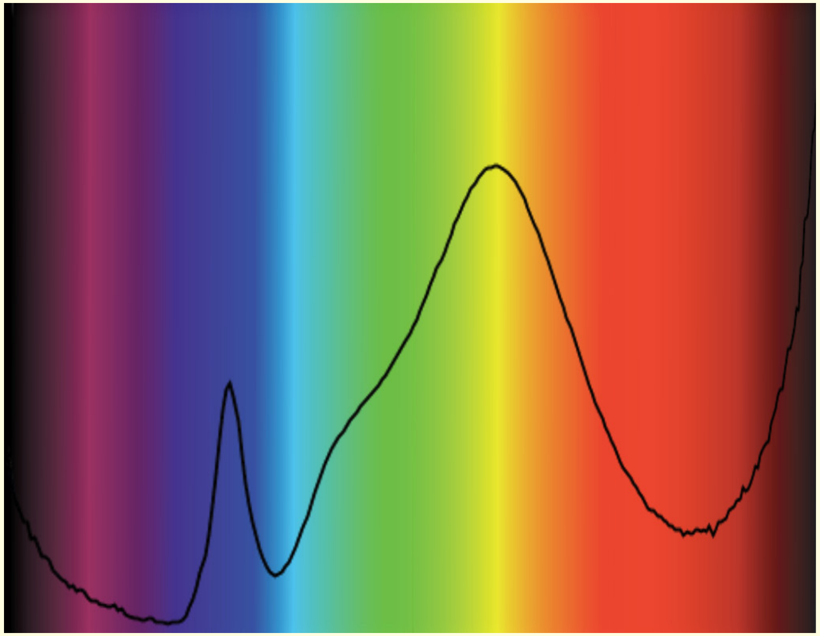


Figure 03_Spectral distribution of common 3000K streetlight

RESEARCH QUESTION

The stance of this thesis is stemming from a variety of living systems using everyday light in different ways. However, the daily rhythms and their perception are similarly to all species directed by the composition of light. This composition can be defined as the amount and ratio of different wavelengths in the electromagnetic radiation that is being perceived by a given organism. This set of different wavelengths spans from short wavelengths of UV (ultra violet), to long wavelength IR (infrared) radiation. In between UV and IR is the visible spectrum for most of the organisms. Therefore, the thesis is dealing with the spectral composition of light placed in public spaces, where it directly influences the living systems and their wellbeing.

Thus, this thesis is aiming to investigate:

Site Specificity - The site specificity in the context of this thesis is linked to the species composition in the area. Focusing on specific requirements (light perception, rhythmicity) of the present species can further inform design about who are the main stakeholders and how can we mitigate the negative impact.

Balancing Spectral Needs - The spectral needs vary throughout the day. The design can support morning commuters with high energy lighting, whereas later at night, it might be more suitable to different species- based on who is the dominant user of the site at that given time throughout the day, month, year.

Ecological Nighttime Environment - A healthy lighting environment accounting for the needs of all users of the site.

How can site-specific lighting design balance the spectral needs of humans, plants, and animals to create ecological nighttime environments?

METHODICAL APPROACH

Aa s baseline, this work accumulates the existing knowledge regarding the topic of ecological nighttime environments with focus on lighting. Following literature study shapes a theoretical base and indicates certain knowledge gaps. From the lighting design perspective, spectral power distributions are to be a driving parameter for all actors in the nighttime environments and thereby require attention within the literature study. The following terms were used to search efficiently using academic search engines:

‘lighting spectrum’ and ‘plants’ or ‘animals’
‘perception of light’ and ‘plants’ or ‘animals’
importance and darkness
‘circadian rhythm’ and lighting
urban and lighting
‘obstacle detection’ and pedestrian
‘safety perception’ and darkness
‘monochromatic red lighting’ and ‘safety perception’

After the initial search, the snowballing method was applied in case the articles were referring to other relevant documents. Beyond that, information from diverse initiatives, local and national guidelines, was compiled for a better understanding of legal directives regarding public lighting (see Appendix).

This thesis practical methods are divided into four parts - site scouting, site analysis followed by laboratory tests and on-site lighting intervention.

Site scouting was observational. Due to the lack of cohesive and unanimous definition of urban areas matching our interest, a decision was made to set our own criteria based on which the final site has been selected. The site had to be in the form of a park with present wildlife, but still used by people during the day and night.

Later, site analysis was of an explorative nature. All available documents and local development plans were compiled. This compilation served as a base understanding of the space (beyond the personal observations) and showed a range of restrictions and possibilities within the parks in question.

Then, the laboratory test was conducted following DS/EN 12464:2021 measuring standards.

Lastly, the site intervention tests were participatory. A set of tasks for the quantitative collection of data was applied. One of the site tests and its methodology was inspired by de Lange (2022) and his study about obstacle detection in real outdoor scenarios. Further, for combined data collection, a brief questionnaire with two types of questions was used. The first type of questions were closed questions with predefined answer possibilities that helped with mainly quantitative data collection. The second type of questions were open-ended questions, where participants could express their own opinions and feelings regarding the intervention and thus served as a source of qualitative data (see Figure 04).

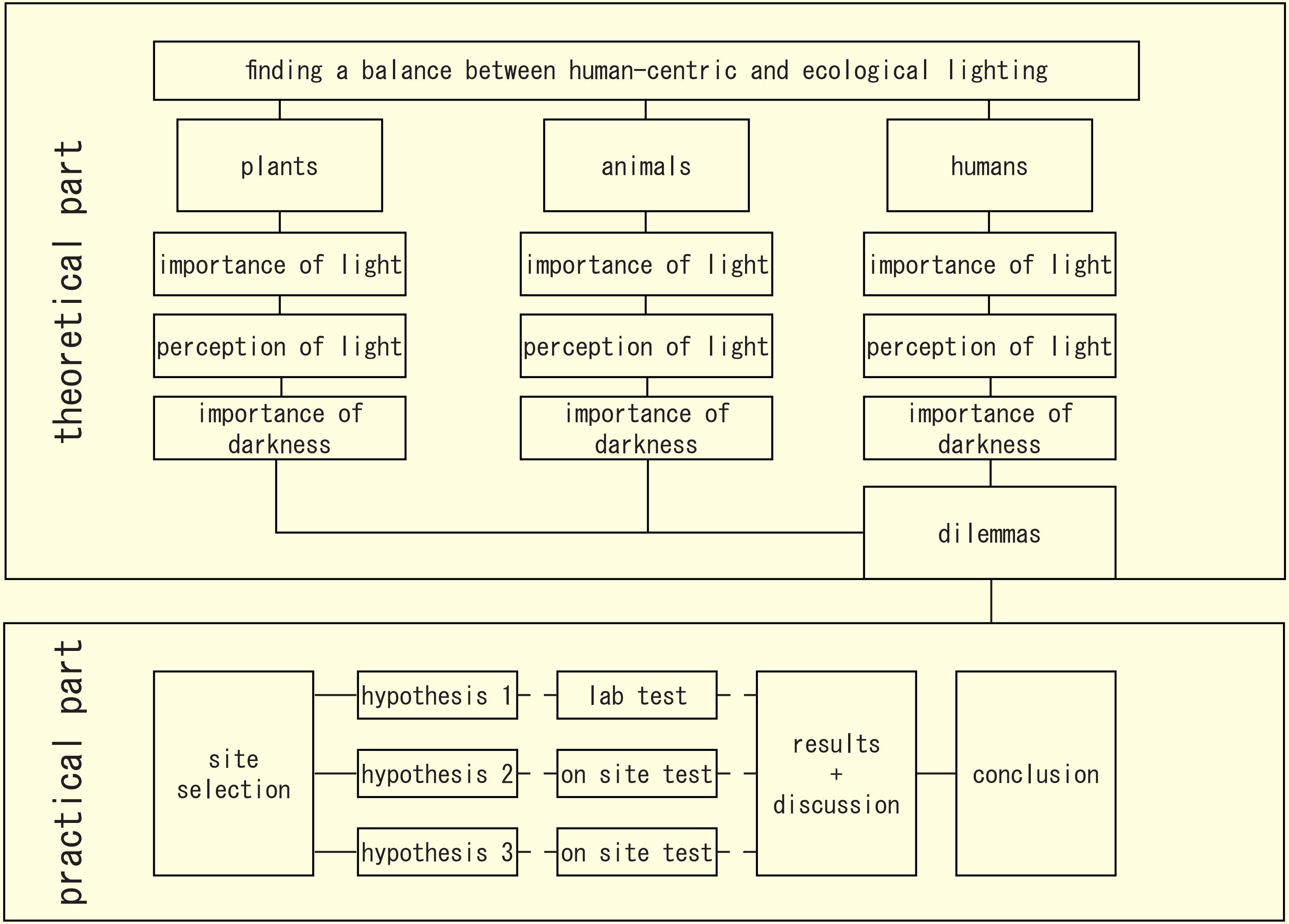


Figure 04_Scheme of thesis tasks

THEORETICAL PART

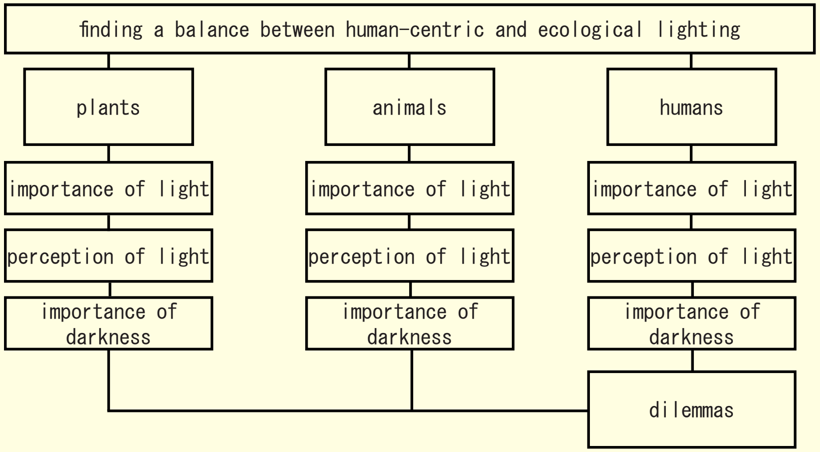


Figure 05_Scheme of theoretical part of thesis tasks

The theoretical part of this thesis summarizes the knowledge on the importance of light, darkness, and perception of light for different kinds of users. Described users are divided into three main groups: plants, animals, and humans. All of these groups have different apertures for perceiving light and utilize lighting in different ways. Finally, this body of knowledge is translated into dilemmas arising when designing for ecological nighttime environments (see Figure 05).

PLANTS

IMPORTANCE OF LIGHT

Light is an essential element of plant survival because it provides both the energy required for growth and information about the surrounding environment (Kang, 2020). Importance of light radiant energy is utilized by plants in two distinct ways: as a source of energy and as a source of information. Compared to other environmental cues plants have a reactionary system adapted for, light is highly informative, as it carries a high level of detail. Unlike other existing factors such as gravity, temperature, water, nutrients, and wind, which provide data in fewer dimensions, light conveys information across at least four dimensions: quality, quantity, direction, and periodicity (Hart, 2012). Quality provides insights into lighting composition in terms of spectral range and wavelengths. These qualities change with location, for example in shaded or underwater environments, and affect plant form and growth habit. For instance, high content of blue wavelengths in the spectral composition can promote compact growth and increased leaf expansion. Similarly, plants have developed a system for detection of shaded environments through incoming spectral composition within the red wavelengths and their corresponding ratios. When a plant detects a low ratio of red to far-red light, it often signals crowded conditions or above-canopy shading. This ratio stimulates elongation in stems or internodia in order to escape shade conditions (see Figure 06). Light quantity is a source of information that changes dynamically with climate, season, or habitat, and influences resource allocation and tissue distribution. Shaded plants tend to develop larger and thinner leaves to capture more sunlight, whereas plants in locations with substantial sun exposure often invest in smaller in area, thicker leaves to optimize resource use and prevent light stress (Hogewoning, 2010). Light quantity also plays a role in carbon allocation strategies. Under low light conditions, plants prioritize shoot development to enhance light interception, while high-light conditions can encourage a stronger root system to support increased metabolic supply. Directionality of incoming radiation onto the plant provides spatial information on the relative positions of both the light source and the receiving plant tissue. This has a direct influence on phototaxis (plant movements) and plant phenology (timely changes), and allows the plant to position its organs more efficiently for capturing radiation to enhance the effectiveness of photosynthesis. Periodicity is a temporal cue, affecting both short- and long-term cycles. It provides necessary insights into seasonal progression and triggers physiological responses that prepare the plant for upcoming environmental changes, such as leaf fall or budburst. As temperatures may vary abruptly due to weather extremes, light-based signals offer the plant response system more consistent information for timing of biological events.

Light serves not only as a provider of behavioral cues, but also a primary energy source through the process of photosynthesis. Lighting properties influence photosynthesis on multiple levels, with both immediate and cumulative effects reflecting in plant health and growth rates. The spectral composition of light plays a major role in photosynthetic efficiency, as plants have evolved to respond to the full range of visible spectrum and beyond (from UV-A to far-red) to ensure a complete understanding of surrounding conditions. Photosynthesis is activated by the absorption of photosynthetically active radiation (PAR). PAR is expressed in units of photosynthetic photon flux density (PPFD) as $\mu mol/m^2/s$. The total amount of absorbed light over time is referred to as the daily light integral (DLI) and is expressed in $mol/m^2/day$. Optimal DLI levels vary greatly between species, depending on their ecological origins. In relation to photosynthesis, plants operate within predefined thresholds. The light compensation point is the minimum light level at which photosynthesis equals respiration. Below compensation point, the plant consumes more energy than it produces. On the other end of photosynthesis efficiency, the light saturation point defines the maximum effective level, above which further light input no longer improves photosynthetic production apparatus. These differences in light utilization are reflected in a range of growth strategies. Plants in high-light environments having compact, thick foliage with low surface area, whereas shade-adapted species exhibit larger, thinner leaves to improve light capturing ability. Structural differences also include shifts in root-to-shoot ratios and carbon allocation strategies, which are linked to light access and energy requirements. In the case of low-canopy plants, lighting requirements are typically less demanding, as these species have adapted to grow in the shade of taller vegetation. Many perennials adapted to forest understories grow slowly but persist over time with minimal light, while fast-growing annuals are often more light-dependent and adapted to open habitats.

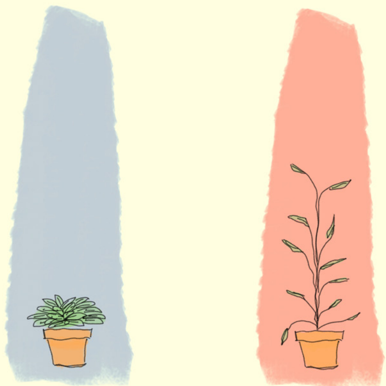


Figure 06_Illustration of light spectrum effect on plant growth

LIGHT PERCEPTION

Plants perceive light with the use of photoreceptors located within the plant above-ground tissues. Generally, light quality is quantified using color segments: ultraviolet, blue, green, red, and far-red (Gallemí, 2016; Kang, 2020). Plants have photoreceptors for each waveband: phytochromes for red and far-red, cryptochromes and phototropins for blue and UV-A, and UVR8s for UV-B (Franklin, 2010; Possart, 2014; Montgomery, 2016)(see Figure 07).

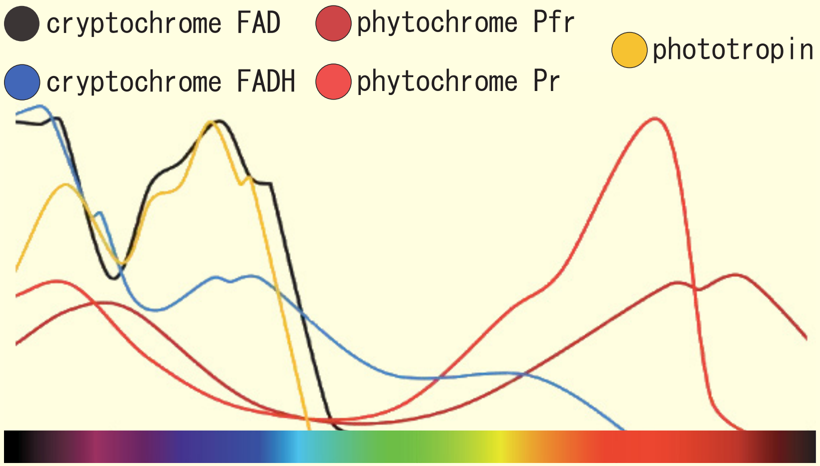


Figure 07_Plant photoreceptors with corresponding absorbtion curves (Battle, 2020)

The phytochrome photoreceptor system acts as a biological light switch, with a peak absorbance in red wavelength of 665 nm and far-red wavelength of 730nm (Franklin, 2010). It monitors the level, intensity, duration, and color of environmental light by shifting between two chromoproteins- phytochrome r (Pr) and phytochrome fr (Pfr). The ratio of Pr and Pfr is the cornerstone of long-term light perception and seasonality detection. As the daytime radiation involves more red radiation, Pr transforms into Pfr during the day. When exposed to darkness (night, shade), longer wavelengths prevail and biochemical processes slowly transform Pfr back into Pr (see Figure 08). The ratio of Pr and Pfr is monitored at all times, triggering a cascade of biological processes.

