Dark Adaptation in Urban Environments

An Innovative Design Framework for Pedestrian Lighting

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Dark Adaptation in Urban Environments: An Innovative Design Framework for Pedestrian Lighting

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Abstract. Outdoor lighting has mainly been approached as an engineering subject throughout its history. The current urban lighting requirements are established upon factors which mainly refer to motorised traffic dynamics. As a consequence, excessive lighting levels are found in the city environments with a negative impact on the human as well as the environmental sphere. By synthesising scientific knowledge on human visual system and outdoor lighting theories, this research seeks to formulate strong arguments to point at the lack of human scale in the contemporary practice and to question the adequacy of the standard requirements for human vision in nighttime settings. The knowledge gained from scientific studies and ongoing research shows how the nighttime visual experience of pedestrians is still an untapped dimension, unveiling the lack of defined guidelines and methods to approach the design of urban lighting through the lens of this target. With a focus on soft mobility, the aim of the study is to address dark adaptation as a human factor in the design of urban lighting and to provide evidence on the human eye's ability to perform in dim conditions. Important findings from the literature review were used as requirements to formulate a methodology to approach the design of pedestrian lighting in urban environments. Strong conclusions could be drawn on the figure of dark adaptation and important lighting requirements were identified to facilitate this process in the condition of soft mobility. Even though further research and experimentation are required to implement dark adaptation in the design of urban lighting, this paper's goal is to open up new perspectives in the field, shaping the vision for the future of cities with reduced urban illumination.

1. Introduction

Outdoor lighting in urban environments has mainly been approached as an engineering subject throughout history, with its main purpose of regulating conflict between motorised and non-motorised traffic, to additionally providing society with a sense of safety and security and boosting the economy after dusk [1]. The set of requirements for urban lighting are regulated by the so defined "class" categories, which are established upon a set of parameters mainly referring to motorised traffic dynamics, regardless of the presence or absence of motorised vehicles in the city space of interest. In fact, the methods employed to design lighting for different targets than motorists, such as pedestrians (class-P) are generally a smaller-scale imitation of traffic route methods [2,3]. Many experts are questioning the correctness of defining lighting classes by means of parameters that are highly related to motorised traffic, which do not find any correlation within urban areas that are limited to low speed traffic such as bicycles and walkers [4].

Furthermore, a number of contemporary issues related to the human as well as the environmental sphere gravitate around the misuse of lighting in urban environments [5,6]. While standards and regulations have become embedded in the urban infrastructure allowing governance of spaces and urban life after dark, today they pose big challenges to the lighting design practice because the way they classify and rule different urban areas no longer meet the demands of contemporary planning [7]. In the context of this discussion, many authors and researchers have been investigating the impact of outdoor lighting on the nocturnal environments as well as the way the human visual system responds in nocturnal scenarios, in order to use this knowledge to improve urban lighting applications. Vision science explains how the human eye's sensitivity response to light changes according to brightness levels [8]. This defines three modes of vision respectively depending on high light levels conditions (daytime/photopic vision), dark conditions (nighttime/scotopic vision) and dark/intermediate light levels conditions (mesopic vision). Moreover, many studies have proved that the way humans perceive brightness at daytime completely differs from nighttime [8]. In addition, modern measuring system devices and the established units are based on the eye response curve of photopic vision (high light levels), meaning that the measured brightness does not correspond to the perceived brightness at nighttime [9]. Following this line, new research is urgently needed to understand that we are using excessive lighting that may not be needed, especially when it concerns pedestrians and soft mobility, where the visual needs are not as demanding as the vision of drivers. Besides high energy consumption, overly bright urban areas have caused issues of lighting pollution in many contemporary cities, which impact negatively on the biological nocturnal environment [5,10]. Therefore, alternative approaches are needed to frame and solve this environmental problem.

By collecting, reviewing and synthesising scientific knowledge on the topic of dark adaptation, this paper seeks to promote evidence on the human eye's ability to perform in dim conditions and to formulate a proposal for a novel approach to pedestrian lighting providing designers with a set of requirements to take into consideration to facilitate the process of dark adaptation.

