IOP Conference Series: Earth and Environmental Science

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To cite this article: S Dincel *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1320** 012002

IOP Conf. Series: Earth and Environmental Science 1320 (2024) 012002 doi:10.1088/1755-1315/1320/1/012002

Light formed through urban morphology and different organism groups: First findings from a systematic review.

S Dincel[1], U Besenecker[1], D Koch[2], KM Zielinska-Dabkowska[3]

[1] Lighting Design Division, School of Architecture, KTH Royal Institute of Technology, Osquars backe 5, 114 28 Stockholm, Sweden;
[2] School of Architecture, KTH Royal Institute of Technology, Osquars backe 5, 114 28 Stockholm, Sweden;
[3] GUT LightLab, Faculty of Architecture, Gdansk University of Technology, Narutowicza 11-12, 80-233, Gdansk, Poland
Corresponding author's e-mail: dincel@kth.se

Abstract. The prevailing implementation and usage of contemporary lighting technologies and design practices in cities have created over-illuminated built environments. Recent studies indicate that exposure to electric lighting effects formed through spatial characteristics has visual, physiological, and behavioural effects on both humans and non-humans, such as wildlife. In order to gain a better understanding of the impact that electric lighting has on space and different organism groups, a comprehensive literature review was conducted applying PRISMA 2020 systematic review guidelines. Results of the searches from various databases, such as Web of Science, PubMed and Scopus, identified 5260 related studies. A total of 55 papers connected to four themes: (1) urban morphology; (2) human visual impressions; (3) ecological impacts; and (4) design approaches and methods were analysed with a focus on urban morphology. The review provided the following general findings: lighting properties alone are inadequate to depict visual impressions of pedestrians, patterns formed through light interacting with spatial characteristics can contribute to understanding how spaces are visually perceived and help characterising the exposure of wildlife organisms to potential disturbances.

1. Introduction

1.1. Background

Built environments, whether indoor or outdoor, affect people's experiences through visual impressions. Electric lighting supports people's movements after darkness falls and engages them with their surroundings [1]. Outdoor spaces are utilised in different ways and for different purposes after dark, including recreation, socialisation, commuting, training, and a range of other activities. For most everyday purposes, good visibility of relevant objects and the overall environment is essential for the readability of public space. Some activities, for example, walking in an urban park, may be restricted by the lighting conditions this demands, and lighting conditions are also part of constructing habits and behavioural patterns [2, 3]. The process of vision and perception is mediated by the anatomical and psychophysical responses to light. Human vision is influenced by optical and spectral characteristics of light sources and visual perception and interpretation processes [4]. Human vision adapts and operates differently in environments of varying light levels and spectral content. The three states of vision are photopic (at light levels higher than 5 candelas per square metre, cd/m^2), scotopic (at light levels less than 0.005 cd/m^2), and mesopic (between light levels of 0.005 and 5 cd/m^2); they operate respectively during daytime, night-time, and transitional periods [5]. Visual perception processes occur in connection with the interplay between illuminated objects and the illumination of the areas surrounding them [4]. The visibility of objects located in immediate and distant surroundings depends on the object's size and the contrast ratios created by the varied light levels [6]. The material form of the city affects lighting and vision in many ways, be it through, e.g., size, shape, density, articulation, or surface materials. This suggests that the integration of urban morphology, that is, studies of e.g., the growth and form of settlements by considering land use, building structures, and plot and street patterns [7, 8, 9], with lighting design research should be of interest. Aside from how the shapes of buildings and infrastructure organise, open and limit space and vision, the choice of surface materials is also a determinant factor on regulating where and how light can pass or be reflected [10]. Visual impressions created through the interaction of light with spatial characteristics unfold an architectural dimension that is not limited to easily measurable physical lighting characteristics in urban contexts [11]. This review aims to inform a better understanding of the interconnectedness between lighting, spatial characteristics, and the states of vision that play a role in the actual visual experience of illuminated after-dark environments.

Environmental issues related to lit urban areas call for urban lighting research to engage with sustainability. With an increasing interest in the well-being of humans and the preservation of ecology, particularly two of the Sustainable Developments Goals (SDGs) put forth by the United Nations become relevant in this context of lighting research and practice. These are SDG11: Sustainable Cities and Communities and SDG15: Life on Land, which address the needs for sustainable, inclusive human settlements and the preservation and restoration of terrestrial ecosystems. The health-related impacts of exposure to electric lighting in human and wildlife organisms can range from physiological changes to survival capabilities [12]. Implementation of contemporary lighting technologies, e.g., conversion to energy-efficient LEDs, came with increased adverse effects on ecological habitats [13]. Besides the direct effects from light sources, atmospheric conditions, such as cloud cover and weather, alter the environmental impact when combined with the reflected illumination [14]; this can generate skyglow, leading to disruptions on some wildlife organisms [11, 15]. The human-centric perspective of planning practices resulted in the human-ecology dichotomy as these entities have been only addressed respectively, lacking an overall holistic consideration in research and practice [16]. The intersection between ecological responsibility and the visual experiences of pedestrians would entail a comprehensive design approach for simultaneously embracing human and wildlife organism groups' needs in urban green environments. The authors hypothesise that connecting lighting and spatial characteristics could support reassessing contemporary lighting technologies and their potential to minimise the ecological impact of electric lighting.