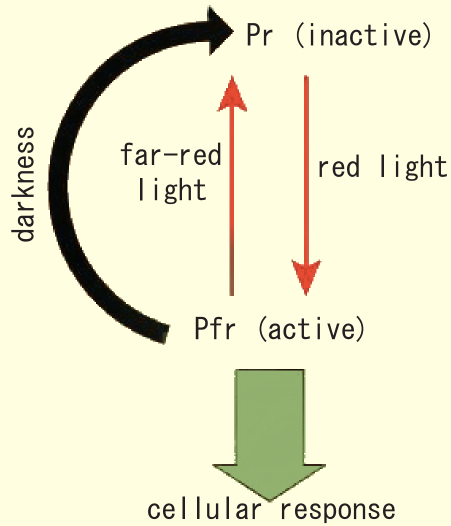


Figure 08_Phytochrome activation scheme (Clark, 2018)

Phototropin receptors are most reactive with radiation of blue wavelengths, with a peak at 445 nm, and are primarily responsible for phototropism, enabling plants to orient growth towards a radiation source. Phototropins are crucial for optimizing light capture by regulating stem elongation, leaf positioning, and stomatal opening. In response to directional blue light, phototropins initiate cell elongation, causing stems and leaves to bend towards the light source. They also play a key role in chloroplast movement within cells, adjusting their position to maximize photosynthetic efficiency under varying light intensities.

Cryptochromes function as plant rhythmicity regulators, acting as key components in the circadian clock and light-mediated developmental processes. Their absorption peaks lie in the short-wavelength range of the visible spectrum, primarily in the blue and UV-A range. Cryptochromes contribute to the process of de-etiolation- transition from skotomorphogenesis (growth in darkness) to photomorphogenesis (growth in light) by inhibiting excessive elongation and promoting leaf expansion. Additionally, they are also involved in the flowering timing, ensuring that floral initiation aligns with seasonal changes relative to daylight duration.

The plant science community is currently using different units (as mentioned above) compared to conventional light perception (illuminance and luminance). Namely, three related units:

photosynthetically active radiance (PAR)
photosynthetic photon flux density PPFD) (μmol/m2/s)
daily light integral (DLI) (mol/d/m2)

Importance of using different metrics is directly connected to photosynthesis and the absorbance peaks of the relevant photosystems. Human eye has a single peak in the green range (more on this later in text) and plants have two peaks, one in blue and second in the red range. This prevents efficient assessment of plant-suitable lighting with human-oriented metrics. As a rule of thumb, 200 μmol m-2 s-1 light flux density equals approximately 10000 lux (Dominici, 2021)

Responses of plant to light are spectrum-dependent. Red wavelengths lead to tissue elongation and shorter wavelengths to stunted growth and thicker tissues.

Plants do utilize most of the visible spectrum, but some wavelengths have more importance for the functionality, when most important wavelengths lie within the blue and red ranges. Red wavelengths, which are naturally absent at night, are typically present in artificial lighting. During the day, plants are exposed to a balanced spectrum of light, including red and far-red wavelengths, which influence their biological processes. However, when artificial lighting is added during the night, the red-to-far-red ratio is artificially restored, creating a “daytime-like” environment. Blue wavelengths serve as a non-harmful high-energy radiation well suitable for photosynthesis. UV wavelengths, similarly to the reaction of animals, are healthy to an extent and induce antioxidant production within exposed tissues. Shorter, higher energy wavelengths of UV-B and shorter harm plant tissues. The green wavelengths have been undergoing a reconsideration in terms of usefulness in the plant functionality and have gained credit for certain processes.

IMPORTANCE OF DARKNESS

The plant is affected by lighting in two time ranges, a long- and a short-term one. The short-term range can be tied to the daily photosynthetic process, whereas the long-term one influences seasonally induced changes in the plant structures. In terms of photosynthesis, during the lightless period, the plant still undergoes the respiration cycle and converts stored glucose into energy and uses it to repair and/or build tissue.

In case of the long-term effect of artificial illumination, ALAN causes artificial daytime prolongation and thus can also influence plant-perceived seasonal prolongation. Trees fail to recognize one of the primary cues to shift hormone production to dormancy (“cold season mode”) and thus become less resistant to winter temperatures. As the plants do not perceive (are prevented from perceiving) the lighting environmental cues, deciduous trees do not manage to lose their leaves in time for winter, which causes them to become weaker and more vulnerable to climate changes and/or pest infestations. These key processes of photoperiodism, leaf fall, dormancy and finally also seed germination are regulated by the amount of photoprotein phytochrome and its two forms. Primarily, illumination of urban areas (compared to rural areas with no outdoor lighting) directly influences the climate change impact within the cityscape. During spring, the combination of temperatures commencing earlier and extended photoperiod of illuminated trees and plants causes their leaves to bud prematurely (Meng, 2021). Ffrench-Constant (2016) found that budburst occurs up to 7.5 days earlier in brighter, light-polluted areas. This makes buds and new shoots more prone to frosts during the spring season. The health of urban trees and plants is important as they counteract air pollution by converting carbon dioxide into oxygen, reduce noise and the urban heat islands, and create ecosystems for other organisms such as birds, insects, and mammals. As mentioned above, light signalling also influences plant architecture, where lighting can induce uneven leaf fall, misshapen trees with a tendency of branches to snap off, and eventually influence the habitat options for other species. Furthermore, lighting and its effect on bud break can have adverse effects on plant populations as early-flowering species might not align with pollinators' activity and thus face uneven competition in future years in comparison with later blooming species. According to Bennie (2016), constant exposure of plants to light leads to disease susceptibility, and artificial lighting at night leads to increased sensitivity to ground-level ozone and leaf damage.

The issue with imitating nighttime through manipulation of the red:far-red ratio is that photosynthetic stimulation of red can not be counterbalanced by the addition of far-red. Additional far-red would result in triggering the shade avoidance response and thus alter the plant physiology in an undesired way. The only viable solution to simulate night for plants is with the use of low illuminance levels. The sufficient level for night illumination is to be found under the compensation point, but varies among species. However, it can be generalised for sun and shade plants. Sun plants' compensation point ranges from 10 to 20 μmol m-2 s-1, whereas corresponding values for shade plants are 1 to 5 μmol m-2 s-1 (Taiz, 2015). These values can be converted to human vision units of lux if the SPD of the used lighting is taken into account. For example, 1 μmol m-2 s-1 of natural daylight 6500K is equivalent to 43 lux. Thus, in the case of commonly used 3500K, where we have a higher ratio of non-photosynthetically active wavelengths, we need to provide 62 lux to reach 1 μmol m-2 s-1 of PPFD (waveformlighting.com)(see Figure 09).

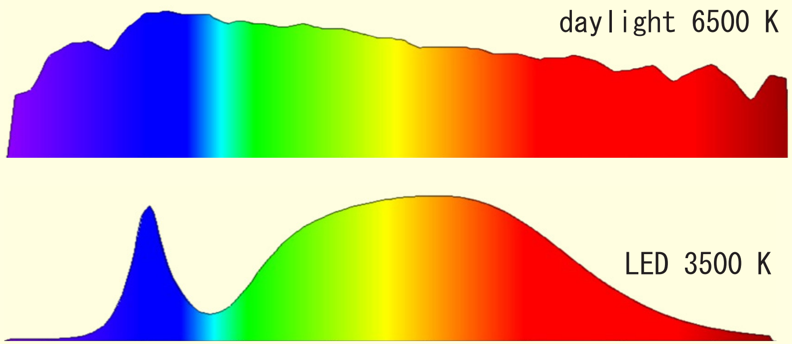


Figure 09_Spectral curves of 6500K and LED 3500K (waveformlighting, 2025)

ANIMALS

IMPORTANCE OF LIGHT

Diurnal species have evolved to use light and its intensity as a navigational and behaviour guide throughout the year, either on the visual (direct) or the nonvisual (indirect) basis (Bourgin, 2016). Birds, for example, use polarization patterns of the sky during sunrises and sunsets to calibrate their internal compasses for better orientation, especially in premigratory seasons (Muheim, 2006). So, besides the duration of the light exposure, they also orient themselves by the position of the light source - the Sun.

The presence of light and darkness cycles also helps the animals to anticipate the daily changes, also known as circadian rhythm (Bonmati-Carrion,2017). This approximately 24-hour-long rhythm is conducted by the light's duration, intensity, and spectrum. The spectral composition of the light is also important concerning biological responses in animals. The most prominent on diurnal species' activity is the short-wave spectrum of light (van der Merwe, 2019). Many studies involving circadian disruption by light utilize white light, but it is important to recognize that biological effects can vary with different wavelengths of light. Intrinsically photosensitive retinal ganglion cells (ipRGCs) are maximally responsive when exposed to wavelengths of light around 480 nm, corresponding to blue light, and least responsive to longer wavelengths of light, which appear red (Berson, Dunn, & Takao, 2002; Dacey et al., 2005; Lucas, Douglas, & Foster, 2001). The specific wavelengths of light that maximally activate ipRGCs can vary between species. For example, in chicks light of 560 nm elicited the strongest response, corresponding to green light (Jiang, Wang, Cao, Dong, & Chen, 2017).

Nonetheless, in general, long wavelengths of light in the red spectrum elicit the least response, whereas shorter wavelengths of light in the blue spectrum elicit the greatest response (Emmer, 2018)

Another nonvisual effect of light can be presented as the photoperiodic behaviour of most diurnal animals. Animals use the information about the length of the day and adjust their behaviour accordingly. Examples can be the mating season, when days become longer, and the hibernation or migration season, when days become shorter again. It could impose serious problems if animals are not able to correctly determine the upcoming season based on the cues they are used to sourcing their information from (Helfrich-Förster, 2024).

LIGHT PERCEPTION

Color vision, the ability of an animal to use the spectral composition of light independent of intensity as Der Kooi, 2021). However, the number of different wavelengths perceived differs throughout the animals. There are dichromats, trichromats, quadra- and tetrachromats. Dichromatic vision of diurnal animals is caused by presence of two types of cones in their visual aperture. An example of dichromate animal is horse, where there are present cones with peak sensitivity to short wavelengths around 428 nm and cones responsive to long wavelengths around 539 nm. These cones provide base for dichromatic colour vision (Carroll, 2001).

Trichromatic vision is vision similar to humans and mostly present in primates. This type of vision allows perception of three different wavelengths of light. The most sensible wavelengths are in S (short waves) in blue spectrum, M (medium waves) in yellow/green areas of visible spectrum and then

L (long waves) in red end of the visible spectrum.

Tetrachromacy is the extension of the 3-coloured vision that is further developed in UV wavelengths of the usually non visible spectrum. Such development of 4th or more additional cones receptors is often linked to the environmental necessity of the specific species (Sabbah, 2013). This vision is usually present in birds and fish.

Mammals are most sensitive to light spectrum ranges of 400-500 nm, 450-630 nm, and 500-700 nm (Jägerbrand, 2018). Birds are most sensitive to light spectrum in ranges of 543-571 nm, 497-510 nm, 430-463 nm, and 362-426 nm (Hart, 2001). Furthermore, the amphibians are most sensitive to light of 430 nm and 500 nm (Stebbins & Cohen, 1995), and large amounts of insects are most sensitive to 350-650 nm (Briscoe & Chittka, 2001) (see Figure 10).

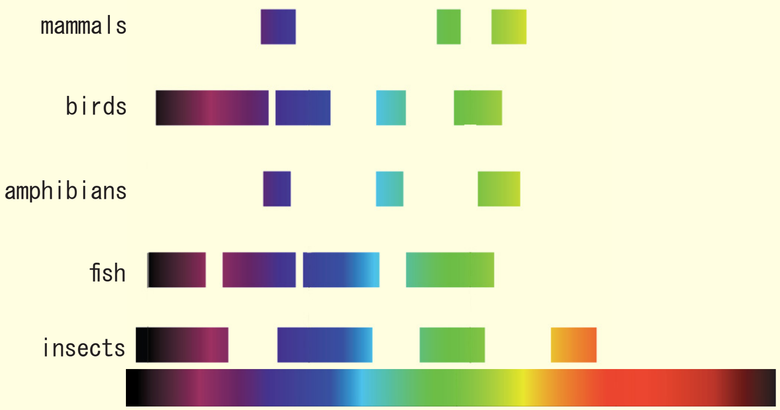


Figure 10_Vision spectral ranges of various animal groups (Bergan et al, 2024)

IMPORTANCE OF DARKNESS

Worldwide, around 30% of vertebrates and more than 60% of invertebrates are nocturnal (Hölke, 2010), of which a substantial part is being directly and/or indirectly affected by ALAN. Heinen (2023) has researched the effects of short-term reduction of illumination (i.e., turning lights off during parts of the night) and the effect on insect populations, which has been proposed as a potential mitigation strategy to improve general insect population health. However, an increased negative effect on population growth has been shown in scenarios when lights are temporarily switched off during the night compared to night-long illumination. This showcases the range of how lighting can affect an organism with effects being species and conditions-specific. Although some generalisations and rules of thumb have been made based on recurring result prevalence. Boyes (2021) found that street lighting strongly reduced species abundance compared with unlit sites (47% reduction in hedgerows and 33% reduction in grass) and also affected development. A separate experiment in habitats with no history of lighting revealed that ALAN disrupted the feeding behaviour of nocturnal caterpillars. Negative impacts were more pronounced under white LED streetlights compared to sodium lamps. This indicates that ALAN and the ongoing shift toward white LEDs (i.e., narrow-to-broad-spectrum lighting) will have consequences for insect populations and ecosystem processes. The night-time outdoor illumination of streets, buildings, and urban parks also attracts insects that can hasten insect decline (Boyes, 2021). Many of them are crucial for the pollination process, and without their contribution, humans and ecosystems would not survive, as 80% of food production requires pollination by other living organisms. Exposure during the nighttime to blue-rich white light has numerous adverse effects on the environment and can lead to problems with reproduction, the avoidance of suitable habitats, changes in seasonal migration routes, and a reduction in numbers or even the extinction of some pollinators (Cougnard-Gregoire, 2023). Findings of Boyes (2021) revealed that insect numbers attracted to different lighting technologies can not serve as a direct evaluation of their environmental impact, as has been previously done in other academic publications (Pawson, 2014; Wakefield, 2018) and that flight-to-light behavior is not the principal mechanism via which insect populations are negatively affected by ALAN. The extent to which insects are attracted to light varies according to several factors. It has been recognised for many years that shorter wavelengths are, in general, more attractive (Frank, 2006), when attractiveness peaks at wavelengths of 400nm (Cowan, 2009). The degree of attraction and preferred wavelengths vary (Merckx, 2014); typically, larger eyes are more likely to be attracted to light dominated by shorter wavelengths (van Langevelde, 2011; Somers-Yeates, 2013). Variation also appears to exist between sexes, where males of some species are significantly more likely to be recorded at light traps than females (Garris, 2010), affecting the mating (Altermatt, 2009). Effects of ALAN on nocturnal insects have been categorized by Owens (2018) as in Table 01:

ecological impacts	functional impacts
mortality	species attracted to light may be killed
migration	artificial light disturbs natural movement patterns, migration and orientiation
population size	reduced or increased foraging because of presence of light
indirect competition	light can benefit certain species at the expense of others
communication	light can disturb species communication
health and circadian rhythm	light can influence various physiological processes that can impact health and circadian rhythm

Table 01_Influences of ALAN on nocturnal insects (Owens, 2018)

ALAN sources can cause temporal disorientation on various time scales (circadian, circannual, and/or circannual). ALAN may cause temporal disorientation, desynchronization of organisms from their typical biorhythms. Most terrestrial species have circadian, circannual, and/or circumseasonal patterns of activity (foraging, reproduction, migration, etc.) that are synchronized to daily, monthly, and yearly light cycles. ALAN may also result in spatial disorientation, disrupting an organism's navigation abilities. In nocturnal landscapes, the lack of visual cues makes navigation difficult. For insects, the most constant landmarks of visibility are the moon and stars. Even though these cues vary throughout the night and seasonally, nocturnal insects use the moon or stars and calculate navigation. In this case, lighting can have a negative impact in two ways. Either in the form of astronomical light pollution-disrupting moon and star visibility, or ecological light pollution- introducing new light sources in the visual field of insects, new moons and stars. Many flying insects are attracted to ALAN through positive phototaxis. Some orbit around the light source, while others linger on or under the light. About 30%-40% of insects that approach streetlamps die soon thereafter, either because of collision, overheating, dehydration, or predation (Minnaar, 2015). Insects get lost in a "light sink" and become unable to search for mates or food, especially in cases of different sexes being disproportionately attracted to ALAN (Altermatt, 2016). As the nocturnal animals evolved for darkness, their natural vision is highly sensitive to low lighting levels and becomes saturated at modest light levels. Stark (1985) showed that when exposed to ALAN light sources containing short wavelengths, some insects may be temporarily dazzled or even permanently blinded. ALAN can hinder the ability of nocturnal insects to recognize objects, such as predators or food sources. This recognition ability is dependent on both the wavelength and intensity of the ALAN (Davies, 2013).

Macgregor (2019) has found that illumination only during part of night did not have a strong effect on pollination success or quality within researched nocturnal insects, and therefore may have less biological impact than lighting being on during the whole night.

Research by Davies (2013) examined the effect of various lighting sources (low pressure sodium, LEDs, high pressure sodium and metal halide) on various species groups (reptilia, mammalia, insecta, aves and arachnida) and clearly concluded that low pressure sodium lamps were significantly the least disturbing to all examined groups.

Similarly to insect behaviour, patterns of attraction and repelling response have been observed with birds. Birds are known to, similarly to some insects, aggregate around artificial light and collide with illuminated objects, which may be the result of attraction or disorientation. In other contexts, birds are also repelled by artificial light, as it can also change the perceptions of habitat quality, resulting in selection or avoidance of illuminated areas (Adams, 2021). Syposz (2021) showed that the repellence by artificial light also changes dynamically with the spectrum and intensity of the light.

Some species of birds possess a better low-light vision compared to others and thus might obtain predatory advantage. With use of ALAN however, this advantage might be hindered with possible ecological consequences. For example, Jolkkonen (2023) tested how the fear of predation was perceived by wintering Eurasian curlew foraging on tidal flats changed with lighting intensities. The flight initiation distance of individuals under varying levels of natural and artificial illumination was significantly reduced at low light levels compared to ALAN.