1.1. Background work

Zooming in urban spaces, it is possible to experience in different ways the consequences deriving from the misuse of lighting such as excessive brightness levels, poor targeted lighting, glare and trespass which have all shown to influence people' stress level and to disrupt nocturnal ecosystem patterns [5,12]. Additionally, the aforementioned lighting class categorization provides requirements which generally fulfil specific areas' needs, regardless of the surroundings, and therefore this non-comprehensive approach results in great disparity of lighting levels throughout the urban environment. Pedestrian crossings or passages in junctions between trafficked roads and residential areas or urban parks are just a few examples of the spatial context this paper refers to.

Figure 1. Examples of dramatic variations of lighting levels in urban scenarios.

It can be truly challenging to classify all the possible cases from the urban environment in which incongruencies of the different lighting class requirements generate unwanted results, specifically as excessive brightness against naturally dark areas. In the attempt to identify possible spatial characteristics of such cases, it becomes important to additionally take into account the different features shaping the context of each case, such as the social and cultural traits amongst others. Brightness as a tool is differently understood and managed across socio-cultural contexts. The individual experience of brightness and darkness does not only rely on the physiological visual response, but expectations are influenced by the cultural background and prior experience [11].

However, as case studies have been suggesting, a domestic scale of urban lighting favours the presence of people in an urban space, which naturally promotes a collective sense of pride and safety [13]; this contradicts the governance formal control, which justify higher brightness because it allows a higher degree of surveillance that in turn increases the perceived safety amongst people [14]. In recent years lighting engineers have been able to measure the impact of brighter illumination on road safety and light pollution, yet there is still little knowledge on how to measure the social embodied and affective impacts of higher brightness [15]. In spite of how much the context may differ across the various spatial, social and cultural backgrounds, the issue of excessive brightness is present at different scales in the urban environment. Therefore the intent of this paper is to tackle the problem by proposing a comprehensive approach which addresses the eyes' potential of dark adaptation as a design objective.

As research has proved, the exposure to dramatic variations of brightness levels as found in urban areas can influence the inherent ability of the eye to adapt to dark environments [6]. This consideration emerges from collecting knowledge on the way lighting levels influence the state of adaptation of the human eye, which determines the vision mode [8]. Exposure to bright light levels causes blindness or temporary visual discomfort (technically known as discomfort or disability glare) when suddenly entering a dark area, compromising the process of adaptation. Additionally, with the technological advancement of light sources, urban lighting has tended to switch to smaller but brighter sources, implemented at different scales. This has increased the brightness exposure of pedestrians while walking through urban areas [16]. This important matter reconnects to the acknowledged lack of human centric approaches in the design of urban lighting.

1.2. Research question

The knowledge gained from scientific studies and ongoing research shows how the nighttime visual experience of pedestrian mobility is still an untapped dimension, unveiling the lack of defined guidelines and methods to approach the design of urban lighting through the lens of this target. With the goal of creating a new approach to this topic, a research question was formed which this study aims to answer: *How can we define a lighting design methodology to facilitate dark adaptation for pedestrians transiting from bright to dark areas?*

The following sections will unfold the intentions of this paper by firstly describing the methods and search strategy deployed for the literature review, which is the backbone of this study. Secondly, it will provide the reader with fundamental knowledge synthesised from the literature topics and it will identify essential parameters to finally implement in the design process. The resulting design framework will propose guidelines to develop lighting solutions in support of pedestrian dark adaptation. The paper will also discuss practical considerations in the implementation of the design framework to then finally open up suggestions for further development of this research.

2. **Methodology**

The methodology employed in this work should aim at identifying, selecting, processing, and analysing information about the topic of dark adaptation, with the interest of developing a design framework guidelines of lighting for nocturnal urban wanders. To this result, an exploratory research model [17] is followed, trying to explore and investigate dark adaptation. An explanatory study aims to explain how certain phenomena function. In other words, explanatory research is an attempt to connect different ideas to understand the nature of cause-and-effect relationships. It analyses problems and explains how variables interact with each other. In this context, a literature review [18] for the