To explore possibilities and collect knowledge on bridging the human-ecology dichotomy created by urban lighting applications, this paper reviews research on the impact of LED illumination in urban parks. This literature review was conceptualised to help identify the relevant lighting parameters and spatial characteristics within green areas that influence the pedestrian visual impressions and wildlife organisms to be later tested in a full-scale field experiment. The objective was to understand the state of the art (and gaps) in lighting technology and to interpret the interplay between lighting properties and urban morphology impacting different organism groups from an architectural perspective. This review is based on papers that include relationships between lighting and spatial characteristics, visual experiences of pedestrians, and impacts on wildlife; papers with other focus areas that did not inform the review topic were excluded based on a set of criteria, see section 2. for more details.

1.2. Research questions
To explore and inform a comprehensive urban lighting design approach by involving considerations on both pedestrian's visual needs and ecological concerns in designing and planning processes, the following questions have been formulated to guide the review and research. To explore the link between urban morphology and lighting design:

1. How do spatial characteristics in urban form influence the effects created by electric lighting that impact different organism groups?

To more specifically define these effects and properties, the additional questions:

2. What lighting properties can support pedestrians' visual impressions after dark?
3. What lighting properties can be tuned to minimise the impact on local wildlife organism groups?

Overall, the research that this review paper is part of aims to explore the broad inquiry:

4. How can responses in human and wildlife organism groups to electric light exposure inform urban lighting design approaches and methods?

These four questions, or themes of inquiry, were used to categorise the review (Fig.3). Note that this paper focuses mainly on discussing the research questions 1–2 and broadly addresses the questions 3–4. The latter questions (3–4) in the reviewed studies will be respectively analysed and discussed in-depth in separate, dedicated papers.

2. Materials and methods

This systematic review paper includes research studies published from 2000 onwards in English. The review process follows PRISMA 2020 guidelines to identify and screen studies (Fig.1). Initially, keyword combinations in English were established by forming categories of areas and organism groups for the literature search. Keyword combinations for searching literature were arranged into four categories, and three separate searches were performed by combining categories. The defined keywords were searched, combining the areas of lighting and urban morphology with the respective organism groups of humans and non-humans (Fig.2). "AND" is used to bind keywords (e.g., lighting and urban morphology with humans), and "*" to broaden the search finding by including word stems or plural forms of the keywords. The three-stage review process included identification, screening, and inclusion phases.

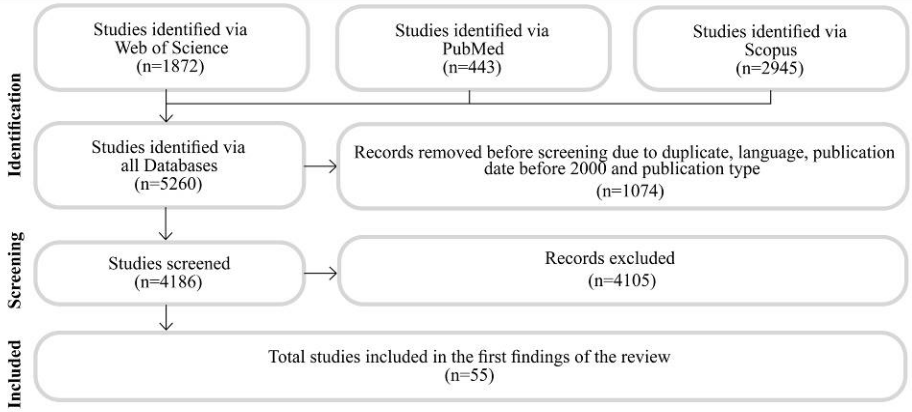

Figure 1. Flow chart for the literature search process and selected studies for review using PRISMA 2020 guidelines.

Areas	Lighting	"urban light*" OR "artificial light*" OR "electric light*" OR "street light*" OR "outdoor light*" OR "exterior light*" OR "city light*" OR "lighting design" OR "urban illumination"
	Urban morphology	"urban env*" OR "built env*" OR "urban plan*" OR "urban design" OR "urban space" OR "architectur*" OR "park*" OR "green area*" OR "green space*" OR "greenery" OR "vegetation*" OR "tree*" OR "pathway*" OR "pedestrian space" OR "spatial*" OR "material*" OR "reflect*" OR "weather" OR "snow" OR "rain" OR "asphalt"
Groups	Humans	"human*" OR "people" OR "pedestrian*" OR "anthropogenic" OR "visibility" OR "visual" OR "percept*" OR "vision" OR "accessibil*"
	Non-humans	"wildlife" OR "animal*" OR "species" OR "bird*" OR "mammal*" OR "rodent*" OR "shrew*" OR "hedgehog*" OR "mole*"

Figure 2. The keywords for the category of areas and organism groups.