Furthermore, bats, being the prime predators of nocturnal insects are being exposed to ALAN and thereby danger as their sensitive nighttime vision suffers under ALAN. The light-avoiding behaviour is then associated with the need to combat the predation risk caused by the poor vision. Some bats, however, might have adapted and begun to use the ALAN to their advantage and have been reported hunting for insects attracted by the lighthouse light (Cryan,2007; Voigt, 2017). Aversion to lighting by some species but not others has been reported to cause shifts in the composition of communities, potentially altering competitive balances from natural conditions (Seewagen, 2021). Foraging in illuminated areas also exposes the other nocturnally adapted species, such as owls, cats, diurnal hawks, crows, etc., to the risk of predation (Stone, 2009). Illumination of the bats' nesting and foraging sites for aesthetics or tourism has exposed these species to dramatic decreases in numbers (Patriarca, 2010; Katabaro, 2022). Pauwels (2021) points out the importance of public lighting planning and management to use the lowest amount of light possible, whilst considering pedestrians and vehicles to limit excessive lighting and light spillover into semi-natural habitats. There have been multiple approaches on how to limit the spill light, where a more directional flux of streetlighting results in less light spillover. Also, it is recommended to include shielding on the streetlight or to plant a hedge to reduce trespass (Kinzey, 2017). The most influential parameter is the placement of the streetlight. The decision to keep an installed streetlight or add a new one remains the most effective measure of light pollution (Pauwels, 2021). Apart from inland, animals living in water bodies are significantly influenced by ALAN, with 22% of coastal regions exposed to artificial light (Davies, 2014; Davies, 2020; Ayalon, 2021; Smyth, 2021). 20% of the world's Marine Protected Areas are exposed to ALAN (Davies, 2016; Marangoni, 2022). The potential for ALAN to impact the wide array of organisms, processes, and habitats in the sea for which light cycles are critical had remained largely unexplored until recently (Davies, 2014; Longcore & Rich, 2004). These processes include diel vertical migrations (Berge, 2020)-the largest migration of biomass on the planet (Hayes, 2003), coral spawning (Ayalon, 2021) and symbiosis (Ayalon, 2021)- are paramount for the survival of coral reefs, migrations and orientation of marine organisms (Navarro-Barranco, 2015; Torres, 2020); and the recruitment of sessile invertebrate larvae into marine habitats (Lynn, 2021). All mentioned processes are known to depend on the cycles, spectra, or intensity of sun or moonlight (Marangoni, 2022).

HUMANS
IMPORTANCE OF LIGHT

The importance of lighting to people is the ability to see surroundings, our environment, either static or in motion. Essentially, this perceptive ability enables us to stay safe. Safety, however, has many forms, and its true essence can not be objectively quantified, so it can be evaluated as one's feeling, as a subjective opinion based on both our current and lived experience. Lighting is long known to have a strong impact on this perception during nighttime, as it influences our visual ability. But whether it does affect the amount of actual crime can be easily quantified and has been done multiple times. However, the literature exploring the effect of lighting qualities on crime rates does not agree on any specific outcome. For example, Steinbach (2015) does not show any significant effect on crime, while Tompson (2023) talks of reduced crime in areas with reduced lighting. On the contrary, research by Fotios (2021) suggests that only certain types of crime are discouraged by the decreased visibility, while other types of crime may be even higher in lower lighting.

For example, after an energy-saving initiative in Essex County, Dunmow Broadcast newspaper published a series of dynamically evolving articles on this topic. On 3rd July 2008 first article was published under the name "Petition to turn the streetlights on", stating "A massive rise in crime has been recorded since the trial of a money-saving scheme plunged Dunmow into darkness at night. The scheme, by Essex County Council, was to save taxpayers' cash by switching off street lights between midnight and 5 am." (Dunmow Broadcast, 2022).

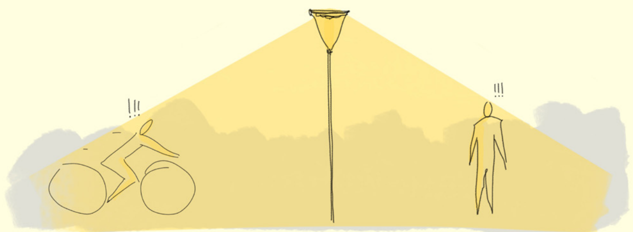
A week later, on 10th of July, an article "Correction: Crime is falling" was issued, stating: "The Broadcast wishes to retract a statement made in last week's article on street lights in Dunmow. In the story we stated "a massive rise in crime has been recorded". In fact, figures indicate that there has been a substantial fall in crime, particularly in the hours the street lights have been switched off." (Dunmow Broadcast, 2022).

Welsh (2008), in Fotios (2021), describes that improved nighttime lighting leads to decreased crime rates for two possible reasons. Firstly, improved lighting (in this case, meaning higher illuminance values) increases surveillance of potential offenders by improving their visibility to others. Lighting may also lead to an increase in people's usage of the space after dark, and hence surveillance of offenders is further supported by an increase in the number of people who might notice their behaviour. Furthermore, improved lighting enables people to see more clearly at greater distances: it enables the law-abiding to act, either assertive, preventive, or avoidant manner, and exposes the criminal to greater public scrutiny. According to the surveillance theory, improved lighting would result in decreased crime during the hours of darkness. The second theory talks of improved lighting as a signal of community investment in the area, leading to increased community pride, community cohesiveness, and thereby informal social control. Increased feeling in higher illuminance of safety also corresponds to findings of Himschoot (2024), where participants reported on 5,0 lux as safer compared to 0,5 lux. The same study also touched upon CCT, where warm lighting was perceived as safer than amber lighting.

In another study, Lis (2023) evaluated legibility as a paramount parameter of safety perception. It has been found that legibility increased with an increase in illuminance, but only of the background landscape. Increased lighting on paths did not prove to have any significant effect on safety perception. The positive effect of lighting in the background was specified as vertical lighting of elements, rather than horizontal surroundings.

As per Lis (2023) the safety perception did not increase with increased illumination of path. On the contrary, it lowered the preference among participants as the path was deemed with lower privacy. Furthermore, participants' preferences were tied with paths where the background was illuminated and made the surrounding landscape more legible.

The feeling of safety can be indirectly translated into our feeling of joy, usually perceived incautiously. Studies have shown that using participants' preferred lighting can generate positive emotions, increase satisfaction, or have a healing effect (Veitch, 2008). Low CCT and low illuminance lighting are more emotionally demanding, making people feel emotionally relaxed and at ease (Hao, 2017), while high CCT and high illuminance lighting make participants feel awake and focused, and are conducive to increasing the excitability and attention level of the brain when performing visual tasks (Kim, 2017). In the context of safety, both of these scenarios have been shown to trigger feelings of unsafety, as low lighting hinders the ability to see and high illuminance triggers the suspicion of previous mischief.



Other studies claim that white light high in Kelvin (metal-halide or LED light sources) permits facial recognition in pedestrian areas, increases well-being, and even activates commerce and nightlife because of its excellent chromatic reproduction (Raynham and Saksvikrønning, 2003).

In a study by Hao (2022), it has been shown that two factors (higher CCT and focused light) are positively correlated with perceived discomfort. Thus, for instance, Zhu (2013) showed that CCT of 3000 K is perceived as less glare than 6000 K. However, Sweater-Hickcox (2013) and Villa (2017) showed that the surrounding lighting might cause a diminishing effect with higher CCT. As to moderating factors, Villa (2017) showed that while engaged in walking, participants tend to rank discomfort lower than when standing and gazing. One of the further findings by Hao (2022) shows ambient temperature affects the perception and preference of lighting parameters (CCT, illuminance), when higher ambient temperature increases the preference for higher CCT. This correlates to the cultural phenomena of inhabitants of warmer environments having a preference for "cooler" lighting of higher CCT. Also supported by a study of Bellia (2021), where 163 volunteers were exposed to two different lighting scenarios of either warm (3000 K) or cool lights (6000 K), both at a fixed illuminance of 300 lx. Xu (2014) proposes that turning on the light can also trigger the hot emotional system (emotional reactions). A combination of six studies shows that ambient brightness makes people feel warmer, which increases the intensity of their affective response, including perception of aggression in others, and generates more extreme affective reactions toward positive and negative situations. Results suggest that these effects arise because light underlies perception of heat, and perception of heat can trigger the hot emotional system. Thus, turning down the light can reduce emotionality in everyday decisions, most of which take place under bright light (Xu,2014). This result can be translated into control of affective behaviour in public spaces.

Relating purely to outdoor lighting in a natural environment, a study by Masulo (2022) showed that high illuminance made people more nervous, whereas low illuminance made people feel calmer. On the other hand, low illuminance has made participants feel more tired than in other conditions. Overall, the combination of the cool CCT and high illuminance conditions produced the worst impact on participants. Masullo (2022) also found that high illuminance and warm CCT resulted in the worst combination at motivating participants to explore the park. High illuminance resulted positively only in making participants perceive the park as safer than other conditions, and this is reasonable because higher illuminance provides better vision at night. Nevertheless, this did not motivate people to explore the park. This seemingly contradictory finding can be explained by the fact that, as results suggest, although high illuminance promotes better vision, it can still be annoying and, when combined with warm lighting, even tiring. In other words, it is the specific combination of illuminance and CCT that determines whether a park will be explored or not. In line with this, Oi (2007) showed that different combinations of illuminance and colours were preferred based on the context of judgment.

Therefore, preferences can change based on the type of activity people are to perform (Masullo, 2022). Activity can be related to movement, where various movement types and speed of motion shift the perception of safety, partially due to focus adjusting to, for example, obstacle detection. In a study by Uttley (2020), locations with no road lighting showed a significantly greater reduction in cycling after dark compared with locations that had some lighting. A nonlinear relationship was found between relative brightness at a location at night and the reduction in cyclists after dark. Small initial increases in brightness resulted in large reductions in the difference between cyclist numbers in daylight and after dark, but this effect reached a plateau as brightness increased. These results suggest that only a minimal amount of lighting can promote cycling after dark (Uttley, 2020).

While cycling, driving or walking it is important that lighting provides a sufficient amount of illumination for safe obstacle detection. According to Fotios (2017) there was negligible reduction in obstacle detection when the light illuminance was decreased from 20 lux to 2 lux. However, once the illumination decreased below 2 lux, the obstacle detection performance shifted significantly.

The intensity of light has to be also taken into consideration in terms of who the users of the space are. As Uttley (2017) expressed, elderly people might need higher CCT illuminance to ease with safe obstacle detection than young people. It is caused by the physical aging of the eye, obstructing the light from reaching the retina. The shortwave light gets scattered more before it reaches the visual receptors, which could imply that different spectra of light could have different effects on obstacle detection in older people.

Besides the light having different effects based on the age of the recipient, many studies have also shown the negative effects of ALAN on human health, causing cancer and other problems (Cho, 2015). Quality lighting can support both aesthetic enjoyment of the solution, whilst also decreasing the probability of ALAN-induced health issues. For example, nightshifters perceive the night environment as something they live in and work in, not stroll in after work hours.

Nocturnal illumination is known to acutely suppress melatonin formation (Lewy, 1980). Particularly blue light is highly effective in suppressing melatonin, which is explained by the spectral sensitivity of melanopsin-containing retinal ganglion cells (Berson, 2002; Gooley, 2010; Lall, 2010) In shift workers, the transient melatonin deficiency induced by nocturnal light is not compensated during later sleep phases for reasons of temporal position of the circadian clock.

LIGHT PERCEPTION

Human vision is based on receptors that are located in the retina. There are two types of them, specialised for different purposes. Electromagnetic radiance (light) that the human eye can see spans from deep blue (on the verge of ultraviolet) up to deep red (on the verge of infrared). The energy is perceived in the eye by the sensor, rod, or cone, depending on the lighting quality and quantity. First of all, rods are responsible for vision in low-light settings. Second, cones are functioning in brighter lighting conditions and enabling color vision. Those further differentiate into three distinct types for long-, middle-, and short-wavelengths (Tuten, 2017).

Depending on the light intensity, the vision changes. During the day, it is photopic vision, mainly utilising cones. During the night, the scotopic vision is dominating, as the rods are fully utilised. Human-centred lighting in the form of ALAN is, in its essence, stripping rods from ever being in full use and keeps the photopic vision on at all times of human existence. Thus, a new range of vision has been identified on the verge of the photopic and scotopic range, when rods are already in use, but not as if full, natural darkness was present. This vision is termed mesopic and ranges between high luminance conditions (above 3

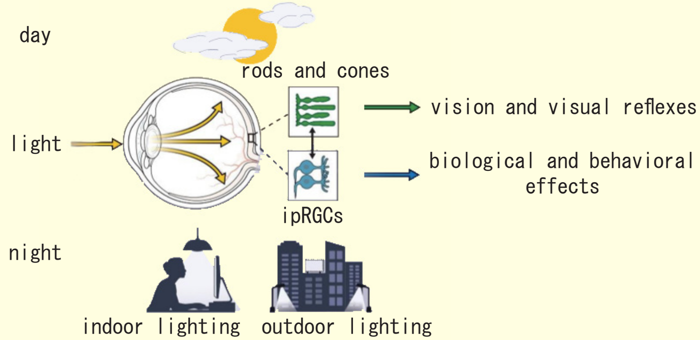


Figure 11_Illustration of two major human photoreceptive pathways (Zielinska-Dabkowska, 2023)

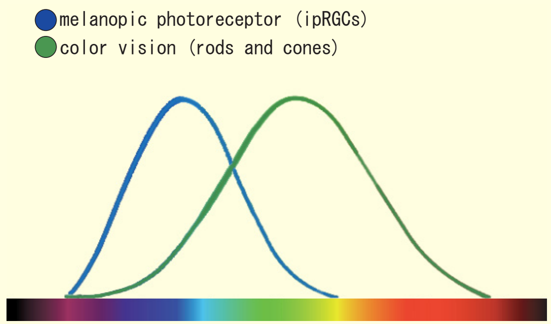


Figure 12_Visual system efficiency of human photoreceptors along visible spectrum (Zielinska-Dabkowska, 2023)

cd/m2) and low luminance (below 0.01 cd/m2) (Oliveira Grando, 2021). This range usually represents the luminance of public lighting (Navarrete-de Galvez, 2021).

Besides the visual perception of light, there is also another input information process happening within the visual perception aperture. It is through ipRGCs receptors (Intrinsically photosensitive retinal ganglion cells) that react to light, but not on a visual basis. These receptors are responsible for so-called ‘‘non-visual effects of light’’ and are often referred to as melanopic vision (Figure 11 and 12). The cells are then responsible for giving information to the body for the secretion of melatonin or its suppression, depending on the amount of blue light entering the eyes. Therefore, it is connected to circadian rhythm in the human body that is being affected by blue light present in the light around us.

IMPORTANCE OF DARKNESS

The darkness plays an important role in terms of the circadian rhythms of human beings. This rhythm is mainly regulated by the light and darkness throughout the day, where the brain receives the luminous information through the eyes and reacts accordingly by secretion and suppressing relevant hormones. The circadian rhythm can be disrupted in two ways by light. Either it can be by light spectrum containing blue (short) wavelengths, or the duration of being exposed to a certain type of light source. Therefore, it is important to promote healthy and ecological nighttime environments that would not collide with the humans' internal clocks, melatonin levels, and promote overall well-being (Blume, 2019). Melatonin is a molecule that is released as a hormone mainly during the night. Reduced melatonin levels can be observed in various diseases, such as types of dementia, some mood disorders, severe pain, cancer, and type 2 diabetes. Melatonin dysfunction is often related to changes in amounts, phasings, and coupling of circadian rhythms (Hardeland, 2012)

Another aspect of darkness lies in its aesthetic ability to shape the experience of a space at night. The darkness has been perceived across different cultures in great duality. Used by artists to draw inspiration, but also feared by people who were missing the understanding of it. The dark places would induce both introspective moments of reconnection with oneself and eventual danger zones, that would obscure the world in the unknown. The latter is known as a ''westernised'' understanding of light, as it is deeply rooted in the times of the Enlightenment colonialistic period, where light was a symbol of positive, knowledge, and civilisation, while the dark was connected to the unknown, fearful, and dangerous (Dunn, 2020; Stone, 2021).

Therefore, modern society, greatly supported by technological developments, overpopulates otherwise dim places with artificial light in the quest of colonising the night, making the light take a moralizing tone. Over-illumination of certain places can be directly connected to the fear of darkness or its consequences (Dunn, 2020). Ironically, the amount of created light would have its own shadow, in terms of social inequalities, environmental degradation, and detachment from natural daily cycles. (Kalemis, 2024). In many cultures, but most importantly in nature, darkness is a temporary, yet necessary part of existence. This existence is, however, more and more focused around the urban areas, and its inhabitants are not necessarily aware of the loss of nights. There is a rising necessity projected in modern society as a tendency to reclaim the darkness into the modern lightscapes of urban areas. This reclamation has become an urgent problem, as the light pollution has been proven to be a cause of multiple issues to humans and all the ecosystem participants. There shall be a focus put on the word ''co-existence'', since humanity mainly exists in a secluded perception of humans and nature or society and nature (Yee-Man, 2020). Most other ecosystem participants would also experience darkness in duality, similar to humans, in the form of a threat or a shelter. Due to the artificial light during the night, the overlit environment does not facilitate the necessary darkness for nocturnal species, nor humans. It became too invasive and normalised, so that ''darkness became a luxury needing protection and preservation'' (Stone, 2021). Preservation led to the creation of dark sky reserves and parks. On one hand, this initiative of, f.x. The Dark Sky Association is very valuable, as this approach helps to raise awareness about light pollution and creates a culture of a visible night sky. On the other hand, creation of such secluded areas could further nurture the separation of ‘’ urban night’ ’ and ‘’ wilderness night’ ’ and would not allow those two to intersect deeper (Stone, 2021).