phenomenon of dark adaptation is conducted. A literature review provides a critical analysis of the relevant contributions that have been made in the field of dark adaptation. During the literature review, the theoretical foundation for the research is identified, the novelty and relevance of the research are identified, and the focus, research questions, and design framework guidelines are clarified and refined. In order to answer the research question and frame the process of adapting to dark environments and the shift of brightness, three separate inquiries were conducted to maximise the chances of finding relevant studies: Dark Adaptation, urban artificial lighting qualities for pedestrians, and one for Scotopic and Photopic terminology. Literature was searched by publications indexed in Researchgate, Scopus and ISI Web of Science and more, using keywords such as dark adaptation, artificial lighting at night and additionally using the key words photopic and scotopic. The terms were searched in titles, abstracts, and keywords of the papers. The desired papers were refined to include peer-reviewed search articles and articles in press, short surveys, books chapters, and books. The searches were performed in two different periods of time: spring of 2020 and winter 2022. The goal was to identify studies that investigate urban lighting practice with particular attention to human factors. All studies were examined by title and abstract in order to determine if the studies satisfied the eligibility criteria. If they had a valid number of academic references with professionals or somewhat recognized authors and included the research keywords, the full texts were examined. The content of the studies was analysed to map out the function of the eye and the process of adapting to dark environments when travelling from a lit environment. The data was used to form a lighting design framework for artificial lighting at night in urban environments.
The aim with this literature review is to better understand the function of the human vision and its modes. Furthermore, to raise the discussion of facilitating more human-centred sustainable nocturnal lighting design in the future. Important findings from the review of existing knowledge were gathered to formulate a proposal for a novel approach to address dark adaptation in the design of urban lighting for pedestrians transiting from bright to dark areas.

3. Review on adaptation mechanism

In order to understand the factors involved in the process of adaptation, it is of course important to explore the human eye as a complex mechanism; eyesight is only one of the five senses we perceive within all environments. The human visual system depends upon a few essential components of the eye. Figure 2 illustrates the eye's structure with its photoreceptive components [19]. The photoreceptor cells are responsible for how humans perceive light and furthermore adapts to darkness. The photoreceptors placement within the retina structure at the back of the eye distinguishes the different visual field regions foveal and peripheral of which cones and rods are respectively responsible [8].

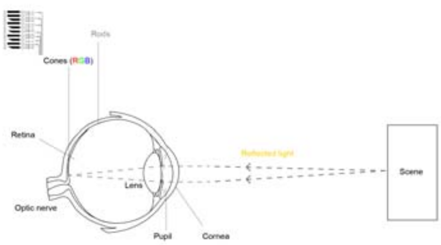

Figure 2. Human eye structure.

3.1. The vision modes

The state of the different conditions of the photoreceptors are referred to as photopic vision mode, scotopic vision mode and mesopic vision mode [20].

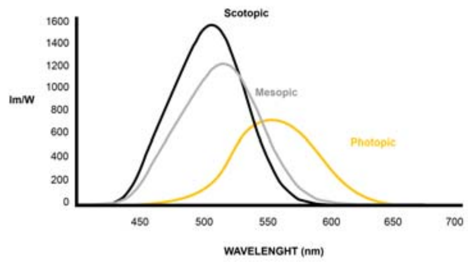

Figure 3. Vision modes sensitivity curves.

When the luminance levels range from 0.001 to 3 cd/m2, the transitional state from photopic to scotopic modes is referred to as mesopic vision. In these illuminance ranges, which are those usually found in urban nocturnal settings, both photoreceptors are engaged in the retinal response to luminance, enabling humans with peripheral and foveal perception [8]. It is important to stress at that point that due to a different presence in the number of the photoreceptors in the retina (92 million rods and 4.6 million cones), rods are still the most influential for the eye's sensitivity response in the mesopic mode [20]. This means that considering the rods' higher sensitivity to brightness, studies state that, provided of not being impaired, any person regardless of the age can detect trip hazards on the ground with only less than 1 lx horizontal photopic illuminance [3].

3.2. The dark adaptation process

Dark adaptation occurs when the retina photoreceptors sensitivity adapts to lower illuminances, and this process consists of four factors. Firstly, the intensity and duration of the pre-adaptation light. Secondly, size and orientation of the retina contribute to the process of dark adaptation. Thirdly, the spectral distribution of the pre-adaptation luminances and, lastly, the regeneration of rhodopsin [21]

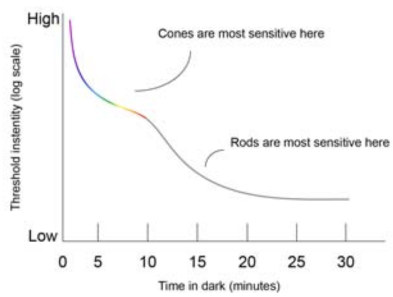

Figure 4. Graphical representation of dark adaptation process.