The literature searches were performed using Web of Science, PubMed, and Scopus search engines during the period of February to March 2023, and the papers were reviewed from March to July 2023. The literature search was aimed to detect and include only peer-reviewed articles, proceedings papers, and book chapters. In the identification stage, a large number of articles that were not relevant to our inquiry were eliminated. 1074 papers were excluded due to duplication, language, publication date, and type. Because our review concerns the specific case of pedestrian lighting for urban green spaces, screening was performed by applying exclusion criteria to the studies, including the following aspects:

- Outdoor lighting that concerns only motorised vehicles or/and cyclists.
- Outdoor lighting focusing exclusively on people's perception of safety, health-related or social aspects, atmosphere, artistic installations, and energy efficiency.

- Lighting for visually impaired people.
- Street lighting for roadways or areas adjacent to buildings and facades.
- Non-human organism groups that are not relevant to wildlife research in the Nordic countries.
- No inclusion of the use or comparison of LED light sources.
- Unidentified non-human organism groups and undefined light sources, e.g., only described broadly as ALAN ("artificial light at night" or "anthropogenic light at night").

	Amoruso et al.	Bandopadhyay et al.	Cafuta, M.R.	Capron et al.	Choi et al.	Davies et al.	Dominoni et al.	Dunn N.	Dwimirnani et al.	Esposito et al.	Gaston et al.	Feng et al.	Fotios et al.	Hvass et al.	Karamouzi et al.	Koen et al.	Johansson et al.	Li et al.	Lin et al.	Liu et al.	Maccheroni et al.	Markvica et al.	Masullo et al.	Moeck M.	Navvab et al.	Ogando-Martínez et al.	Pan et al.	Patching et al.	Pedersen et al.	Pérez Vega et al.	Portnov et al.	Pracki et al.	Rahm et al.	Rea et al.	Ross et al.	Sakici et al.	Schroer et al.	Toet et al.	Tripathy et al.	Valetti et al.	Viikari et al.	Vitasek et al.	Wänström Lindh et al.	Žák et al.	Zhang et al.	Zielinska-Dabkowska, KM.
Theme 1 Light and Urban Morphology			x		x			x	x			x		x	x			x		x	x	x				x	x	x			x				x	x			x	x		x	x			x
Theme 2 Light and Visual Impression	x	x	x	x									x	x			x		x				x	x	x				x				x	x	x			x		x	x		x	x	x	
Theme 3 Light and Non-humans						x	x				x					x																			x		x									
Theme 4 Design Approaches and Methods			x					x		x				x			x						x							x		x			x			x		x					x	x

Figure 3. Papers corresponding to the four themes (research questions) based on the first findings of the literature review.

The exclusion criteria were constructed to focus on reviewing papers on light parameters that influence pedestrians' visual experiences concurrently causing ecological impact in urban green areas. The aim is to establish an ecological understanding for embracing a more responsible use of contemporary lighting technologies designed to enable human activities after dark. After scanning titles and abstracts in the screening phase, full texts were reviewed for identifying and assembling results. The results were categorised based on four themes related to the research questions: (a) light effects formed through urban morphology, (b) pedestrian visual impressions, (c) responses in wildlife organisms, (d) design approaches and methods (Fig.3). A total of 55 studies were included in the first stage of the systematic review.

3. Results

This review on urban lighting design is aimed at the integration of how urban morphology conditions are affected by light, human perception and ecological considerations. The detailed review results are described and discussed below. The results indicate that urban morphology, together with the physical properties of LED light sources, is a contributing factor in shaping patterns of light and dark, thus influencing pedestrian visual impressions and impacting wildlife. Moreover, physiological and behavioural effects of exposure to direct and indirect electric lighting properties on wildlife organisms were identified.

3.1. Interplay between urban morphology and electric lighting

3.1.1. City planning and morphology. An indirect result of the exclusion criteria applied for this paper demonstrates what is generally true also for the remaining included papers: planning and morphological research tends to focus on analysing lighting as a means to an end and rarely engages directly with light perception. In the included papers, arguments regarding the sense of safety [17-19], effects on use intensity [17, 19-22], attraction and comfort [17, 19, 22, 23], and energy efficiency [19, 20, 24] are dominant. In line with morphological research traditions, historical reflections are included in several papers [3, 20-22] but remain brief and broad rather than specific, while one can find it central for the discussion [3] or specifically related to the analysed area [22]. The papers primarily concern methods for improving lighting and fall into either empirical study of lighting effects on behaviour or perceived quality [17-19, 21, 22] or methods to optimise lighting based on sourced or assumed priorities [20, 23, 24]. Only a few directly address relations between morphology, lighting, and the evaluation criteria of the respective paper—e.g., attractiveness, behaviour, use intensity, etc.—and most empirical papers used either perceived or reported light quality, intensity of use, or observed behaviour of pedestrians. Almost all papers treat lighting as complementary: as an addition to urban form rather than integrated into urban design thinking. Importantly, while most papers report little direct links between lighting and behaviour [19, 21, 22], perception and evaluation are consistently reported to be impacted [17, 19-21]. The paper on Dark Design [3] stands out in this regard. While lighting is generally considered intrinsically good, two papers [3, 20] question lighting not only from efficiency or ecological perspectives but also from human and social perspectives and highlight how electric lighting has and will change how individuals and societies relate to light and darkness.