However, the Dark Sky association has created a set of zones that are based on the amount of ambient luminescence in the area. There is a lighting zone (LZ) 0 all the way to number 4, which correlates to no ambient luminescence in dark sky preservation (LZ0) to highly dense and bright areas of ambient lighting (LZ4). These zones can be used as descriptions of areas and benchmarks for new developments that shall be fulfilled. Besides this set of zones, the association , in collaboration with Illumination Engineering Society (IES,) also brought a set of five principles as a form of combating light pollution. The recommendations are:

Use light only when needed.
Direct light so it falls only where it is needed.
Light shall be no brighter than necessary.
Use light only when needed.
Use warmer colour lights where possible.
(DarkSky, 2025)

DILEMMAS

From the three chapters above can be inferred the fact that lighting was invented solely by humans for humans. Everything else, living and non-living, does not demand artificial light, only humans. This stems from the evolutionary superiority of humans and their desire to exist comfortably in all places and at all times without appropriate consideration of original ecosystems. This can be characterised as a form of interspecies colonialism. Further down the timeline, lighting has been developing technologically in the direction of monetary gain and manifests itself in a strong association with socio-economic status. Urbanistudies investigating the effects of light pollution are prone to be confounded by other factors (Widmer, 2022). Unfortunately for humans, the most prominent development in energy-efficient lighting with the highest lighting output per energy (lumen/W) was the blue LED. The issue of this being that blue wavelengths are generally the most stimulative spectrum range for living species, including humans, making them unsuitable during dark hours.

As described earlier, the spectrum of light is a carrier of both visual and non-visual effects on all living organisms. Yet, besides humans, all the other organisms are accustomed to the natural daylight cycles and their spectral qualities and timely changes. Animals and plants follow those daily rhythms and behave accordingly. On the other hand, the humans expanded the day into dark hours - and thus carried the daytime spectrum into the night, where it becomes disturbing to remaining organisms. This effect has been further increased by the great implementation of LED technology, with a rising amount of research on impacts on human health and well-being. The reasoning behind the health issues research is connected to public lighting,as LED light has high blue content in its SPD, even at visually relatively warm 3000K. The reaction of the human visual system is similar as if it was daytime. This causes the body to hinder the production of hormones in the evening and disrupts internal circadian clocks. Similar responses have been recorded with plants and animals. A simple solution would be to decrease the light's spectral blue wavelengths to the lowest possible minimum.

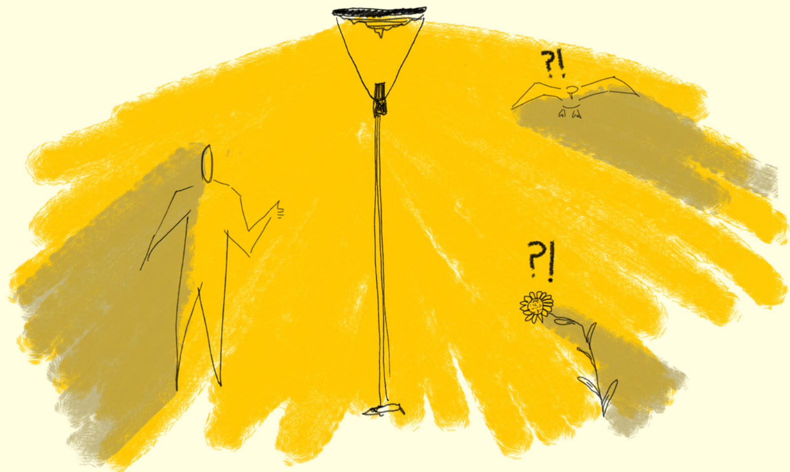
Stripping the PLS of blue wavelengths is, however, not easy to achieve. The more environmentally friendly SPDs are usually of amber/red hues. These tend to have negative connotations to humans and could offset psychological impact, especially when applied in public spaces such as parks or squares. It is important to account for those psychological effects. Nevertheless, it is humans who have the means to shift the blue-rich lighting stereotype. However, if the red hues are being generally perceived negatively, difficulties might arise in the general public and its acceptance of environmentally appropriate solutions with an altered light spectrum.

The generally applied lighting spectrum today is divisive. There are humans with their diurnal visual systems and need of daylight in the nighttime in order to exist, and animals and plants generally not needing artificial light either in case of diurnal or nocturnal species.

The fact that humans require lighting for their comfort does not mean they have adapted to this. Widmer (2022) talks of the connection between ALAN and a variety of health issues (such as cancer, depression, and obesity), shown by correlating the medical records and patients' residencies with the light pollution data. There exists evidence of the human brain releasing specific hormones based on the amount of light received by the eyes, leading to lower or overproduction of the hormones (Keshet Sitton et al., 2016; Weiler et al., 1997). Besides melatonin, estrogen, progesterone, and dopamine are hormones that are regulated by the circadian clock of the body, and their negative fluctuations in production can cause similar health issues (Liu et al., 2020).

Another issue of ALAN can be envisioned through the phenomenon of light pollution. This pollution source is relatively new, as it has been recognized by astronomers in the first half of the twentieth century (Chant, 1935), as it started to interfere with their celestial observations. Soon thereafter, this phenomenon attracted the attention of a wider audience (Riegel, 1973). Many studies from broad disciplines have demonstrated that light pollution is one of the fastest-growing and most pervasive forms of environmental pollution (Kyba, 2017). Intensive light pollution is expected to cause ecological damage (Widmer, 2022). The places considered truly dark areas are being monitored and shown to be disappearing. However, this trend seems to be location dependent. As of lately (Widmer, 2022) Netherlands, Luxembourg, Poland, and Belgium have experienced the largest increase in light pollution, whereas Iceland, Ireland, and France have darkened.

The visual disturbance in the form of light has been shown to be successfully hindered in these countries. This is achievable, especially in areas that are not busy during the nighttime hours. Places where human activity drops significantly after sunset shall be primarily lit (or rather not lit at all) in an environmentally considerate fashion. The default standby state of the human-centric lighting is causing more harm to the ecosystem than its actual value to the scarce number of passersby at night. If the light shall be on at all times, it is more appropriate to select a less disturbing spectrum of the light source.



PRACTICAL PART

Based on theoretical studies, collected knowledge is put into practice and its functionality is examined through a series of experiments and evaluated (see Figure 13).

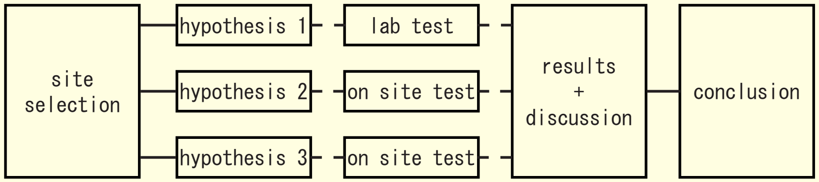


Figure 13_Scheme of practical part of thesis tasks

SITE SELECTION

Following the gained information from the literature search, the site has been chosen based on evaluation of traits corresponding to the goal. Aim was to select an area with potential, where human activity is low enough one can afford dimming down and manipulating other light characteristics to an extent which is favourable to other species, yet still usable by humans.

To find areas fitting the above description, requirements of urban typologies that are generally prone to have these traits are green corridors and (urban) parks. It was also a necessity for the site to be within reach of the Copenhagen commune, due to the expected practical intervention and general ability to observe and analyse the site physically.

Furthermore it was important to find a site with gradual transition from urban to purely natural environment, as it was considered an interesting aspect of the final lighting design proposal.

SITE ANALYSIS

A site deemed worthy of further analysis is a space located within an urban environment, yet with a wide variation of land use. Spanning between the districts of Bispebjerg, Østerbro, Nørrebro, and Hellerup in the northern part of Copenhagen (see Figure 14). It consists of two aligned parks of Lersøparken and Ryvangs Naturparken, and a communal garden colony connecting these two parks. Together, these three areas create a unified body of greenery within the city, stretching from Mimersparken in Nørrebro till Tuborgvej in Østerbro. The entirety of the strip is approximately three kilometers in length and consists of 4 main parks: Mimersparken, Lærsøparken, Kolonihave Parken, and Ryvangens Naturparken (see Figure 15). However, Mimersparken has not been analysed any deeper than the other parks, as it is more of an urban area rather than a natural space.

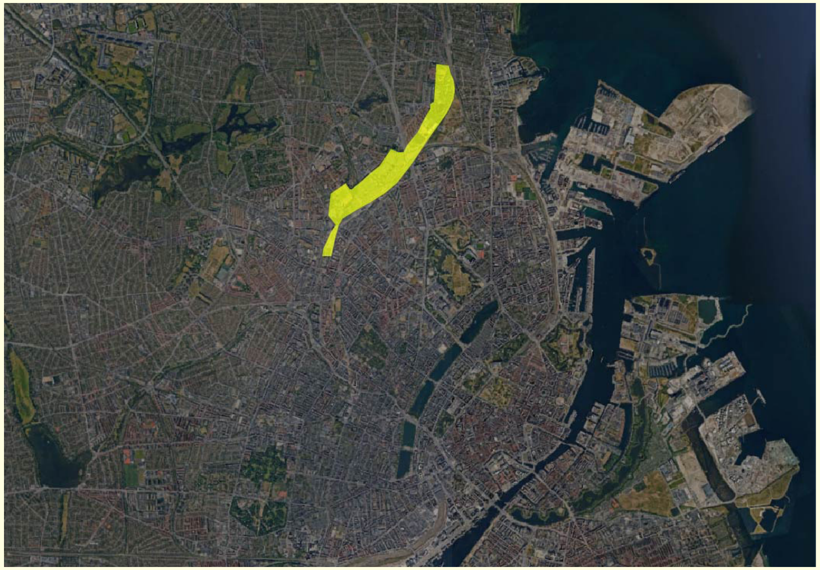


Figure 14_Planview of the site location within the city

This stretch is characteristic of its park-like appearance, with occasional urban or infrastructure features. The area is calm in the parks, but the sounds of the main roadways of Tagensvej and Lyngbyvej remind us we are still located within city limits. This is also enhanced by the occasional passing of S-trains running alongside the strip as well as right through it.

Lersøpark and Kolonihave Parken were established in the early 1900s on land that once held the Lersø lake, a former water source for Copenhagen and refuge for marginalized city dwellers. Historically used by basket makers for material gathering, the area underwent major changes as Copenhagen expanded, including soil infill and the later addition of train tracks in 1977, which reduced some colony properties. Since 1969, Lersøpark has been protected as a recreational green space with evolving public access. Nearby, Ryvangens Naturparken, originally a swamp used for military training from 1893, transitioned into a public park in 1997 after military use ceased. Efforts in the 1980s and early 2000s focused on cleanup and conservation, emphasizing both ecological restoration and historical preservation of these areas.

Figure 15_Distinct areas differentiation within site

Lersøparken and Kolonihaveparken are on the southeast border of the neighbourhood of Bispebjerg, in the northern part of Copenhagen. Lærsøparken has indeed the natural elements and clear representation of a park, whereas the Kolonihaveparken consists of multiple buildings spread across its premises. The Lersøparkens main attribute is in the open spaces that are throughout the flat central areas in the park. This openness of the park and the ability to see the sky are one of the main features that are being maintained, as it is specific for this area. Many types of bushes are helping to keep the park hidden from the surrounding traffic and school yards. The Kolonihaveparken has one big central promenade dedicated to pedestrians and cyclists. The area is more in a settlement atmosphere, as the local small gardening houses are present.

Finally, Ryvangens Naturpark is an approximately 10 ha extensive green area north of Copenhagen, right between Ryparken, Rymarksvænge, and Østerbro. There is also a train track going along the park, and there are several public and private institutions for kids. The Ryvangen Naturpark is a large body of vegetation with occasional open spaces and a dominant lake located in its center. It is a contrasting opposite to the surrounding urban development. The park takes pride in its wild appearance and vegetation that is present, and any attempts to make this park more 'classical park-like' might be harmful for the overall experience. There is still a strong connection to the history of the park in the form of bunkers and foundations of barracks. They are not generally advised to be removed, due to their historical value; however, if the reason arises, they can be removed.

All three parks—Lersøparken, Kolonihaveparken, and Ryvangens Park—are connected by a continuous lane featuring an underpass and two bridges. Lersøparken and

Kolonihaveparken have an extensive pedestrian path network, some wheelchair-accessible, with mostly 24/7 access except for restricted areas like colony houses and kindergartens. A Green Cycle Line runs through these parks, and car access is limited to residents and colony users. Ryvangens Park is fully open to pedestrians at all times, though its lake and islands are off-limits, and motorized traffic is prohibited without special permission.

These parks are primarily used by colony house owners and their associations, as well as local institutions, schools, and nearby residents. Lersøparken is popular for football on its main grassland, picnics in its southeast area, and relaxation on benches and table sets scattered in shaded spots. Kolonihaveparken serves mainly as a pleasant thoroughfare for walkers and cyclists, with a central alley lined with benches. Ryvangens Park is used by locals and institutions, but also attracts visitors with interests in fishing, birdwatching, and biological fieldwork.

The parks feature a mix of wild grasses and plants. Tree species, mainly beeches, range in size and age, with many planted during the park’s early development, making them over a century old. Prominent greenery includes tree-lined open spaces and a main cycle lane flanked by rows of trees. While no official fauna analysis has been completed, data from gbif.com and observations from local groups like the Feltbotanisk Klub indicate rich biodiversity—Ryvangens Naturpark alone hosts 175 plant species and serves as a significant habitat for water birds. The GBIF database (2025) records 4,419 species occurrences across the site (see Figure 16).

Figure 16_Planview of species records taken within site (gbif, 2025)

The main animal groups present on the site could be, to a certain degree, generalised in terms of light spectrum sensitivity, as in Table 02:

Anas platyrhynchos	415, 452, 506, 567 nm
Mamestra brassicae	360, 460, 540, 580 nm
Pararge aegeria	360, 460, 530 nm
Vulpes vulpes	438, 555 nm
Sciurus carolinensis	444, 543 nm
Plants	385, 450, 660 nm

Table 02_ Species list with visual peak wavelenghts

EXISTING LIGHT CONDITIONS

The lighting in the park did not show any signs of presence sensors, and they unanimously turned on by nightfall. The lighting design in the area was purely functionalist.

Currently, there are 3 main types of lamps used across all 3 parks. First type, ParkView from Philips Lighting (now Signify), is being placed along the path between Kolonihave Parken and Ryvangens Naturpark. This luminaire is 4 meters high. Its luminous head has its light source well shielded. However, its 360 degrees light distribution in the horizontal plane allows direct illumination of areas that do not necessary have to be lit - i.e., the green areas in the immediate proximity of the path(see Figure 17).

Figure 17_Sportslighting spilling from usage area

The second type that was widely used in Lersøparken and Kolonihave Parken is luminaire Nyx 330 by the company Focus Lighting. It is also a 4-meter-high fixture. This luminaire has a circular light distribution. However, its luminous head is directed towards the ground, making the light spill on the horizontal plane less profound (in comparison to the previous fixture). On the other hand, its light source is not anyhow shielded, just focused using optical lenses (see Figure 18).

Figure 18_ Lamp row unnecessarily illuminating surroundings

Lastly, the most dominant lamp type in the remaining Ryvangens Naturpark was a non-identified bollard luminaire. Its luminous head was directed towards the ground and thanks to its height being only 900mm, the light fell only onto the path, where it was needed and having thus indeed minimal visual spill light (see Figure 19).

The measurements of the existing lighting conditions were taken on 22. February 2025, in the period of 18.30 to 21.30. The information of interest was CCT of the luminaires, their colour rendering abilities, and their luminous intensity. There were measurements taken first on the horizontal plane of 0m right by the foot of the lamp, then in the middle of the path that the lamp was illuminating, and the last measurement was taken in between two luminaries of the same type illuminating the same path (see Figure 20).

Figure 19_Low luminaires in Ryvagens Naturpark

In the summary Ra values show the CRI of the measured luminaires (Ra1 for 1st measure, Ra2 for second measure, Ra3 for last measure), CCT shows correlated colour temperature and last three columns show lux levels on each measuring spot.

Overall the CCT of luminaires on site were spanning between 2700-3000K with colour rendering properties from 73-87 (see Table 03 and Figure 21).

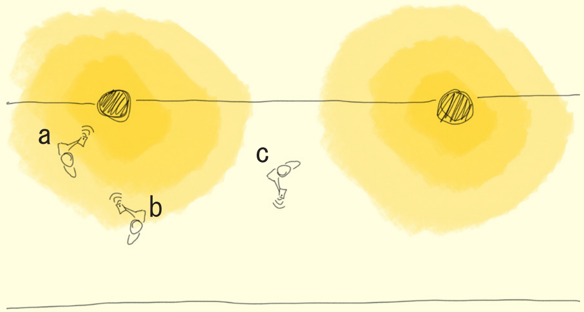


Figure 20_Measurement methodology (A= under lamp, B=in the middle of the path, C= in between lamps)

Source	CRI 1	CRI 2	CRI 3	CCT 1	CCT 2	CCT 3	UNDER LAMP	MIDLLE	BETWEEN
1	87	92	91	2867	3497	4793	29.9	9.5	4.2
2	73	75	79	2970	3074	3155	25.2	23.4	11.1
3	81	87	92	2895	3175	6458	21.8	9.4	2.3
4	82	84	95	3000	3095	3746	33.4	21.3	4.5
5	76	78	84	2897	3019	5841	26.2	13.2	1.9
6	75	78	81	2852	2960	6279	23.7	13.6	1.9
7	82	88	82	2759	4784	5697	22.5	1.5	1.7
8	87	94	88	2698	3649	4845	4.5	3.1	2.4

Table 03_Lighting values of fixtures on the site.

Figure 21_Photos of measurement locations

The Lersøparken, Kolonihaveparken, and Ryvangsparken have certain documents that dictate their appearance, use, and other conditions. The main documents in close contexts of this masterthesis interest are:

Copenhagen Lighting Masterplan (Københavns Belysningsmasterplan)

A document published in 2014, providing guidelines on public street lighting design within Copenhagen's municipality. The text comments on planning the lighting of green areas, and the importance of so-called 'dark tunnels'. These tunnels are crucial infrastructure for the well-being of nocturnal species, as they might perceive continuous lines of street lighting as a barrier. Therefore, successful lighting planning allows an unobstructed movement between green urban areas. Furthermore, the document talks of introducing scheduled/automatic lighting systems, as it lowers the energy consumption when the area is not in use.