The degree of influence of the pre-adaptation exposure largely depends on the brightness level as well as directionality. Under most conditions light adaptation generally is an extremely rapid phenomenon, and humans adjust to the levels shift within seconds [21]. The photoreceptors engage in the process fairly quickly compared to rods, as rods need the photopigment rhodopsin to be produced and get activated. When transitioning to darkness after exposure of high or prolonged luminnances, a proportion of the visual pigment in the photoreceptors gets ''bleached'', therefore it can take several minutes to return to normal visual sensitivity. This very slow recovery in which rods are engaged, is called 'dark adaptation' [21]. Following this line, research shows that the level of pre-adaptation exposure determines the state of the adaptation. In urban environments, the exposure to artificial lighting can reach light levels up to 150 lux at nighttime, showing an increasing negative impact on the biological life of humans and animals [6]. Even though important information on the mechanism of dark adaptation is found in scientific studies, this knowledge fails to be addressed in the contemporary urban lighting practice, determining a new problem area which calls for further investigation and new approaches.

3.3. Lighting qualities for dark adaptation

Understanding the behaviour of the human eye in outdoor dim conditions is essential to determine the visual needs of active people at nighttime and how lighting can be used to aid the accomplishments of tasks within a specific context. Nowadays, lighting is used for a range of purposes in the outdoor environment. Lighting in cities is aimed at people and property 'safety and security', as well as emphasising the architectural and historical identity, to attract people and to create meaning throughout their spaces. Though, a big portion of this realm is concerned with road installations for motorised vehicles and other alternative means of navigating through the urban environment. This consideration leads to identifying different targets which the lighting in the urban spaces is designed for. According to the condition of experience of the urban space, whether it is static or dynamic, and whether it has different speeds in the condition of mobility, the design of urban lighting can be aimed at motorists or pedestrians and soft traffic users, as well as it could be targeted at different categories together. As specified in the paper introduction, the target focus for this research are pedestrians. Based on the understanding of this target visual needs in the condition of navigation, this section provides a set of parameters which call for attention when designing lighting for this target.

3.3.1. Topology. Before identifying the quantitative parameters of lighting to consider as tools for shaping the nighttime visual environment within any given urban space, it is important to consider the physical arrangement of the lighting sources. The physical placement of the lighting is defined by the distance between sources and mounting heights and it is highly determined by the lighting requirements of the area, usually defined by the class and the spatial geometry of the environment.

In outdoor settings, the selection of luminaires will be determined by the specific context of application, as an urban area may have different requirements in relation to whether it is a highly motorised trafficked area or a fully pedestrian zone and so on. As explored in the analysis on the human visual system with its different vision modes, an important piece of information is that the main photoreceptor engaged in the scotopic and mesopic vision is the rod [8]. Photoreceptors responsible for visual-forming effects *(rods and cones)* have different placement within the eye's retina [20]. Rods photoreceptors are placed in the peripheral part of the retina, improving peripheral vision in scotopic illuminations. Since all photoreceptors are equally engaged in the process of mesopic vision, the peripheral region becomes more sensitive due to its rods' high sensitivity to brightness [19]. Research also shows that photoreceptors cones are placed in the center of the retina, enabling in photopic settings sharp vision with high details discrimination in the foveal region [8]. Through the visual experience under mesopic vision, the foveal and peripheral views are shifting in which is being most dominant according to the illumination levels. Following these claims, it can be stated that because of the high sensitivity of rods cells, there should be no glare exposure, therefore creating visual comfort in dark environments. Extreme contrast between the visual field regions would bleach the photopigment rhodopsin and impairing the photoreceptors in adapting to lower levels.

3.3.2. Colour appearance and S/P ratio. Colour appearance, as a perceptual concept, is an essential quality of light which contributes to the way space and objects are perceived. According to the spectral composition of a lighting source, the human eye's photoreceptors respond differently to specific light wavelengths, influencing the visual perception process. The parameter which quantifies the spectrum of a lighting source, which will also influence its colour appearance, is the **Spectral Power Distribution (SPD)** [19].