3.1.2. Scale and edges. Brightness, contrast, uniformity, distribution, and surfaces are significant factors for altering impressions of scale, boundaries, and form of the urban landscape from a human perspective [25-27]. Jan Gehl's human-scale concept is referred to in lighting design literature, supporting social activities by looking into architectural proportions and urban contexts [1,11]. Design aspects such as lighting layout, luminaire mounting height, the amount and direction of luminaires, and their distribution play a role in changing the scale perception of spaces. Light patterns that are horizontally or vertically arranged can enlarge the width and height impression when overlapped effects increase the brightness regardless of low-level ground lighting [25-27]. Overlapping the light patterns can also positively influence the impression of lighting uniformity, hence strengthening spatial continuity. Furthermore, eliminating the dark spots that break off the continuity makes the space look broader [26, 27]. Detaching the light patterns and illuminating background surfaces distinctively escalates depth perception [27]. A lower luminaire mounting height of four and a half metres is preferred for pedestrian lighting over a higher mounting position of six metres and above, typical in roadway lighting, providing a smaller-scale and personal impression of space despite the non-uniform distribution of lighting at a lower height [26].

3.1.3. Visual permeability. Several studies include Kevin Lynch's five elements: paths, edges, districts, nodes, and landmarks, as a valuable approach to illuminating key urban features [1, 26], constructing a visual representation of the city after dark [11]. Decreasing contrast ratios enhances the readability of architectural characteristics [26, 28]; however, visual coherence between day- and night-time appearances of structures is diminished [29], and spatial order among architectural layers is blurred [11]. Variations in brightness-contrast levels can create either a visual enclosure or openness in the urban context. Thus, perceiving illuminated objects, such as tree trunks, as detached single elements generates visual boundaries, whereas observing them as being part of the background gives a broad and open space impression [25]. Visual boundaries reinforce the space's legibility by applying contrast and non-uniform, peripheral, and vertical illumination [26], thereby supporting the perception of safety [11].

3.1.4. Soft and hard landscape elements. The interaction between electric lighting and soft landscape elements, such as trees and bushes, results in varying effects due to light being reflected or diffused [26, 30]. Illuminated buildings and spatial forms located within a height range of 0-20 metres can produce intrusive and spilled light [30]. The texture of trees, dense or light, determines the visual quality of the surroundings and should be taken into account when planning illumination. Dense-textured trees can effectively be illuminated by fixtures from a distance due to their low light transmittance [31]. Dense and tall vegetation cover at pedestrian height can contribute to an improved perception of the light distribution [26, 30], and broad-leaved trees can act as reflectors and diffusers, leading to the impression of a "large-scale outdoor living room" [30]. In natural surroundings, non-uniformly distributed lighting and sharp contrasts are softened due to tall trees; therefore, large pole spacings of 40 metres become unnoticeable [26]. Low light levels in highly vegetated urban parks have a better uniformity than in areas with high building coverage ratios [30]. Discomfort glare can be reduced by changing the light source visibility and direction towards greenery [32].

The composition of surface materials, such as being specular or uneven, affects the light behaviour by projected light onto these surfaces being reflected or absorbed [10, 11, 33]. Standards that are defined for road pavement reflectance are outdated for obtaining accurate results in computer-aided simulations.

IOP Conf. Series: Earth and Environmental Science 1320 (2024) 012002 doi:10.1088/1755-1315/1320/1/012002

Especially reflectance values of contemporary materials which are developed to combat the heat island effects, such as cool asphalts, as well as porous and stone mastic pavements, are insufficient [34]. Material surface properties can contribute to light uniformity and low luminance values, e.g., a porous pavement in dry conditions performing well at low light levels, such as 2 cd/m^2. High luminance levels that emerge through specular properties of surfaces lead to decreased uniformity and discomfort glare [35]. Lowering luminance levels also supports improved visibility of the surroundings in connection with diminished reflections from glossy surfaces, such as glass panels [28]. Besides visibility issues, reflections from illuminated surface materials can pose an ecological risk due to altered skyglow [11].