Safety Research 2024 and 2023 (Tryghedsundersøgelse i København 2024 og 2023 - Dybdegående undersøgelse af belysning og tryghed)

The perception of safety among Copenhagen citizens has gained importance since its first measurement in 2009. However, the report shows there is still room for improvement. Many respondents mention that green areas, parks, and playgrounds tend to feel unsafe after sunset. The 2024 study has not provided any clear conclusion on the connection between lights and perceived safety. Light has the potential to help in specific situations, but is not the singular provider of safety. Therefore, it is important to remember the overall context of where the public street light is designed - specifically in park areas, there is a higher chance of high contrast between light and dark zones, which has been also described as a perceived safety issue for some citizens, as this contrast does not allow one to see deeper into the dark.

Respondents expressed preference in variability of lighting sources, distribution angles, and illumination levels, together with special lighting enhancing specific locations.

Lastly, this study recognized three main mechanisms affecting the perception of public safety after dark: visual quality and clarity of an area, users and activity level, reputation for safety

Local Development Plan for Ryvangens Parken

For example, even though the multi-sport pitches in the analysed area are responsible for a large amount of spill light in its proximity, citizens perceive them as positively, because such areas are often associated with liveliness, and thereby reduction of fear due to public surveillance principle.

It is stated in the local development plan for this park that light can be placed only by the existing toilet building and along the green cycle route. This light has to be located low and be non-glaring lighting.

Local Development Plan for Lersøparken and Kolonihaveparken

Local development plans can provide restrictions and guidelines regarding the lighting. In this case, the placement of new light fixtures are allowed only around activity area in Lersø park, on bike lane over highway towards Vermundsgade, new bike lane by Tagensvej, by the connection of The Green Cycle lane and Lyngbyvej and on Bøllemossegårdsvej towards Lundehus church.

HYPOTHESES

The knowledge base of literature forms hypotheses to answer the research question (see Table 04). As this thesis aims to propose lighting solutions inhabiting all living systems, it is necessary to take out the main points from each subgroup and include them in the preliminary design to be tested in the form of hypotheses. In the plant subgroup, it is mainly the photosynthetically active spectrum ranges and lighting levels that disturb the plant. The design should avoid lighting levels higher than 1 μmol/m2/s on the vegetation and avoid stimulation of photopigments, namely in the wavelengths of blue (400-500 nm) and red (660 nm) photosynthetically active radiance. Regarding the animals, it is crucial not to influence orientation, where the spectrum plays a major role, so that longer wavelengths with less disturbance to daily rhythm are preferred. For humans, the design is aimed at not hindering visual clarity nor perception of safety, as these are typically recorded to be problematic when designing inclusive spaces. Essentially, management steps to reduce ALAN as proposed by Gaston (2012) are taken into account when designing the duration of artificial light sources. The reduction of light trespass, the reduction in the illuminance emitted by light sources, and the adaptation of the spectral composition.

Finally, the research question informs the hypotheses, where lighting serves human needs, but does not disturb other species that have been evolutionarily developed for darkness. The following hypotheses aim to explore the visual abilities and preferences of humans under nocturnally friendly lighting.

1_ ‘By filtering the spill light into longer wavelengths of the visible spectrum, a smoother transition to the darkness will be created, improving human visibility of the surroundings.’

This hypothesis stems from the good lighting practice principle of lighting only where required. Based on site observation, where luminaires with circular light distribution were causing spill light outside of the use areas, it offers an opportunity to improve the current situation by shielding the light. However, this simple solution can, inthe case of dark surroundings, cause the effect of concealment, when it is a visual struggle to see behind the illuminated area (Blixt,2020). This led to the idea of red filter application and placement onto the parts of the luminaire in the direction of the spilled light. Thus, the usual white light would be focused only on areas where it is needed for visual reasons.

Once the spill light is stripped of the blue wavelengths, while the ‘’task’’ full spectrum lighting is still illuminating the usage area, the safety feeling shall not be hindered. A lighting scenario consisting only of monochromatic red colour could impose ta ense emotional response (Xing et al., 2022) due to red colour connotations of danger. This emotional response is partially enhanced since, by using the red light at the same intensity as white light, red light will be perceived as darker. However, as per Fristrup (2024), the blending of red and white light leads to a generally more accepted lighting scenario. Therefore:

2_ ‘By using a combination of longer wavelength spectrum and 2000K path light, the safety perception will not be negatively affected.’

Originating from the note that the Vejdirektorat (Road Ministry) is advising not to surpass the MDER (melanopic daylight equivalent) ratio above 0.35 during dark hours, as it is deemed to cause significant melatonin suppression. The lower MDER ratio is correlated with the warmer CCT, and this could play a part in the obstacle detection on the illuminated path (Rahm J. 2018):

3_ ‘By using light spectrum with a melanopic ratio of 0.35 or lower, the obstacle detection abilities of users will not be negatively affected.’

	aim	metrics	place	literature
hypothesis 1	surrounding visibility and light colour gradient	number of gray squares visible + quantitative data from light lab	on site + light lab	Blixt (2020)
hypothesis 2	safety perception	qualitative and quantitative data from a survey	on site	Xie Xing (2022); Fristrup (2024)
hypothesis 3	obstacle detection	obstacles correctly detected	on site	de Lange (2022); Rahm (2018)

Table 04_Hypotheses overview

HYPOTHESES: TESTING

Hypothesis 1_By filtering the spill light into longer wavelengths of the visible spectrum, a smoother transition to the darkness will be created, improving visibility of the surroundings.

Test focused on the useful light in places where it is needed, while the spill light would be filtered out in red colour to have less impact on the surrounding ecosystem and create a more suitable gradient into the surrounding darkness. In this very case, the attempt was to filter out any light that is not directly falling onto the imaginary path. The ability to see more of the surroundings was later tested while conducting on-site tests, since this aspect could not be replicated in a lighting lab.

This hypothesis was tested in an indoor environment of a lighting design lab of approximately 6x6 m, where the lighting conditions can be under control throughout the entire duration of the test. The equipment needed for this test consisted of a street luminaire head, light filters, metal wires, two measuring tools, white fabric, and spectrometer GL Spectis 1.0 Touch + Flicker. The street luminaire head was LP Kipp 3000K 30W 3011lm, borrowed from Louis Poulsen for this test (see Figure 22). This luminaire was selected due to its cylindrical shape and circular light distribution. Next, the red filters used were red lighting filters, Primary Red. Their translucence was measured to be around 10%. The measuring tools were mainly used to mark imaginary boundaries of the bicycle lane that started from the very foot of the street luminaire and was spanning in two meters in width. The white sheet of fabric was used to see the effects more clearly than on the grey flooring of the lighting lab. Lastly ,the spectrometer was used to take precise lighting measurements in each coverage scenario.

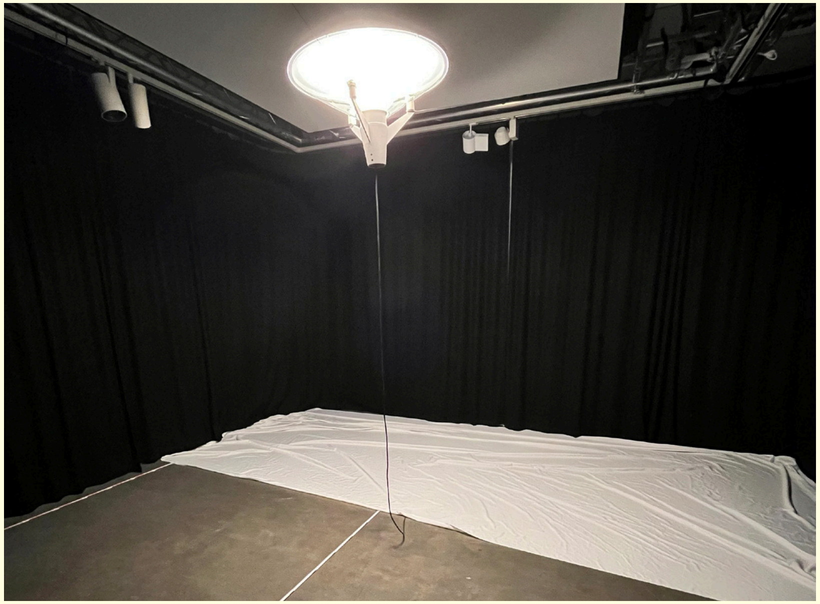


Figure 22_The lighting setup with white fabric and path outlines.

The test consisted of two parts where first, the visual effect (see Figure 24) was in main focus and after the actual measuring of light levels, CCT and CRI took place per each mesuring point on the ground (see Figure 23).

Figure 23_Rectangular grid of 25 spots for measurement.

In the first part of the experiment, the lamp head was hung in the middle of the lighting lab, approximately 2.5m above the ground. The lamp was further covered with lighting filters in the following coverages (see Figure 25):

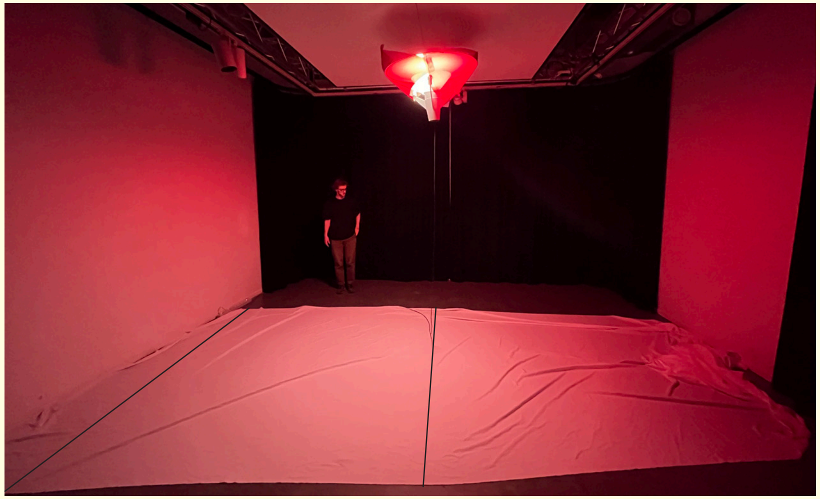


Figure 24_Lighting lab tests

1_amber filter in the area of path illumination, rest covered in two layers of red filter

2_no filter in the area of path illumination, rest covered in two layers of red filter

3_no filter in the area of path illumination, the upper part of the half towards the path is also without any filter, the other half of the luminaire is covered in two layers of red filter

4_no filter in the area of path illumination, the upper part of the half towards the path is also without any filter, the other half of the luminaire is covered in single layer of red filter

5_luminaire without any filters

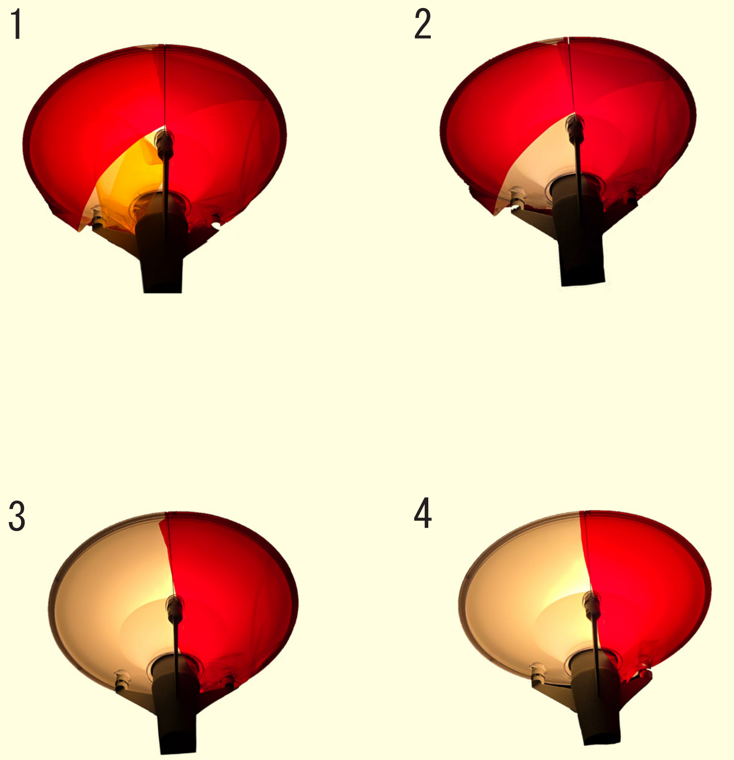
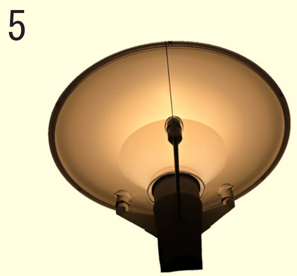


Figure 25_Lighting lab test fixture modifications



In each of the scenarios, a set of pictures was taken for later comparison and reference of the visual effects created by the filter coverage of the luminaire (see Appendix).

As an extension, the first hypothesis was tested on site. The reason was to observe whether the ability to see into the dark surroundings would change under the altered lighting conditions caused by luminaire covered by filters.

The setup of the testing site consisted of three altered luminaires with amber filters for the path lane and red filters for spill light ,and then three luminaires without any alteration to serve for control purposes. This test also needed external participants and eventually, five participants took part in the test. Another tool necessary for this test was Munsell' s gray chart, due to its known reflectances. It was used to assess the visibility in the dark surroundings. The chart was made out of 6 A4 sheets placed next to each other, creating a gradient from pure white to black in six steps. This chart was held at a diagonal distance of 20 meters from participants and between two luminaires, which was the darkest spot (see Figures 26,27,28).

Finally, the participants were instructed to look into the direction of Munsell' s gray chart and say a number of A4 sheets of gradient they see. All responses were recorded by the examiner. This procedure was done for both altered and a control lighting setting (non altered luminaires) in the exact same manner with the exact same number of participants.

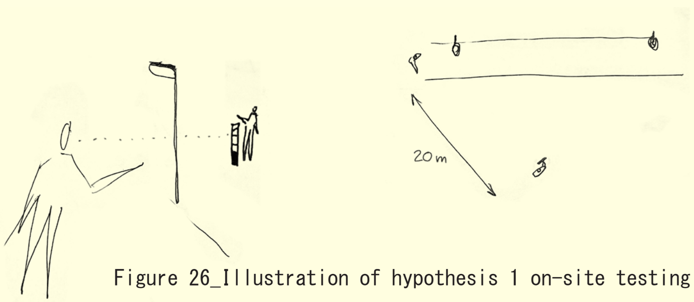


Figure 26_Illustration of hypothesis 1 on-site testing setup

Figure 27_Surroundings visibility testing

Figure 28_Munsell chart for testing

Hypothesis 2_By using a combination of a longer wavelength spectrum and 2700-3000K path light, the safety perception will not be negatively affected.

The second test was conducted on the site of Kolonihave Parken. The idea behind this test is that people might be connecting red light with negative or tense emotions (Xing et al., 2022), yet this exact red light is helpful for the ecological nighttime environments.

First, the participant was informed about the aim of the test while they were standing under the altered luminaire and looking towards the other altered luminaires (see Figure 29). Next, the participant was asked the following questions concerning safety perception in this lighting setting:

Do you think this lighting environment encourages community use of this space? -- open answers

What kind of activities would you feel comfortable doing in this lighting environment? -- open answers

The lighting enables me to see the surroundings clearly. -- highly agree to highly disagree

The lighting on the path is sufficient to travel through this space. -- highly agree to highly disagree

I would feel comfortable walking in this lighting at night. -- highly agree to highly disagree

Figure 29_Interview process

Hypothesis 3_By using a light spectrum with a melanopic ratio of 0.35 or lower, the obstacle detection abilities of users will not be negatively affected.

The last test was conducted on the same testing site as test number 2 and was concerning the obstacle detection abilities under different lighting settings. The idea behind this test stems from the municipal advice to use lighting with a melanopic ratio of 0.35 to combat its biological adverse effects. However, such light is connected with a lower CCT around 2000 K. This could have thus impact on the visual abilities of users of this space to note obstacles on the lit path (Rahm, 2018).

Equipment needed for this test was a set of faces with different facial expressions, 10mm thick white tiles covered in black colour on top and exposed edges, measuring tape and altered luminaires (see Figure 30).

Participants were standing under the first of the luminaires of the altered lighting scenario. They were facing backwards, so they could not see the path illuminated by altered luminaires. On the other side, one of the test conductors was standing 6 meters away and holding a printed face with a distinct expression. In between the participant and text conductor were at a distance of 3.4 meters from the participants placed 1-6 obstacles in random amounts. This distance was chosen since it is the distance at which people can detect obstacles and behave accordingly (de Lange 2022)(see Figure 31). Then, participants were instructed to turn around and, in a duration of three seconds, remember the facial expression and number of obstacles on the ground. This was repeated three times, always with different amounts of obstacles on the ground and facial expressions being held.

Figure 30_Obstacle detection setup

The aspect of obstacle detection was mainly tested using the tiles located on the ground. The facial expression task was implemented as a ‘’ distraction task’ ’ as people usually detect the obstacles using peripheral vision and not direct gaze (A.A.J. de Lange, 2022).

This procedure was done for both altered and a control lighting setting (non altered luminaires) in the exact same manner with the exact same number of participants.