The literature review on the human visual system shows how the photoreceptors rods and cones determine the state of the retina and the vision's mode, and they have different sensitivity responses to the wavelengths composing the light spectrum [8]. In mesopic ranges (0.001 cd/m2 — 3 cd/m2), where both cones and rods and engaged in the process of visual perception, the great contribution of the rods alters the sensitivity response to certain wavelengths, influencing the perception of the luminous environment [8]. Following the scientific knowledge on the rods' high sensitivity to short wavelengths, the lighting within a dark area can be reduced to very low brightness levels when working with the blue enriched spectrum, as the rods are most sensitive and most perceptive in these spectral conditions. An important parameter which indicates the effectiveness of light under mesopic condition is called S/P ratio, as in the ratio between the scotopic and the photopic lumens of a source. This value gives indication of the source efficiency in terms of lumen output according to both photopic and scotopic spectral and spatial response [9]. If the ratio value is 1, the light source performs just as good under scotopic conditions as photopic. The higher this number the better the eye performs under the light source.

3.3.3. Levels. In relation to lighting levels, the first observations to be made regard the dual dimension of the context - bright environment against dark environment. The project scope gravitates towards the idea that in dark environments visual comfort can be fully achieved providing previous adequate exposure to low light levels. Therefore, it is essential to understand the relations between the two areas and the degree by which the bright area impacts the experience of the dark environment. As proved by research, the exposure to different high light levels shows to influence the time required by rods to get engaged in the process of visual perception when entering dim environments [6].

Aiming at supporting dark adaptation and at smoothing the transition from the bright to the dark environment, a first step to approach the problem is to analyse the lighting configuration in the bright area and the way this affects the process of dark adaptation for soft traffic users. In relation to this, *illuminance levels* play a fundamental role in understanding this issue, but it is also important to specify that whenever referring to lighting levels, topology and spectrum become interconnected variables. The research work developed by Steve Fotios on pedestrian street lighting states that reduction on illuminance levels recommended by the Standards can be achieved by providing the use of lighting source with high S/P ratio, i.e. source with high blue content in the spectral power distribution. Additionally, lighting topology has a role in determining the distribution of luminance across the space. A regular layout with specific distancing and heights will provide a more uniform distribution with continuous visibility. Fotios experiments show that low illuminances ranging between 0.10 to 0.62 lx are adequate for hazard detection for pedestrians regardless of the age, whereas illuminance levels between 1 and 2 lx are sufficient for cyclists urban navigation, providing the paths are not extremely hazardous [3]. These values become important data to be considered in the design framework, which addresses the need for creating a new approach for slow traffic lighting in urban environments [2,4,16,22].

4. Design framework proposal

The review on the human visual system proved that specific human factors can be integrated in the definition of a framework useful for designing urban lighting to aid the process of dark adaptation for pedestrians transiting urban areas with variations from lit to dark environments. In this context, findings from the analysis provide three essential requirements for the lighting design framework, translating existing data from scientific knowledge into design tools. Considering the high sensitivity of the peripheral vision in dim settings, it is important to provide a physical arrangement of the lighting which minimises glare exposure within the extension of the field of view. Furthermore, due to the rod cells' high sensitivity to brightness and contrast, illuminance levels should be low at approximately 1 lux and uniformly distributed at ground level. Additionally, as research proves, rod cells are most sensitive to short wavelengths of the spectrum, meaning that the average illuminance can be minimised if using blue enriched SPD lighting with a high S/P ratio [4], which indicates that the lighting source is efficient both in photopic and scotopic response. Ultimately, three criteria of lighting topology, spectrum and level become the specific lighting requirements for the new design framework:

- **Lighting Topology:** The lighting is placed to provide a consistent visibility throughout the space and to avoid extreme contrast between zones;
- **Lighting Spectrum:** The sources S/P ratio is high, with short-wavelength enriched spectrum and high CRi;
- **Lighting Levels:** The illuminance level is very low and lighting is uniformly distributed to reduce contrast.

This section covers and explains the steps of proposal to a new framework to approach the design of lighting for pedestrians in the context of urban areas with variations from bright to dark environments. The proposed lighting design framework becomes a new toolkit for designers sharing the goal of improving the nocturnal experience of the contemporary urban environment for walkers, tackling the inadequacy of excessive brightness compromising the visual experience of the dark environment.