3.1.5. Weather conditions. Light pollution is produced by electric lighting and can be increased by weather conditions, cloud thickness, air quality, and lunar phases. Liu [36] measured different light intensities during rainy weather in clear and cloudy sky conditions and demonstrated the highest brightness in the evening hours between 22:00 and 23:30 under clear sky conditions in which the sky colour was described as orange. Cloudy sky conditions amplify artificial illumination effects the most compared to a clear sky and lunar phase. Due to the reflectance properties of snow, sky brightness escalates more than it does under rainy weather. Severely polluted air exacerbates light pollution effects 10 times higher, while lunar phases contribute least to environmental impacts [36]. Despite the minimal impact, illuminance levels of 0.0001 lux on a starry night and 0.3 lux on a full-moon night can interfere with the melatonin production of some of the light-sensitive wildlife organism groups [37]. On the other hand, Vitasek [38] showed that varying fog intensities reduce light distribution. Three separate layers are proposed for assessing electric lighting outdoors: ground surface, canopy, and sky [36].

3.2. Impact of electric lighting on human visual processes and impressions

3.2.1. Human vision under photopic, mesopic and scotopic light levels. Visual perception is influenced by light source characteristics, the properties of object surfaces that the light reflects from, and the receivers and their visual system [39]. Cone photoreceptors in the eye facilitate detail and colour vision at high light levels (photopic vision) and guidelines and tools for outdoor lighting systems [40]. Light levels of 3-5 cd/m^2 are the threshold for mesopic vision, meaning that cone vision decreases with lowering light levels, and the rod photoreceptors become active [39, 41]. Rods are the photoreceptors that enable low light, scotopic vision at levels lower than 0.001 cd/m^2. Rods are distributed throughout the visual periphery and tuned to shorter wavelengths. Therefore, with decreasing light levels, the sensitivity of human vision moves towards shorter wavelengths, colour perception diminishes, and peripheral vision becomes heightened over central vision. While these mechanisms have been known, and the scotopic to the photopic ratio (S/P ratio) is an established measure to evaluate the ability of light to support low-light vision, there is no agreement on designing lighting for the urban and suburban outdoors [42-44]. Early models proposed look-up tables for factors to adjust photopic luminance to mesopic [44], but one of the complexities is that the spectral sensitivity of low light vision changes with light levels [39]. Researchers have explored mesopic vision models to digitally simulate visibility in responses to different light spectra and light levels [43] and related affective responses. Mesopic systems of photometry integrate scotopic and photopic vision models to estimate visual performance; the development of brightness models, however, turned out to be more complex [42]. The role of the intrinsically photosensitive retinal ganglion cells, a recently discovered photoreceptor, is also being researched, and evidence suggests involvement in scene brightness perception [45]. Visual performance is important to detect obstacles and recognise information [42], and brightness perception has been associated with perceived safety [46, 47], although, as highlighted by other research, such effects are also personally, culturally, and historically bound [3]. With decreasing light levels, human visual systems tune increasingly to shorter wavelength, and to take advantage of that notion, earlier research suggested strategies to install short wavelength-rich (cool-white appearing) lighting which would allow the lowering of light output and energy consumption [42]. However, the short-wavelength light contributes to skyglow [48], which raises ecological concerns, and, especially under certain weather conditions, decreases visual comfort and performance by hindering dark-light adaptation and producing more glare than visually warmer lighting [49]. Higher brightness does not necessarily support vision, as it can create high contrast ratios with darker surroundings, challenging visual adaptation [50]. When transitioning from bright to dark environments, it can take several minutes to return to normal visual sensitivity. Lowering light levels and providing gradual transitions could be a strategy to support dark adaptation, increase visibility, and minimise energy consumption and skyglow. Adaptation luminance changes with gaze direction, especially when walking in non-uniformly illuminated outdoor spaces [43]. Research using eye tracking has investigated adaptation luminances in cities and their simulations after dark (0.1 to 10 cd/m^2) [40, 43]. Generally, more light is needed for people over 60, but at the same time, higher uniformity and less contrast. The ability to light/dark adapt decreases with age, while the sensitivity to glare increases [40].

3.2.2. Visibility of surroundings. Navigating the environment includes needs to distinguish risks and recognise objects, that is why having good visibility of the outdoor surroundings is important [11]. Besides the lighting properties, position, angle, and direction of light sources, surface materials influence object visibility by altering luminance levels and distribution patterns [26, 33]. Visibility of the surroundings shifts in relation to the proximity to lighting installations and ambient lighting conditions [51]. Variations of light levels that occur in immediate and distant areas result in contrast ratio differences. Moreover, uniformly distributed high light levels in a particular area increase the contrast ratios to the surroundings [52]. Balancing the ratios through the means of using vertical objects, such as trees, can support peripheral vision by acting as reflectors [27, 32]. However, lower light levels are perceived as insufficient when individuals enter a darker area from brighter environments [28]. Adaptation can be supported; decreasing illuminance levels in immediate adjacent areas don't need to worsen the object visibility except at very low levels, e.g., 20% of the surroundings at ground level [51]. Using an LED with equivalent chromaticity (colour) characterisations but lowering output in the short and mid wavelengths region (metamer) showed no indications of worsened visibility [32].