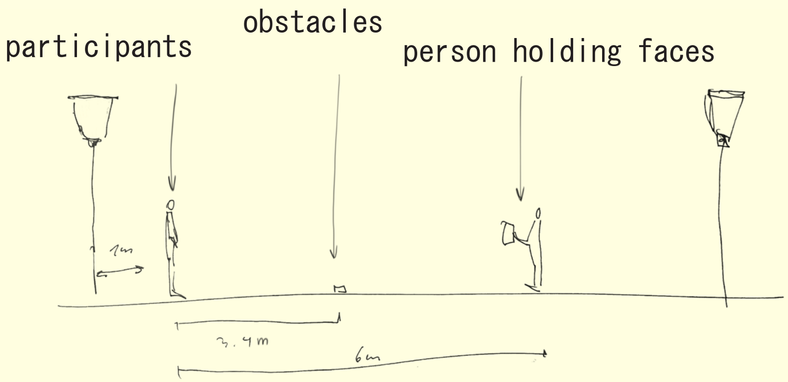
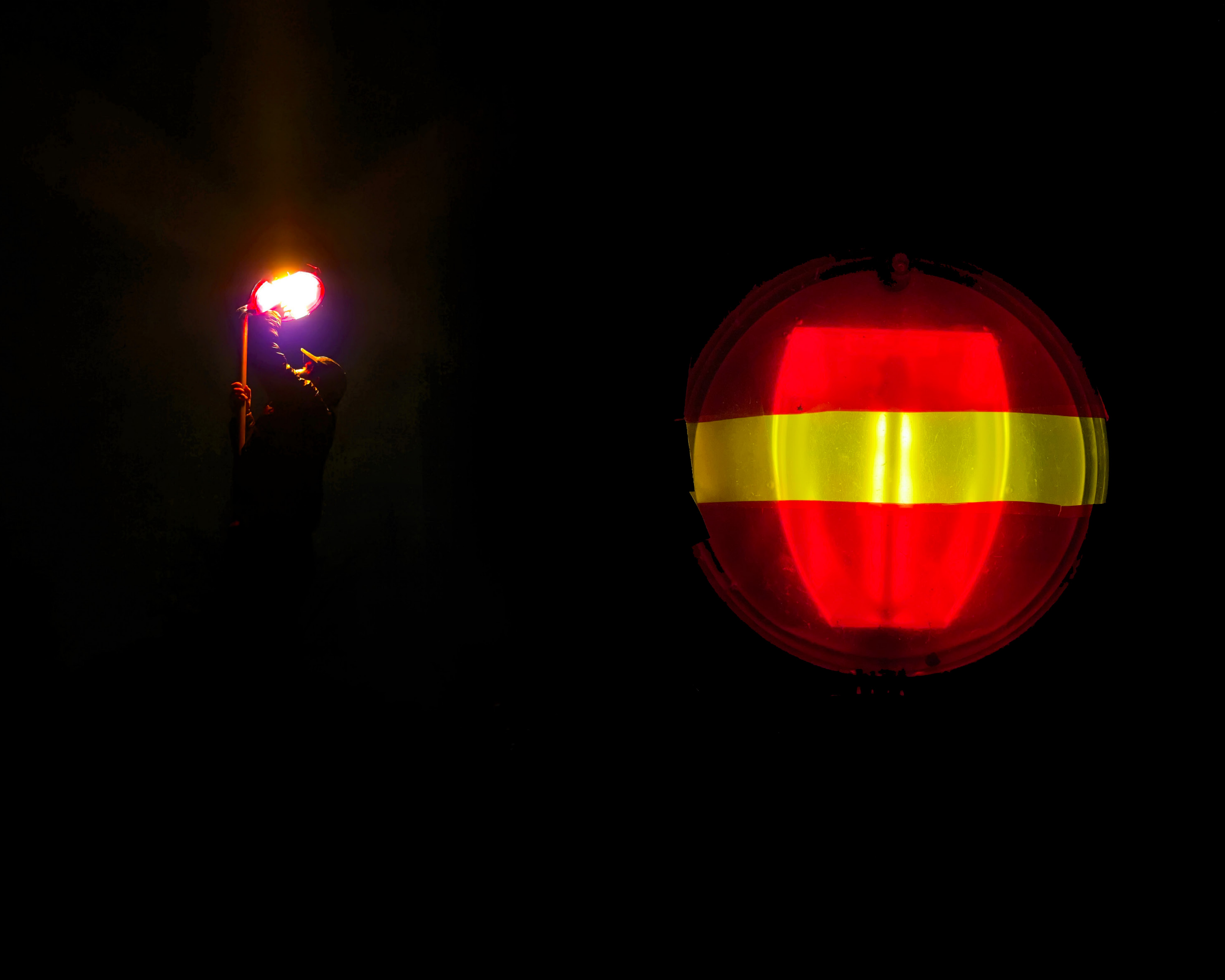


Figure 31_Illustration of obstacle detection on-site testing



RESULTS

TEST 1_ IN THE LIGHTING LAB

The results of the laboratory measurements comprise and present quantitative findings. The data were processed using Excel and eventually a Processing code that served as extractor of relevant data from raw textual interpretation in the original .mmg format imported from the spectrometer. Further, this data was translated back into the visual representation of the measuring grid in the lab (Figures 33,34,35). Each box is correlating with respective coverage scenario:

1_fully covered with amber filter for path,
2_fully covered luminaire with exposed normal light for path,
3_only half of the luminaire covered in 2 layers of filters,
4_only half of the luminaire covered in one layer of filter,
5_completely raw exposed luminaire

,and below each box is the average value of that scenario. Each little square within the box represents one measuring point in the measuring grid. Its measured value is written in the corresponding square.

Spectral Distribution

For each lighting scenario with modified filtering, all points of floor grid have been measured with spectrometer. Their respective values of spectral distribution have been examined to evaluate whether any of the environmentally friendly lighting, that is advising the portion of spectral distribution within the 380-500 nm shall not surpass 6% of total light spectral content (see Table 05 and Figure 32).

scenario	average CCT (K)	average 380-500 nm (%)
1	1400	6
2	1600	9,6
3	2600	14
4	2600	14
5	3000	15

Table 05_CCTs of fixture modifications and respective short wavelenghts percentage

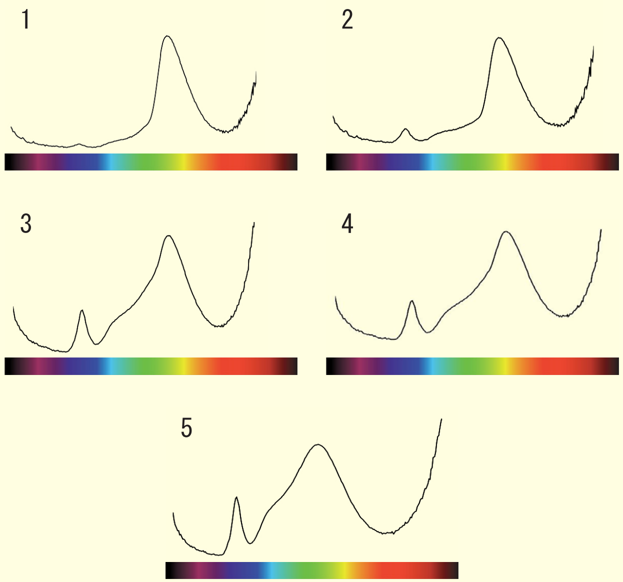


Figure 32_SPDs of fixture modifications

Equivalent melanopic luminance ratio

0,18	0,17	0,19	0,22	0,33
0,23	0,21	0,21	0,24	,032
0,25	0,25	0,25	126	0,33
0,28	0,23	0,26	0,28	0,35
0,32	0,30	0,29	0,32	0,39

0,27

0,39	0,35	0,36	0,41	0,52
0,39	0,36	0,36	0,39	0,47
0,41	0,41	0,40	0,40	0,46
0,42	0,42	0,41	0,41	0,46
0,44	0,43	0,43	0,44	0,50

0,42

0,48	0,45	0,46	0,51	0,61
0,49	0,46	0,46	0,50	0,56
0,50	0,49	0,49	0,51	0,56
0,52	0,51	0,51	0,53	0,56
0,55	0,54	0,54	0,55	0,58

0,52

0,48	0,44	0,45	0,49	0,57
0,47	0,45	0,45	0,48	0,54
0,50	0,48	0,48	0,50	0,55
0,53	0,51	0,51	0,53	0,56
0,55	0,54	0,54	0,56	0,59

0,51

0,55	0,54	0,54	0,56	0,59
0,53	0,52	0,52	0,54	0,57
0,53	0,52	0,52	0,53	0,57
0,54	0,53	0,53	0,54	0,57
0,56	0,55	0,55	0,56	0,60

0,55

Figure 33_Equivalent melanopic ratio distribution among fixture modifications in lighting lab testing (scenario 1-5 from left to right)

The test of melanopic ratio values showed that only the scenario number 1 (fully covered luminaire) fell within the <0.35 range with value of 0,27. Further removal of the filters resulted in expected increase of EMLR as it gradually exposed the original luminaire and the blue content (as seen above on the SPD graphics). Within scenario 3 and 4 no difference was recorder, probably due to substantial light scattering across the lighting lab. Test showed the amount of filtering necessary to fulfill the value presented in literature as good practice.

Illuminance levels

5,7	7,5	7,5	5,9	3,9
11,7	15,8	14,8	10,2	5,9
17,7	28,0	24,5	13,8	7,6
16,8	24,6	23,4	14,1	7,7
11,7	14,9	14,1	10,2	6,7

12,99

7,5	9,0	9,2	7,4	5,1
15,0	20,2	18,6	12,6	7,4
23,1	37,6	32,5	17,5	9,2
21,4	31,9	30,8	18,0	9,5
14,4	18,4	17,8	12,7	8,0

16,59

10,5	12,2	12,3	10,5	8,2
22,5	28,9	27,6	20,4	13,5
39,7	57,1	51,2	33,0	19,8
43,3	59,6	58,6	39,1	22,8
33,9	42,0	41,4	31,3	20,8

30,41

14,1	16,9	16,9	14,6	11,2
27,2	36,2	34,7	25,3	16,8
42,9	62,4	58,8	38,2	23,2
45,3	62,4	62,1	41,6	24,6
34,5	43,0	42,3	32,0	21,3

33,94

38,0	48,1	48,0	37,1	25,2
55,6	76,9	74,0	51,4	31,7
64,2	92,5	87,6	57,1	33,8
53,0	71,1	71,3	50,3	29,9
36,5	44,3	43,8	34,5	23,6

51,18

Figure 34_Illuminance levels distribution among fixture modifications in lighting lab testing (scenario 1-5 from left to right)

The illuminance levels were decreasing gradually with the amount of filters being applied on the luminaire. The light values increase roughly four-fold between scenario 1 and 4, with the biggest relative increment of 200% after removal of the filter between second and third scenario. The test showed the how the filter removal influences light distribution in the immediate surroundings of the luminaire location.

Colour Rendering Index

71,0	72,5	71,6	69,7	63,5
76,0	77,0	77,0	75,0	70,0
81,0	85,0	83,0	79,0	73,0
82,0	85,0	85,0	80,0	75,0
79,0	82,0	81,0	78,0	73,0

76,97

62,0	63,0	64,2	63,2	59,2
73,6	74,8	73,6	71,7	67,2
80,7	84,1	82,5	77,7	72,8
81,7	84,9	83,9	79,5	74,5
79,4	81,1	80,1	77,4	73,9

74,66

71,4	69,9	69,7	70,8	71,4
84,9	84,2	83,3	83,4	81,4
93,3	93,1	92,9	92,2	91,6
91,8	91,1	91,3	92,4	93,9
90,5	89,6	89,9	91,1	93,0

85,92

73,6	72,8	73,1	74,9	76,8
84,6	84,6	84,0	84,4	84,7
92,0	92,2	92,1	91,9	91,6
91,1	90,1	90,3	91,6	93,2
90,1	89,1	89,3	90,6	92,6

86,45

87,0	87,0	87,0	87,0	88,0
87,0	87,0	88,0	87,0	87,0
87,0	87,0	87,0	88,0	88,0
87,0	87,0	87,0	88,0	87,0
88,0	87,0	87,0	87,0	90,0

87,36

Figure 35_CRI distribution among fixture modifications in lighting lab testing (scenario 1-5 from left to right)

The CRI test provided insight into the perceived rendering and objective values, where recorded average rendering quality reached 77% in the most filtered scenario 1. Interestingly, scenario number 2 had lower CRI with 75% due to nonlinear spectral qualities. After removal of the side (from scenario 2 to scenario 3) the CRI averaged at 86 and practically stayed same for scenario 4 and 5. This test showed that initial filtering (scenario 4 and 3) had no major effect on CRI values.

TEST 2_ SAFETY PERCEPTION

The on-site test lighting intervention seved as a collection for both qualitative and quantitative data. Two lighting scenarios (see Figure 36,37) were tested while conducting the tests:

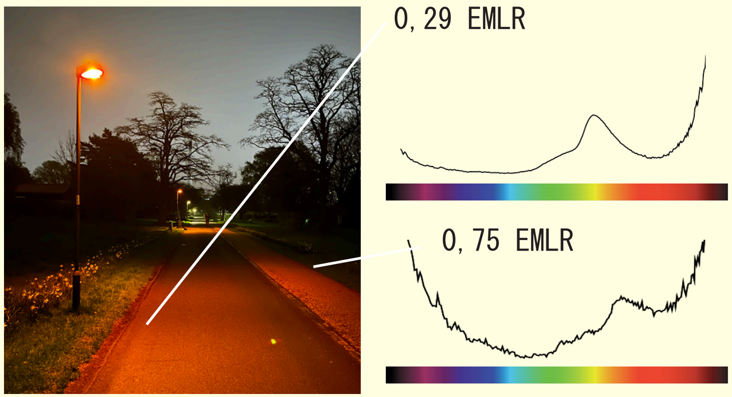


Figure 36_Filtered (altered) lighting 0.30 EMDR, 8lux on the pavement and CCT of 1700K.

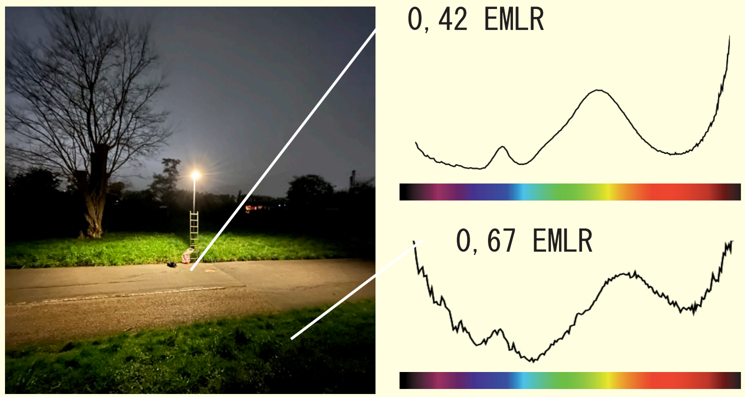


Figure 37_Existing (control) lighting 0.42 EMDR, 24lux on the pavement, and CCT of 2800K

Building upon the laboratory testing, the ability to see into darkness was tested based on the coverage of the lamp measured in the lab experiment. The results of a recognition test of how many rectangles of grey scaled squares participants can see hiding further in the dark area out of the illuminated path (see Table 06).

participant	altered	control
1	5	4
2	3	3
3	0	0
4	3	2
5	3	3
total	14	12

Table 06_Results of on-site surroundings visiblity test

From results it can be derived that the visibility has not been negatively affected compared to control.

The test of the second hypothesis regarding safety perception collected data by recording reactions of participants to statements and open-ended questions (see Table 07):

The lighting on the path is sufficient to see where I am going.

	altered	control
strongly agree	3	3
agree	1	2
neutral	0	0
disagree	1	0
strongly disagree	0	0

The lighting helps me see my surroundings clearly.

	altered	control
strongly agree	1	2
agree	1	1
neutral	0	0
disagree	2	2
strongly disagree	1	0

I would feel comfortable walking here at night.

	altered	control
strongly agree	0	0
agree	3	4
neutral	1	1
disagree	1	0
strongly disagree	0	0

Table 07_Close-ended questions results(1-3/3)

From the results, it can be noted that participants experienced slight discomfort in regards to the altered scenario compared to the control. In all aspects, a minor shift towards answers aimed in the direction of higher comfort has been reported in control. However, this difference cannot be efficiently evaluated as a significant difference in favor of control. From the results, it can be generalised that participants can see sufficiently on both paths of control and altered scenario. Interesting results arise with perception of seeing the surroundings off-path, where participants answered as if lacking visual clarity of the background. However, when the test of surrounding visibility was conducted (test with seeing gray scale rectangles), participants did perform at least as efficiently as with control lighting settings. This showcases the difference between perception and actual visual abilities of participants within altered lighting scenarios.

The closed questions were then followed by a open-ended questions, where participants could express themselves more freely (see Table 08 and 09).

Do you think this lighting supports or discourages community use of this place?

participant	altered	control
1	I feel like red has connotations of danger. It feels like there is less light.	I don not think it hinders or supports community usage.
2	I think the lighting is sufficient for me to see, it feels kinda calm and not overpowering. I actually think it feels safe.	Maybe it could support community usage. The illuminance feels sufficient and kinda cozy, I would even talk to a stranger here.
3	I think the red lighting would discourage the usage of this space. Red does not feel very welcoming to me.	I don not feel like it would actively support any community usage.
4	I think the lighting is chill. Calm, not strong. Teenagers sitting on a bench. Mysterious, would attract different visitors. Artistic.	I don not think it supports nor hinders the usage in any specific way. I think the lighting here has no character.
5	I think it would discourage the usage. I would not like to stay here, if I were walking I would have sped up.	I don not think it supports or hinders community usage.