4.1. Measure

The primary task of the designer is to understand the degree by which exposure to high light levels in bright urban areas affects dark adaptation time when entering dark areas. The more the adaptation process is delayed the longer the users will need sufficient but lower levels to reduce the discomfort effect experienced in dark areas.

The first step of the framework suggests to map the critical points of lighting exposures and create a transitional sequence to collect quantitative data about the bright intervals the walkers are exposed to. The defined transitional sequence gathers important data within the observer's luminous experience along the path, providing information on where the light/darkness shift occurs. These bright intervals from the transitional sequence are defined as pre-adaptation exposures, meaning the bright exposure before undertaking the dark path, determining and potentially influencing the process of dark adaptation. The designer is suggested to gather the following quantitative measurements from the critical points: Lux values at ground level, luminance exposures and source spectral composition.

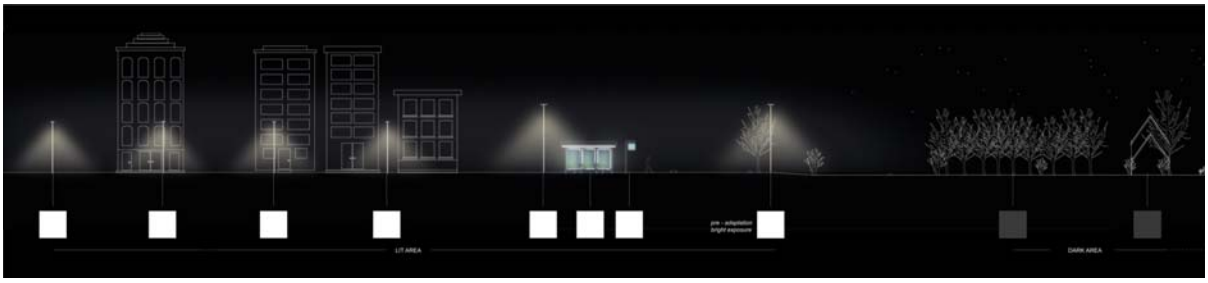

Figure 5. Illustration showing the process of transitional sequence definition.

4.2. Test

The second step suggests reconstructing the scenario of the pre-adaptation exposures in a simulated environment. The aim of the testing phase is to measure the way the exposure to brightness influences the time required to adapt to the dark environment. Subjects should be exposed to a light scene, simulating the real context where the sequence of pre-adaptation exposures is measured. The specific testing setting and procedure require focus on different aspects, such as the time of exposure and the position of the subject in relation to the lighting source. After the bright exposure, the second action would be to monitor the time required by the subject to perform a task-related response like detecting a hazard on the ground. Therefore, each subject will be standing in a simulated dim environment and exposed to bright pre-adaptation light as measured in the real scenario. The luminance will be distributed uniformly onto the retina by means of a source placed at the top of the subject. After the exposure to the sequence of luminance, the response time will be measured. Research argues that different levels of exposures affect the adaptation curve, resulting in different values of dark adaptation time.

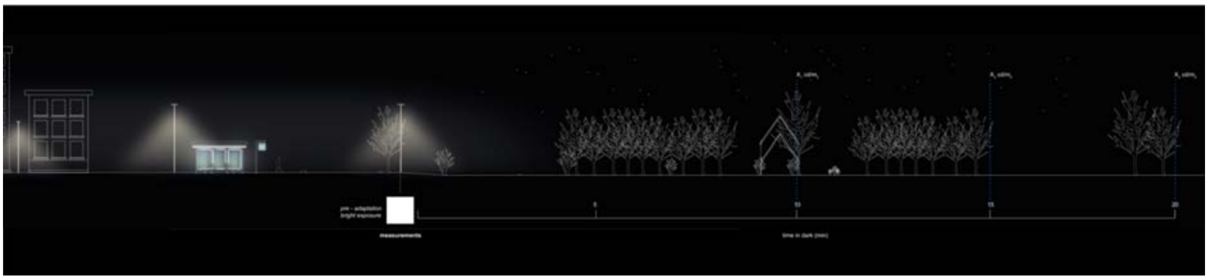

Figure 6. Illustrations showing dark adaptation delays in relation to different bright exposures.