3.2.3. Visual accessibility and comfort. Walking behaviour [51, 53, 54], readability of signs [51, 53, 54], facial expression identification [53, 54] and obstacle detection [42, 54], as well as visual comfort [55], are dependent on the quality of urban lighting. Parameters connected to lighting that influence both visual accessibility and visual comfort are typically characterised in illuminance [53-55, 56, 57] and correlated colour temperature (CCT) [54, 55, 56, 57]; meanwhile, luminance [53, 54], colour rendering index (CRI) [54, 56], distribution [53, 54] and SPD [54] are distinctively relevant for accessibility. The perceived outdoor lighting quality (POLQ) questionnaire was developed to assess the relationship between quantifiable and perceived qualities of outdoor lighting [56]. Perceptual tasks that were performed on a constructed walking path inside a lab successfully demonstrated a high rating on the perceived strength quality (PSQ) dimension when high overall illuminance was combined with a CCT around 3810K, and they showed a deficiency in pleasantness [54]. In a virtual reality study, it was suggested that warmer CCT of around 2700K and high overall illuminance lead to better visual accessibility of areas covered with vegetation [57]. Brightness is linked to ground-level illuminance and CCT [55], while gaze behaviours have no direct association with these parameters [57].

In controlled lab studies, walking speed varies, dimming light levels decrease the speed, and it remains constant even after shifting back to higher light levels [51]. In another study, it was shown that the constant speed persists under light installations that have different photometric characteristics [53]. Readability of signs [51] and facial recognition [53] become the most demanding in low light levels therefore, increasing light levels and uniformity improves readability at longer distances, especially by young users (20-35 yrs) compared to elderly users (60-75 yrs) [53, 54]. Visibility of details and facial recognition is determined by the distance between an observed subject and an observer; hence, a distance range between 12-25 metres is given for identifying facial expressions sufficiently [2]. Despite the adequate ground light levels, facial recognition at the proposed distance of 15 metres is limited, implying the importance of sufficient eye-height light levels. Detecting obstacles that are located outside of a constructed path becomes easier under a high S/P ratio due to the considerable amount of short wavelength content in the spectrum that eases rod-driven peripheral vision [54]. A study suggests that by applying illuminance levels between the range of 4.08-6.99 lux and a CCT of 3126K-4498K, physiological fatigue can be reduced, and visual comfort is enhanced when compared to a higher ground-level illuminance of 10 lux and a CCT of 5600K [55]. Moreover, decreasing excessive light levels [11], such as, high contrast ratios between an immediate area of 200 lux and a distant surrounding of 5 lux [52], directing light sources away from the path towards vertical surfaces [32], and shielding luminaires [11] has been shown to improve visual comfort by reducing discomfort glare.

3.2.4. Overall impression of the environment. Perceived safety [11, 46, 47, 53, 56, 58] and atmosphere [26, 29, 51, 52, 54] are influenced by lighting conditions. In studies, light levels, uniformity, CCT, and CRI are important factors that support perceived safety [47], while contrast ratios and perceived brightness contribute to visual impressions of individuals, thus interrelating lighting quality [56] with the usage of spaces [11, 58]. Spatial brightness and perceived safety have a positive correlation in some studies [46, 47, 56], although evaluating perceived safety impartially is difficult in field studies where other people are present [53] and is affected by a range of interconnected aspects [3]. Unmaintained vegetation cover and mesh fences can enclose pathways and restrict the view, thereby increasing the feeling of entrapment. Such effects regularly lead to avoidance of areas and route changes after dark, especially by women. On the other hand, well-maintained vegetation and illuminated areas can improve perceived safety [58]. It has been shown that lowered contrast ratios between immediate and distant zones lead to a sensation of pleasantness and harmony [26, 29, 52], whereas high contrast ratios that contain uniformly distributed lighting [29] and high overall light levels combined with cooler CCT [54] negatively impacts the overall impression of the environment [29].

3.3. Impact of electric lighting on wildlife organism groups
Technological advances in public lighting are changing the spectral characteristics of illuminated habitats. Reviewed studies indicate physiological and behavioural impacts in birds and non-human mammals, including rodents, shrews, hedgehogs, and moles. The first findings from the systematic review present an overview of the ecological impacts produced by electric lighting without providing impact details for the specific species. For wildlife organisms, light is an influential factor in regulating reproduction, migration, sense of direction, and signalling within and between species [15]. Light levels, spectral content, timing, and duration have varied effects on diverse groups of wildlife organisms [15]. Moreover, the broad spectrum of street and pedestrian lighting allows animals to perceive objects that reflect light over more of the spectrum they are perceptive to, thereby changing the stability of species' interactions [59]. In environments such as urban forest parks and green spaces where wild animals exist, light pollution is correlated to alterations in their circadian behaviour, reproduction, and predator–prey relations [12], as wildlife organisms react differently to the spectral content of light sources and light level thresholds [37]. Skyglow can have an impact over long distances with low light levels, modifying the movement and distribution of other organism groups [60]. Analysed studies provide meaningful data indicating that light levels are increasing where biodiversity is high, demonstrating a global threat to non-human organisms, demanding urgent actions [61]. Increased intensity of ALAN from pedestrian lighting in darker areas can be problematic as thresholds for fauna at night are often associated with the intensities of moonlight and far below new levels [60].