Table 08_Open-ended questions transctripts (1/2)

What kinds of activities would you feel comfortable doing in this lighting environment?

participant	altered	control
1	I would be okay with biking through here, maybe I would have sped up a bit compared to normal.	It is a bit blinding, I feel. I guess I would bike through here or walk with a friend. I am having a bit of trouble seeing into the bushes behind the lamp.
2	I would walk a dog here. I would be okay with walking through here. I would also be comfortable just sitting here.	I could walk, talk here. Bike also.
3	I wouldn't stay too long here I think. I think it is kinda a bad vibe, I would may-be walk or bike through, but not stay.	I can see the points of darkness ahead of me, between the lamp posts. It is a bit too intense under the lamp. Feels a bit weird, unnatural.
4	I would be okay with doing many things here, actually kinda normal, maybe a bit of poor visibility would prevent me from doing some vision-requiring tasks. I would sit here on a bench.	Walk, cycle, drive, and basic activities.
5	I would walk a dog here. I would do some sports like running or some-thing, and other movement-related activi-ties.	Walking, transit, have a walk, stroll. Social walk. Sports. Safe for movement.

Table 09_Open-ended questions transcripts (2/2)

The feelings expressed by the participants show that the responses are location dependent. If the area was more of a lingering spot (such as the nearby play-ground), it can be speculated participants would speak more of spending a longer time period, instead of just passing through, as this is the primary use of trial site. Essentially, recorded mentions of passing through are not caused by lighting, but rather by the site typology.

TEST 3_ OBSTACLE DETECTION

The third hypothesis concerning the obstacle detection under different lighting scenarios provided the following results (see Table 10):

	altered		control	
participant	placed	seen	placed	seen
1	6/4/3	5/4/3	6/6/5	6/6/5
2	6/5/3	6/5/3	4/5/3	4/5/3
3	6/4/3	6/4/3	4/3/6	4/3/6
4	5/4/2	5/0/2	3/6/5	3/6/5
5	6/4/2	0/1/3	6/4/1	0/4/1

Table 10_Obstacle detection results

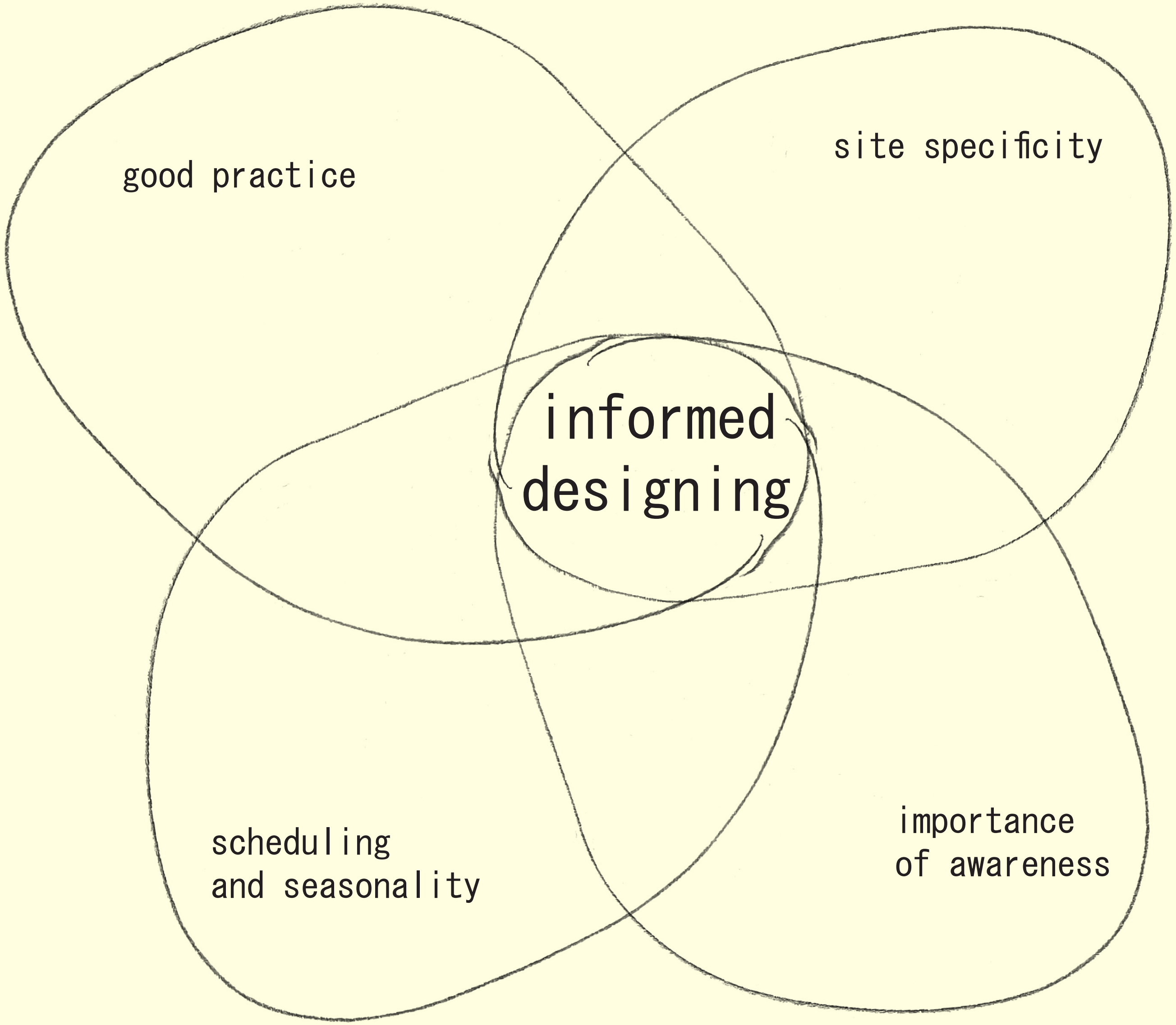
Generally, it can be observed that participants performed with similar precision under both scenarios. The reasoning behind more errors in the first take of the adapted scenario can be attributed to the participant's need of understanding the task before they could perform adequately.

While conducting the on site testings, a unexpected conversations took place with the accidental passer bys. They approached to ask about our tests as they saw the altered lighting in their neighborhood. Even though the three conversations were unrelated, the outcome was always similar, as neither of them had any idea why such lighting would be implemented apart from artistic motivations.

The first conversation took place with a middle-aged woman who had just came for a weekend as a property owner within the Kolonihave. Her thoughts on the altered lighting were that it seemed to be a too dim. After the explanation behind the design, the woman seemed to be less concerned by the fact that it was darker than usual and asked excitedly if it was going to remain on the site.

The next conversation was with a couple having a night walk in the park. They thought the lighting was an art installation. Later they said this was mainly because of the light colour. After explanation of the design they showed interest in the idea of environmentally friendly lighting in this area.

Third conversation was with a female from the Kolonihave approaching us asking about the 'art project' we were working on. Similarly to the previous people, she was also in favor of it being permanent.


good practice
site specificity
informed designing
scheduling and seasonality
importance of awareness

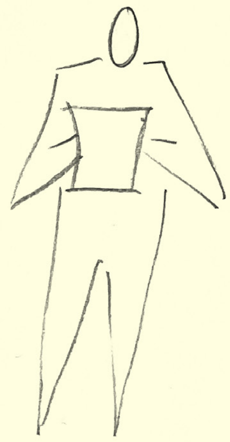
GOOD PRACTICE

Designing for nocturnal environments has long been guided by established 'good practice' frameworks such as those developed by DarkSky and other national and international bodies (see Appendix for more references). These guidelines are traditionally aimed at countering light pollution with use of lighting directionality, intensity, and duration. Today, there is a shift in discourse towards an alternative approach, particularly the spectral characteristics of light. The introduction of metrics such as the Light Pollution Emission Classes (LPEC, 2025) reflects this inovation, putting emphasis on the ecological and physiological impact of various wavelengths.

An effective nocturnal lighting design must account for all species present within a given environment, considering not only visual needs of humans, but also the circadian effects of artificial light on all affected living systems. Current research indicates that reduction of short wavelengths, particularly below 500 nm essential to hinder circadian disruption in both humans and wildlife. Avoiding the melanopically active lighting ensures that nighttime illumination supports the natural rhythms of all users of the area.

Further, lowering of the overall luminance levels plays a paramount role in nocturnal lighting effect on humans, particularly in order to avoid overstimulation of cone cells and to preserve the natural balance of nighttime vision. The recommended luminance ranges between 0.01 cd/m² and 3 cd/m². These levels support mesopic vision, balancing rod and cone input, rather than focusing solely on photopic vision, which is much less appropriate for nighttime settings. Prioritizing mesopic conditions is also as good starting point of minimizing circadian interference within conditions of public lighting.

Altogether, good practice of progressive nocturnal lighting design is defined not only by minimizing visibility of light, but by understanding its biological and ecological consequences. With evolution of standardization, designers shall embrace an integrated approach by balancing lighting functionality, perception, and its environmental consequences.



SITE SPECIFICITY

Lighting solutions should be site specific, based on typology- spanning from fully urban parks through semi urban areas to natural parks—allowing the lighting design to adapt a range of qualities according to the location (see Figure 38).

Site specificity is profoundly dependent on the species present, ensuring the nocturnal environment is as minimally disturbing as possible. For many animals, red or amber lighting is sufficient to avoid interrupting their circadian rhythms. For plants, however, it is also crucial to keep overall illuminance levels low (below 13 lux), allowing them to perceive the light as true darkness rather than a shadow, thus minimizing physiological disruption.

Another aspect of site specificity can be seen in the renovation of existing luminaires. Depending on their typology, final light coverage may need adjustment. If a luminaire includes a perpendicular arm connecting the pole and the light head, the amber/yellow filter can be centrally placed, directing useful light onto the path below. In this case, pedestrians are directly illuminated, enhancing facial recognition and visual comfort. If the luminaire lacks such an arm and is mounted at the side of the path, passersby may be illuminated more by red-filtered spill light, potentially affecting facial visibility. To compensate, the yellow filter should be slightly extended to improve facial recognition (see Figure 39).

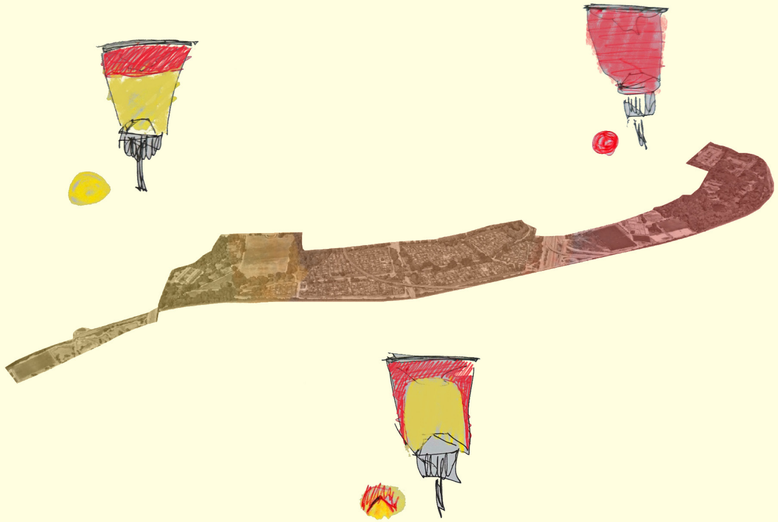


Figure 38_ Site-specific lighting modifications

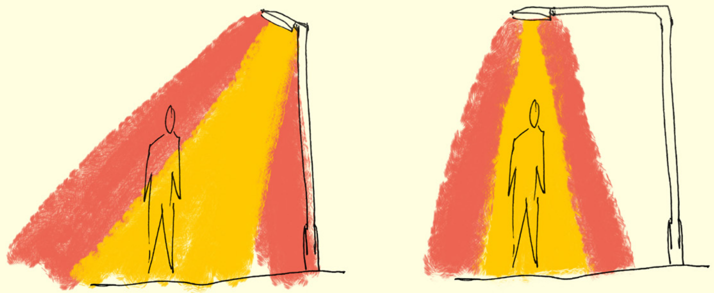


Figure 39_ Lighting distribution effect on facial recognition

Even in fully urban parks (such as Mimersparken), it is important to begin building healthy associations between environmentally friendly lighting and natural areas. In such contexts, the spectral shift is not visually prominent but serves a symbolic purpose raising awareness about the ecological role of red spectrum lighting.

Semi urban parks (like Lersøparken), which serve both recreational and transitional functions, should incorporate warm lighting with a full spectrum, high CRI component along the main paths, gradually shifting to red tones off path and eventually fading into darkness. This approach balances human comfort with the reduction of ecological disturbance.

In natural areas (for example, Ryvangens Naturpark), artificial lighting is generally discouraged. However, if lighting is necessary, it should be entirely free of short wavelength emissions and limited to long wavelength light to minimize environmental impact while still allowing basic human orientation (see Figure 40).

An additional level of site specificity can be achieved through species composition analysis, enabling lighting solutions to be aligned with the visual and circadian needs of local flora and fauna (see Figure 41-43).

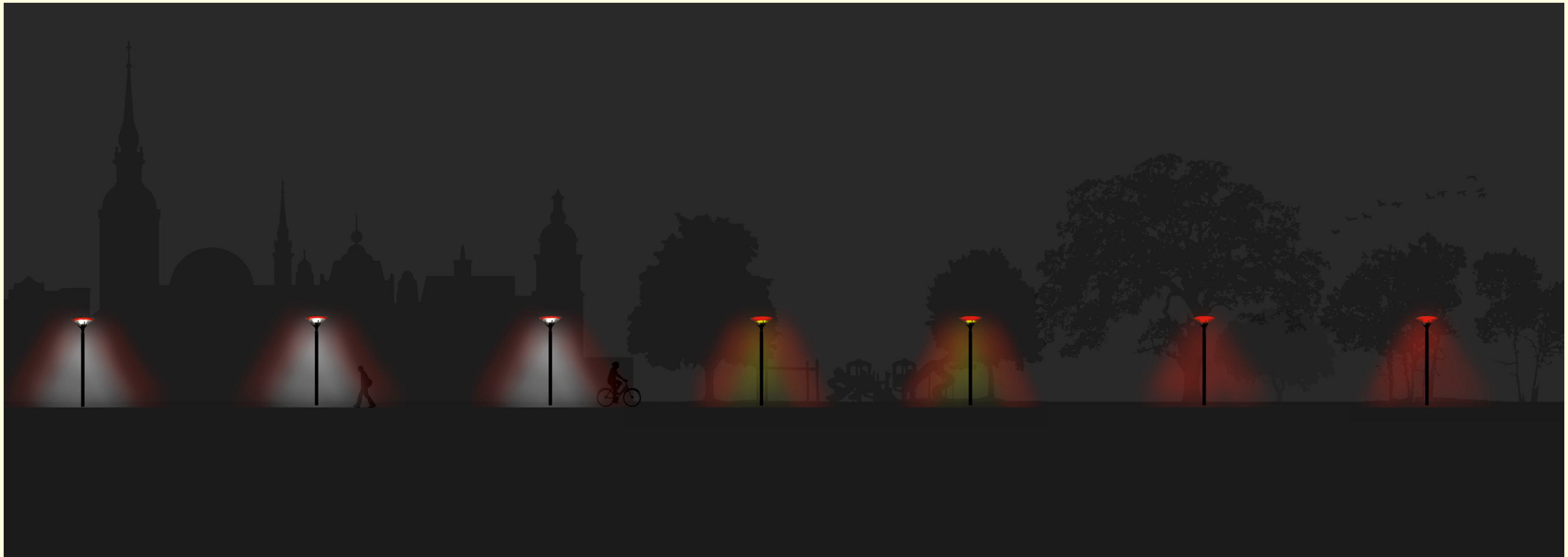


Figure 40_Section representation of changing modification of luminaire

Environmentally friendly urban lighting scenario with red strip to partially hinder negative effects of ALAN in higher canopies, but primarily aimed at creating public conscience of the issue.

Figure 41_Environmentally friendly urban lighting scenario

Environmentally friendly semi-urban/park lighting scenario with combination of red and amber light to hinder negative effects of ALAN off path, but also support human activities within path.

Figure 42_Environmentally friendly semi-urban lighting scenario

Environmentally friendly lighting for natural areas consisting primarily of long wavelengths of visible spectrum to hinder negative effects of ALAN on the animals and plants in their natural habitat, but enable human vision.

Figure 43_Environmentally friendly nature lighting scenario

SCHEDULING AND SEASONALITY

Current findings suggest that people often experience discomfort when exposed to red toned lighting in public spaces. Shifting public perception and acceptance of such lighting is a long term task. Dynamic scheduling of luminaires presents a strategy on how to ease the transition towards more ecologically responsible lighting practice.

By alignment of lighting with the daily activity patterns, especially during early mornings and after work hours, lighting can satisfy human visual and psychological needs while progressively introducing more sustainable lighting solutions. In seasons with shorter daylight hours requiring longer artificial lighting periods to support human work hours, lighting during commuting times can maintain a higher short wavelength content, approaching visual full spectrum illumination (see Figure 44). This strategy ensures visual comfort and functional support during critical periods of human activity.

As these peak periods finish, lighting can dynamically shift to environmentally optimized settings with melanopic daylight efficacy ratio values below 0.35. This threshold has been shown not to impair obstacle detection or recognition, nor to degrade the color rendering index to levels considered inhospitable to human use. Thus, proposed ecological lighting remains functional while minimizing circadian disruption.

Essentially, public night time lighting should draw inspiration from natural seasonal cycles, adapting its spectral and temporal characteristics to reduce disturbance to wildlife. Incorporating these principles into urban lighting design creates a lighting rhythmicity that better supports the coexistence of human activity and wildlife wellbeing.