4.3. Translate

The final step suggests a design approach which translates the measured adaptation time into spatial distance. According to the area usages and users, an estimation of average walking speeds can be converted into distance, defining the area of interest in need of a lighting scheme to aid pedestrians in the process of dark adaptation. The distance is a value measured in metres at which the designer will implement the newly developed lighting scheme to guide and support the users in the process of adaptation to the dark environment.

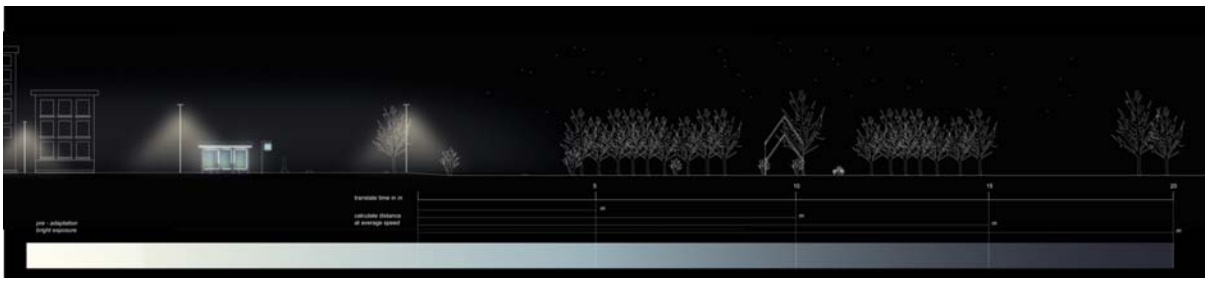

Figure 7. Illustration showing the process of time/distance translation

At this final stage of the process, the designer will reconnect to the knowledge gained in the review of the subject of dark adaptation, and the three success criteria mentioned in Section 4 will be applied as a design tool to improve the urban lighting transition.

5. Limitations and discussion

In spite of this research goal of contributing with practical design guidelines, the applicability of the design framework has its limitations, which the authors aimed at identifying in the following section. Firstly, it is pertinent to raise questions on whether dark areas are a rare scenario or not in urban environments, as excessive lighting is a general issue arising from the urban lighting practice. If this

scenario would be true, then the interest in implementing the design framework would be low.
While city centres shine from clusters of intense lighting, brightness spreads out across the urban environment, covering wide areas with layers of thousands of streetlights, advertisement's screens, architectural lighting and so on. In the contemporary image of urban nights, the highest contrast that can be identified in this scenario seems to be solely found at the edges between the urban environment and natural areas. At this point, it is logical to question whether it is possible to identify a clear taxonomy of areas where darkness is preserved by zooming in the urban environment. The process of mapping out urban cases of lighting transition is an essential operation in order to understand the possibility of application of the developed design framework and how this could be a valuable stepping stone for further research applied in the world of outdoor lighting
Furthermore, it is essential to consider that different cultural and social backgrounds may result in a different understanding of darkness and consequent use of brightness at night. Further investigation and the application of the design framework are required in real scenarios to establish what specific context could benefit or not from the proposed guidelines.

Regarding the framework steps, several limitations of the testing phase must be discussed. The chosen test scenario of the proposed framework refers to a task-related response experiment, in which the subjects need to give note when a hazard is detected on the ground in the dark after being exposed to the simulated pre-adaptation exposures. It can be questioned whether such a hybrid approach is a correct setting for a reliable study. A collection of test hypotheses should be considered for a more comprehensive approach. For instance, the task-related response could be distinguished between object or movement detection, depending on the hypothesis to be confirmed or rejected. Continuing on this line, a focused experimentation should be formulated around the subjects of face recognition and expression discrimination, which becomes an important task for pedestrians to discern movement and intentions of other space occupants [4]. Adding on the test discussion, the difference in the sensitivity of the cones and rods and their placement in the retina lead to question whether the topology of the pre-adaptation exposures have different impacts of the dark adaptation time. According to the testing set up suggested in the design framework, pre-adaptation luminances are exposed to the retina uniformly, allowing the authors to understand how the visual system responds to the exposure of specific luminance values in a simulated environment. In a real urban scenario, luminance values are usually not distributed uniformly across the visual field, and therefore it must be questioned whether different distributions onto the retina can somehow affect the stimuli responses. When testing the bright exposures in a controlled environment, it could potentially be considered if the pre-adaptation luminances should be defined into two types, peripheral and foveal pre-adaptation exposures, and monitor whether they would give different results or not. The luminance maps generated from the bright scenario are a useful tool for understanding luminance distribution in terms of foveal and peripheral exposures. Moreover, it would be pertinent to examine the medical eye´s condition of the target group, as different age, gender and medical condition targets might have different visual responses.
The flexibility of the design framework in applying testing results can also be discussed in relation to the length of the path of interest. In an ideal urban scenario with extended dark areas, a sufficiently long path would provide enough distance for the dark adaptation to be aided by the framework lighting requirements. In a more realistic urban scenario with small dark areas, it can be stated that the scope of the framework should be to minimise the soft traffic visual discomfort caused by the brighter environment when approaching the dark path where levels dramatically drop.