3.4. Urban lighting design approaches and methods
3.4.1. Assessment methods and parameters. The reviewed studies employed both quantitative and qualitative methods for evaluating lighting and data were collected in forms of hand-held light measurement instruments [17, 18, 21, 22, 26, 28-30, 34, 36, 51-54], computer-aided simulations [17-20, 23, 24, 26, 34, 35, 38, 62], virtual reality (VR) [55, 46, 57], eye-tracking devices [40, 57], wearable electroencephalograms (EEGs) [55], participatory simulation interfaces [32], scale models [27], questionnaires [11, 18, 19, 25, 29, 31, 51-56], interviews [17, 25, 58], observations [19, 21, 22, 25-27, 30], photographs [25, 26, 29, 31, 36, 43, 53, 54, 65], and sketching [25, 26]. Some of the theories used in the studies were inspired by Gordon Cullen [26], Jan Gehl [1, 11], Kevin Lynch [1, 25, 26], space syntax [21, 22], and landscape aesthetics [29]. Furthermore, empirical studies were conducted in the forms of field works [11, 17-19, 21, 22, 25, 26, 28-30,

36, 40, 43, 53, 58], lab experiments [38, 46, 51, 52, 55, 57, 58, 63], and computer simulations [26, 27, 34, 35].

Some of the methods presented in the studies to support design and planning processes are: semantic scales describing impressions of illuminated environments, which were established by Flynn et al. and served as a basis for the creation of a considerable amount of questionnaires for rating subjective qualities of spaces [52, 56, 57]; Three-Dimensional Evaluation SEC (suitable for everyone, environmentally accepted and cost-effective) based on site-specific spatial qualities [11]; POLQ questionnaire for assessing the perceived outdoor lighting qualities of pedestrians [56]; immersive virtual reality simulations of urban parks [57]; evaluation of historical architecture features by combining subjective and objective lighting qualities [29]; and multi-criteria assessment procedure, an integrated tool supporting the assessment of aspects related to safety, visual comfort, energy efficiency and environmental sustainability [63]. The papers indicate a need to better understand alignments and differences between effects on perception and behaviour [3, 19, 21, 22] and their relation to light and darkness [3, 20]. Present light measurement parameters, such as illuminance, CCT, and uniformity ratios and instruments targeted to appraise pedestrian lighting fall short of assessing LED applications using high-intensity, non-uniform lighting [37]. Therefore, different metrics are required to analyse the impactful properties of lighting on various species [37].

3.4.2. Ecological design approach in urban lighting applications. To integrate an ecological perspective into projects, the application of environmental lighting zones (E1-E4), including distinctive ambient brightness levels that protect environmentally sensitive settlements, the use of an overall urban lighting plan focused on darkness preservation, and environmental and health impact assessment procedures are proposed [37]. Today, research has established that short wavelength content should be minimised in outdoor lighting solutions to not contribute unnecessarily to skyglow or light-related biological triggers [37, 48]. “Amber” LED lighting and its characteristics are currently being explored in more detail for recommendations, meaning a warm-appearing light with reduced short wavelength content, typically between 1800K and 2200K CCT [37, 48]. Depending on the spectrum, objects and surface colours can still be rendered. However, no concrete short-wavelength radiation thresholds and recommendations are yet in place. Also, amber lighting might negatively impact some species, e.g., the mating of firefly beetles, so it should be carefully applied based on site-specific conditions [64]. Decreasing light levels, directing luminaires attentively, limiting operational times, and implementing adaptable lighting control systems are necessary besides spectral considerations [37]. Mitigating ecological impact can be possible using metamers (light of the equivalent chromaticity but mixed with different spectral compositions) [32]. The ecological impact measurement method of Longcore et al., in which response curves of wildlife organisms can be transformed into “action spectra”, can enable a first estimation of an SPD’s potential effects on species. The total effective irradiance can be estimated based on the plotted action spectrum of an animal group to the respective SPD of the light; lower effective irradiance represents a lower ecological impact [32]. Metamer mixing using multi-channel LEDs is intended to dampen undesired effects produced by phosphor-converted (PC) LEDs through decreasing short wavelength content in the spectrum [32, 37]. However, this method can currently compromise energy efficiency and CRI (depending on configuration) as opposed to white PC LEDs [32]. Furthermore, present standards and guidelines only address impacts that occur over the horizon, such as light pollution [65]. At the regulatory level, environmental aspects are managed in the form of soft laws, e.g., guidelines, that exclude technical parameters about spectrum, flicker, peak luminance, and peak radiance that are relevant to wildlife organisms or encompassing generic information that makes ecological strategies harder to be applied in specific local conditions [37].