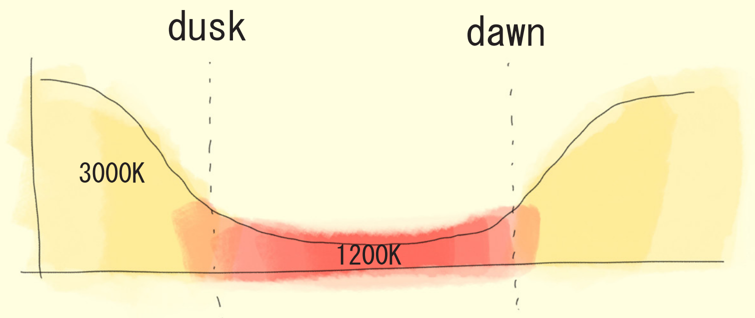


Figure 44_ Illustrative graph of lighting scheduling

IMPORTANCE OF AWARENESS

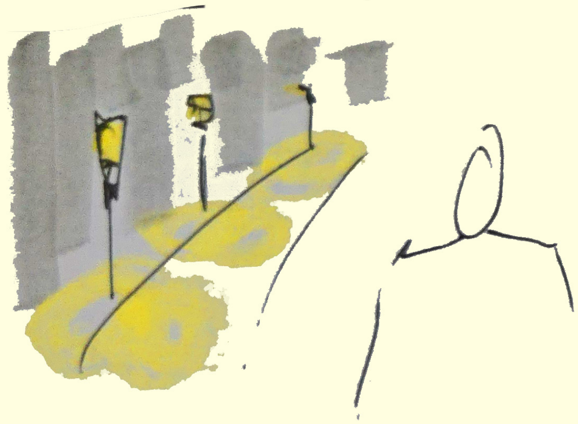
Observations from lighting interventions and accompanying discussions revealed that public awareness is paramount in the acceptance of environmentally inclusive lighting. Participants often perceived light stripped of blue wavelengths, such as red or amber light, primarily as artistic rather than with an environmental purpose. These reactions show a general lack of lived experience and familiarity with such lighting solutions in everyday settings.

Introduction of longer wavelength lighting, particularly in areas where urban life intersects with forms of nature, offers an opportunity to build new associations. By use of red toned lighting in these transitional spaces, lighting community can gradually reshape public perception by linking warm colored lighting with ecological awareness and nature.

By expanding exposure to long wavelengths lighting in urban environments, one can also challenge and disrupt persisting cultural associations of red light and danger. In case the integration is sucessfull, long wavelength lighting can become part of a broader visual language of sustainability and environmental care.

To balance human needs with ecology, a typological gradient in spectrum is proposed. Urban areas, where color rendering and visual clarity are essential consist of full spectrum lighting with high color rendering index. Whereas areas closer to natural habitats benefit from a higher proportion of longer wavelength lighting. These changes are introduced gradually to avoid abrupt unpleasant perceptual shift and encourage expectation and acceptance.

Creating of awareness this way is not only a communicative task but a spatial and experiential design strategy to foster acceptance of lighting practices that support both the human use and ecological inclusivity.



REFERENCES OF PRACTICE

Even though there are already existing projects implementing lighting dominated by longer wavelengths (see Figure 45-46), this thesis suggests that certain adjustments could improve their functionality. The overall red ambience of existing solutions could be accompanied by a precisely focused strip of warm 2000K light sources, dedicated solely to supporting the visual needs of human users. At the same time, it is understandable that many of existing solutions prioritize the environmental protection particularly in sensitive areas such as migratory routes. Therefore, the integration of scheduling strategies is essential to allow the lighting system to adaptations dynamically shifting with changing presence of primary users over time- daily and seasonally.

Figure 45_Bollard sprayed with red (Ryvagens Naturpark)

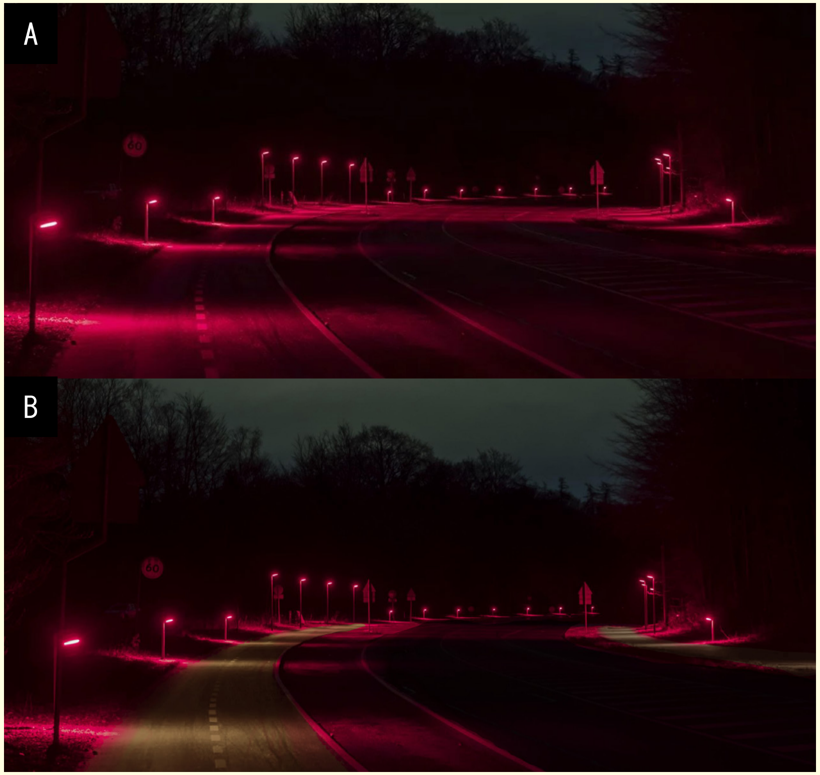


Figure 46_Gladxase nature friendly lighting (A= original, B=adjusted) (Light Bureau)

CONCLUSION

The findings of the thesis reveal there are fundamental differences in environmental light requirements across all stakeholders- plants, animals, and humans. Humans are an only species reliant on artificial illumination due to their diurnal photoreceptory system, simultaneously humans are also the sole source of lighting related environmental disruption. Artificial light extending, spilling over into shared urban ecosystems, interferes with the natural behaviors and rhytmicities of nocturnal species and can also act as a physiological stressor of plants. This spetial interconnectedness highlights the need for outdoor lighting solutions that accounts for the diverse needs of all living systems.

A lighting design approach addressing both ecological impact and perceived safety creates a new lighting strategy. Practical laboratory experiments and lighting interventions demonstrated that luminaires modified with red filtering to hinder unnecessary spill light and amber filtering serving as path lighting have the ability to achieve recommended melanopic ratio values. In these configurations, disruption to circadian rhythms caused by poor lighting can be minimized in both humans and animals.

On site testing in semi urban park settings revealed that altered lighting had negligible impact on participants' obstacle detection abilities. While some participants reported reduced confidence in perceiving their surroundings, quantitative measures indicated no significant difference between control scenario and ecologically aware lighting. These findings suggest that within lighting industry, performance and ecological responsibility are not mutually exclusive, and that perceived shortcomings can be counterbalanced through user education and appropriate design integration strategies.

By alignment of perceptual comfort with environmental awareness, lighting design can contribute meaningfully to more sustainable and inclusive urban nightscapes.

DISCUSSION

The topic of this thesis is highly relevant in the social and environmental climate of today, as we face an increasing number of challenges stemming from global ecological change. While large scale solutions to climate shift often feel abstract and unattainable, changes to outdoor lighting in our cities and towns represent an actionable and tangible intervention with clear impact.

Such solutions not only benefit biodiversity but can also contribute to reduced energy consumption in public lighting systems. Lower light levels, warmer spectra and scheduling reducing unnecessary output and smart controls improving efficiency. This supports both ecological goals and public sector efforts toward sustainable urban infrastructure.

However, evaluating the long term success of these lighting strategies requires sustained observation. Key indicators should include actual safety metrics, such as trends in crime rates in areas with implemented solutions and ecological metrics, such as biodiversity dynamics recorded over long time periods. This shows the demand for more comprehensive site specific species datasets and interdisciplinary collaboration, for instance by including biologists in lighting design teams of municipality projects to provide ecological assessments early in the design process.

There is also a clear need to foster a market that recognizes and values the ecological and aesthetic qualities of environmentally sensitive lighting. Public sector demand can drive the market in the right direction, but only if the benefits and visual potential of these solutions are clearly communicated and required by such institutions. A cultural shift is needed to chenge the value of darkness, where it is measured not only in monetary terms, but also in terms of ecological resistance and public wellbeing. This shift requires a narrative of lighting design being focused on sustainability, rather than only on providing humans with visual clarity in order to gain profit.

The study showed that this understanding is not yet widespread. Public awareness of the environmental effects of outdoor lighting is low with many people initially responding with skepticism or discomfort, especially when exposed to lighting stripped of blue wavelengths. However, as observed, once are these individuals informed about the reasoning and ecological necessity behind these spectral changes, they tend to become more receptive and supportive. This underscores the importance of education and communication in improving broader acceptance and success of sustainable lighting strategies.

FUTURE WORKS

Building on the findings of this thesis, several areas require further investigation. As the ecological impact of lighting intervention would emerge over extended time period, long-term monitoring would be essential to observe and evaluate the potential impact. Therefore, sustaining a collaboration between lighting designers, biologists, and municipal stakeholders is necessary to track and evaluate the outcomes of emerging environmentally sensitive lighting strategies. An interdisciplinary cooperation could facilitate the integration of ecological lighting into standard urban planning and design practice, as well as bring important insights and help to shape further progress.

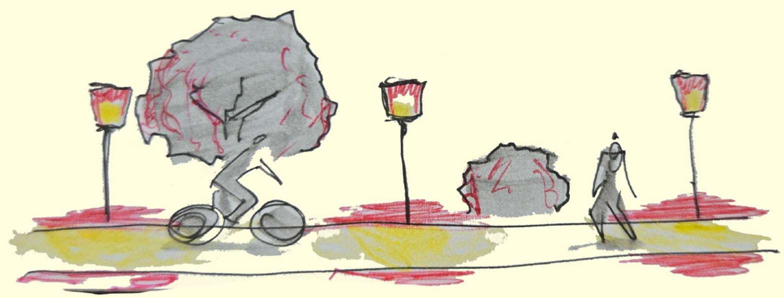
A potential promising direction involves the development of designated environmental zones within urban sites. These zones could serve as test-sites for implementing context-sensitive, site-specific lighting typologies, as they would be selected based on their respective ecological profiles. The zoning approach would enable more tailored and scientifically informed lighting design, connecting the urban infrastructure with specific biodiversity needs of each zone.

As much as it is important to look forward, an important part of research shall also further examine how animal species have already responded or adapted to artificial lighting environments. As there has been reported a phenomenon of biotic homogenization, where native species are displaced by more light-tolerant generalists, as mentioned in Reed (2012), as better understanding of these adaptive strategies would show whether current lighting approaches are either tolerated or actually sustainable.

The progress within automation industry and high environmental data collection level present an opportunity for responsive lighting system development. By integrating various datasets regarding species presence and behavior, lighting could be adjusted dynamically and precisely across both daily and seasonal cycles.

Such systems would allow for spectral tuning that aligns with the biological rhythms of species on site. These systems shall be technologically available, yet any mentions of these have not been noted, posing an open opportunity for further research.

Finally, public engagement is to be critical for succesfull implementation of ecological lighting solutions. There is a need for educational initiatives, such as workshops and also participatory design processes, as these could foster a deeper understanding of the environmental implications of urban lighting and promote its public acceptance. Raising awareness is an essential step not only for behavioral change, but also for building societal support chain for sustaining long-term, ecologically responsible urban lighting strategies.



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LIST OF FIGURES

*full page figures created by authors

LIST OF TABLES

APPENDIX

<u>List of international guidelines and initiatives regarding the environmental lighting:</u>

LEVEL BODY//INITIATIVE TYPE RELEVANT CONTENT//ACTIONS EUROPEAN UNION

Environmental Impact Assessment (EIA)//Directive (2011/92/EU)// Directive Requires assessment of significant environmental effects of projects, including lighting.

Strategic Environmental Assessment (SEA)//Directive (2001/42/EC)//Directive Ensures environmental impacts (e.g., light) of plans/programs are considered.

Birds Directive (2009/147/EC)//Directive//Indirectly relevant: disturbance by lighting can affect protected species.
Habitats Directive (92/43/EEC)//Directive//Article 12/13 prohibits disturbance of protected species - includes effects of lighting.

8th Environmental Action Programme (to 2030)//Framework//Includes targets for reducing light and noise pollution.

Nature Restoration Law (Draft)//Regulation//Suggests MS address light pollution in all ecosystems.

Future Brief (2023)//Research/Policy Paper//Identifies mitigation measures for environmental protection.

Brno Appeal (Czech Presidency, 2022)//Workshop//Outcome Advocates' three key principles: necessity, shielding, and spectral regulation.

Spanish Presidency (2023-24)//Policy//Focus Highlighted LP in the State of the World's Migratory Species Report.

PLAN-B Project (Horizon Europe)//EU-Funded Initiative//Tackles light and noise pollution for biodiversity.

AQUAPlan Project//EU-Funded Initiative//Focus on LNP impacts on aquatic biodiversity.

EULE Mission / DARKERSKY4CE//Ongoing Initiatives//Developing frameworks for LP reduction and awareness.

APPENDIX

List of national guidelines regarding the environmental lighting:

NATIONAL//LOCAL COUNTRY//REGION RELEVANT LAW//POLICY DETAILS

Croatia//National//Act on Protection against Light Pollution (2021)//Lighting zones, max parameters, voluntary commitment, and monitoring without sanctions.

Germany//National//Federal Nature Conservation Act (2022)//Insect protection: bans UV/ALAN in reserves, restricts CCT to max 3000K, and time limits.

France//National//Environmental Code, Biodiversity Strategy 2030//Mandatory LP reduction measures incl. curfews, administrative sanctions, and urban lighting reform.

Austria//Upper Austria//Environmental Protection Act (Amendment 2024)//Limits light intensity/duration, municipal responsibility, and binding lighting standard.

Czech Republic//National & Local//Light Pollution Conference (Brno 2022)//Highlighted LP reduction in EU policy through the Czech presidency's efforts.

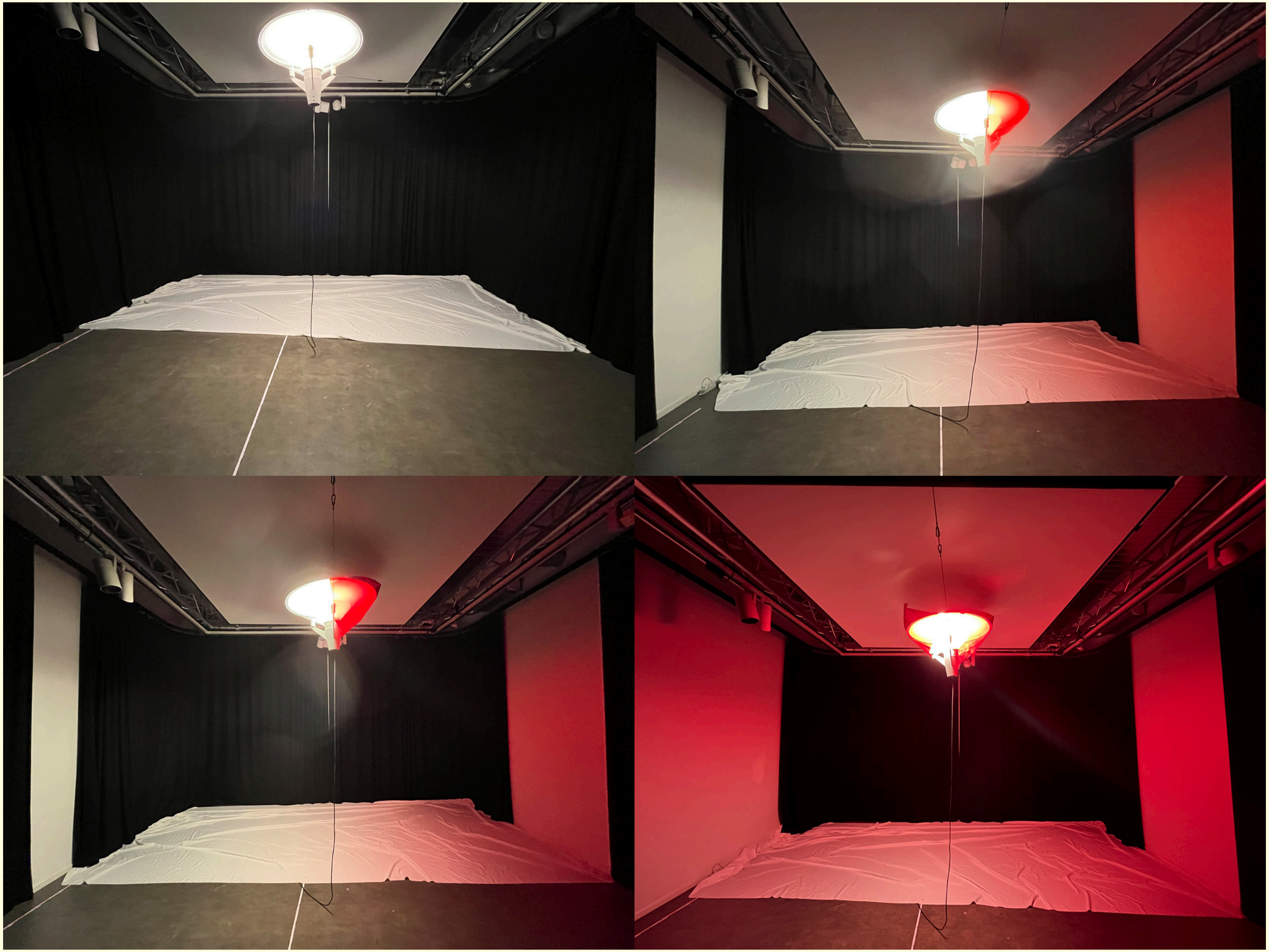
Other sources of knowledge regarding the environmental lighting:

OTHER ENTITIES//ORG, INITIATIVE//TYPE//RELEVANT ROLE

DarkSky International//NGO//Advocacy, Guidelines//Promotes LP mitigation, provides technical guidance (shielding, spectrum control).

Independent Research//Conferences & Academic Events//Knowledge Sharing//Conferences like Brno 2022, Dark Sky Conference promote awareness and cross-border action.

APPENDIX



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