In essence, from the big picture of the city environment, the urban areas presenting high contrast from brightness to darkness where the framework could be successfully applied seem to be found more often at the edges with the natural areas, as mentioned before. Additional considerations should be stressed on whether the lighting requirements suggested to support nighttime vision and aid the process of dark adaptation can potentially impact wildlife patterns in urban environments. Spectral content of the applied lighting system as well as the integrated topology in the spatial context should be carefully evaluated in order to minimise negative impact on animals and plants from the natural dark area. Finally, reconnecting to the unwanted consequences arising from incomprehensive approaches, the design phase's main focus is the prevention or reduction of the negative impacts of excessive brightness, which is an ever growing contemporary issue due to excessive illumination in big cities. Many outdoor lighting researchers and practitioners have shown resistance for how the standardised approaches and their unclear design principles somehow promote a misuse of brightness in urban environments [23]. By drawing attention to existing scientific knowledge on the eye´s dark adaptation and its design potential in the context of pedestrian lighting, the framework proposes a way to resist the pre-definition of design needs for slow traffic areas exclusively by means of standards and regulations. Since a collective resistance to the challenges posed by these regulations has been widely shown, it is clear that a reformulation and reassessment of lighting planning principles is yet needed. For instance, the redefinition of lighting classes for slow speed areas according to different weighting factors than traffic volumes and motorised vehicle presence, such as specific physical characteristics, brightness exposure of neighbouring areas and adaptation process.

6. Conclusion and future work

Despite existing scientific studies on the human eye abilities, this knowledge still fails to be addressed in most contemporary urban lighting applications.
As a result of synthesising knowledge on human vision, three main findings are converted into three success criteria, which constitute the foundation of new lighting requirements for dark urban areas in need of illumination, facilitating the process of adaptation to dim settings for nocturnal urban wanders. Based on the information gained on the figure of dark adaptation, it could be concluded that the process demands time to be completed, consequently requiring sufficient distance to be available in most dark urban paths. This has led to questioning the applicability of the proposed design framework in urban context. However, these reflections frame the key point of this study, shaping a vision for the future encouraging coherent lighting master plan for modern cities, with no excessive and unnecessary use of lighting and with the consideration of its negative effect on the human and environmental spheres. The overarching vision of this research is to deploy the lighting design framework on a bigger urban scale, potentially triggering a domino effect of reduced lighting levels throughout the city environment. By addressing dark adaptation as a human factor for non motorised navigation, this research aims at providing evidence on the human eye's ability to perform under dim conditions, giving a new perspective on the outdoor lighting design practice and contributing to a human-scale-oriented urban development. By tackling important human factors in various design disciplines within the urban environment, many contemporary issues affecting the human as well the environmental sphere can be framed and potentially solved, strengthening and sustaining livability in future cities. In relation to this, opportunities for future experimentation arise and interesting directions could be undertaken to strengthen dark adaptation as an important factor in the design of urban lighting. A future development of this research would initially see the conduction of a protocoled testing phase in a real urban scenario to collect scientific evidence on the figure of dark adaptation and the parameters which affect it, opening channels for new studies.
Future directions to be considered for this new research area are the following:

- Combining design-oriented approach and medical examination of the eye in the study of dark adaptation. Due to the physical/chemical nature of dark adaptation within the eye anatomy, the use of medical equipment would aid the production of scientific data, supporting the task-based approach to study the subjects’ response in a spatial dimension.
- Consider the possibilities offered by VR as a digital tool for advanced design-oriented testing, studying subjects' responses in a simulated condition of navigation through an enhanced reproduction of urban scenarios.

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