4. Discussion - Towards a comprehensive urban lighting design approach

Existing knowledge related to urban lighting design considers various factors and impacts, e.g., perceived light qualities from a human perspective [56] and physiological and behavioural alterations on species [15]. Few studies concentrate on the interaction between spatial characteristics and lighting [17-27, 28-38]; others focus exclusively on either human vision [39-50, 62], perception [51-54, 58] or environmental impacts [12-15, 59, 61, 64]. Thus, the overall knowledge on the contribution of spatial characteristics in transforming the light effects in urban contexts, impacting pedestrians and ecology, appears fragmented and not holistically integrated. Together with the changing abilities of the human eye and vision under different light conditions, the interplay between material forms of built environments and electric lighting transforms spaces in different ways. For instance, illuminated spaces can be perceived as small, large, personal, visually accessible, or safe from a human perspective. Such experiences are embodied beyond quantifiable metrics, highlighting the importance of social, spatial and temporal situatedness for the visual qualities of spaces. This review shows that subjective impressions can be altered in relation to spatial characteristics, physical properties of lighting, luminaire configurations (e.g., layout and mounting height) and contextual conditions. In natural settings, vegetation, specifically dense and tall trees, can ease sharp contrasts and glare issues from non-uniform distributions and large spacings between light sources. Luminance levels of surfaces in immediate and distant areas can have more effect upon the visibility of objects than the illuminance levels at those areas or surfaces. On the other hand, surface characteristics of materials altered by light and weather conditions result in either reflected or diffused illumination and can wield unexpected light patterns, potentially causing increased discomfort glare. In addition to disturbing humans, produced light effects can expose wildlife organisms to uncontrolled ecological disruptions due to direct exposure, generated light trespass in their habitats and skyglow, including physiological and behavioural changes. Although the impact of light properties varies among species, to mitigate ecological disturbances, some general considerations are: lowering light levels, avoiding light trespass into unwanted areas, and minimising short-wavelength (blue-green) content in the light spectrum. In a design process, overlooking the qualities of space, lighting, human vision, or wildlife habitat is problematic, as impacts and perceived lighting effects are interdependent and interrelated. Therefore, a comprehensive design approach is needed to respond to the needs of pedestrians and wildlife organisms, at a minimum, allowing the coexistence of both, especially in urban green spaces. To enable this, integrative design thinking is necessary where properties of electric lighting are planned and specified in regard to project-specific considerations of the spatial structure, visual objectives of pedestrians, and local wildlife. By determining thresholds necessary for people’s visual purposes in urban parks, design strategies can be incorporated into lighting applications to minimise the ecological impact.

With this in mind, we note that in the reviewed studies, theoretical inspirations from urban design are mostly limited to the approaches of Kevin Lynch and Jan Gehl, leaving the potential to transfer different urban theories and concepts into lighting research for supporting meaningful analysis and design of illuminated spaces. Furthermore, it needs to be asked to what extent perception or use of outdoor spaces after dark should be evaluated by how much they deviate from daytime or peak activity patterns; this may be both unrealistic and limiting for lighting design work. Conversely, this study also, albeit indirectly, suggests that urban morphology and urban design studies can better integrate advanced lighting design knowledge; we are aware there is a wider inclusion of “lighting” discussions in urban design discourse, which is either not captured, or excluded, by the criteria of this review. The authors noted that several reviewed papers, especially shorter conference papers, could have used more accurate terminology, a conclusion based on findings and clarity of illustrations. While we did not exclude such papers if they introduced interesting research in the area, terms were paraphrased and corrected where appropriate.

5. Considerations

The results of this review indicate that knowledge is fragmented in the domain of lighting design-related research that conjoins the perspectives of humans and wildlife organisms in shared outdoor spaces. Urban lighting research calls for more extensive, integrated knowledge and research-based design guidance for developing new approaches, assessment methods and design methodologies for tackling today's sustainability challenges, hence providing inclusive and ecologically sustainable illuminated outdoor environments. It also points to a need to further develop an integrated view of design fields, allowing lighting design knowledge to inform work with the structure and shape of the built environment, and vice-versa, rather than working with light where the environment is largely seen as fixed. This systematic review aims to support identifying, selecting, summarising, and critically assessing the relevant research which is connected to lighting and urban morphology for responding to the needs of both humans and wildlife of urban green areas after dark to be directly applicable to the lighting practice.

Acknowledgements: This work is financially supported by NordForsk and the Swedish Energy Agency.

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