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Virtual Reality for Smart Urban Lighting Design: Review, Applications and Opportunities

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Abstract: More and more cities are evolving into smart cities, increasing their attractiveness, energy efficiency, and users' satisfaction. Lighting systems play an important role in the evolution process, thanks to their ability to affect city life at night along with people's mood and behaviour. In this scenario, advanced lighting design methods such as virtual reality (VR) became essential to assess lighting systems from different points of view, especially those linked with the city users' expectations. Initially, the review highlights a list of objective and subjective parameters to be considered for the lighting design of three main city areas/applications: roads, green areas and buildings. Besides, the state-of-art in using VR for outdoor lighting design is established. Finally, the Unreal game engine is used to analyse the ability of VR to take into account the lighting parameters, not yet investigated in current literature and to highlight the VR potential for augmenting lighting design. The results confirm the benefit of using VR in lighting design, even if further investigations are needed to establish its reliability, especially from the photometrical point of view.

Keywords: city outdoor lighting; immersive virtual reality; smart lighting design; smart city; energy savings; unreal engine; road lighting; green area lighting; architectural lighting

1. Introduction

Today, more than half of the world's population lives in cities, leading to a lot of problems linked to the explosion of the urban population in towns [1]; to solve these problems, countries are progressively improving the use of new technologies to make cities smart.

In Europe, 240 of the 468 cities of the 28 European Union countries with at least 100,000 inhabitants can be considered smart cities [2]. In particular, the percentage of smart cities decreases as the city size decreases, ranging from about 88% for the cities with more than 500,000 inhabitants to about 43% for cities with between 100,000 and 200,000 inhabitants [2]. Over the years, the concept of a smart city has changed its meaning. Generally, a smart city is a place where information and communication technology (ICT) is used to improve the efficiency and the management of the city itself [3,4]. However, this definition is considered to take into account only the technological aspects, leaving out the people and the processes of city design. For these reasons, the technical aspects are no longer the focus in the conversion process of transforming a city into a smart city but rather the city users' satisfaction [5,6], together with additional factors such as sustainability, quality of life, urbanization, and smartness [3,7]. To improve the livability and sustainability of the city, more and more smart city projects have started, each facing different challenges [7]. In this scenario, public lighting plays an important role in the development process of smart cities [8]. Many smart city projects started from or included the renovation of the lighting system, considering it as the main aspect of the conversion process [7–9]. The availability, in recent years, of more efficient and flexible light sources (in particular light emitting diodes—LEDs), as well as innovative and more cost-effectiveness control and communication systems, has facilitated this shift. Moreover, the light systems were used not only for functional interventions (i.e., energy saving, basis for actuators or sensors to have information about crime, traffic or pollution) but also for emotional aspects (affecting people's mood, behaviour, and sense of safety).

Nevertheless, the effects of light on people's behaviour and acceptance are not fully known. Several projects have foreseen the use of smart lighting systems in different city areas (squares, open public spaces, etc.) to make the public space safer and more attractive for city users and support the local entrepreneurs [9,10]. Lighting systems can no longer be considered a system to provide a defined amount of light but must to be considered as smart systems able to adjust the quantity and quality of light according to the needs of the city and people.

Today, there are several tools and software that designers use for lighting design [11–15]. In particular, RELUX 2020.1.5.0 [16] and DIALux evo 9 [17] are free computer applications known by lighting designers all over the world [11,15]. These traditional tools used in the lighting design of indoor and outdoor environments. However, in the design of a large infrastructure, such as a street lighting system, which is a complex task in the context of smart city and smart grid approaches, a graphical representation called the 'general environment model' (GEM) is often used instead [13]. Another traditional but automated tool is the "gCalc" which uses the exact shapes of roads and lamp locations to perform precise calculations [14]. This traditional software allows users to calculate and professionally verify all the parameters for the lighting system, providing clear and precise results. However, these traditional tools used for lighting design are not suitable for a design that takes into account the subjective responses of the user because they do not give the possibility of creating an immersive virtual environment.

In this scenario, the conventional design protocols and software do not allow for a comprehensive assessment of the new aspects, especially those linked with the city users' subjective responses, which are required for smart city lighting systems. For these reasons, new and smart design systems and software have to be used. Multisensory design tools may be the answer, allowing for the evaluation of many aspects linked with the light system from different points of view.

From this perspective, immersive virtual reality (IVR), by combining realistic reproduction of a virtual environment with the possibility of interaction between the user and the virtual environment itself [18], represents one of the most powerful multisensory design tools. It allows ecological assessments among different design solutions, with high levels of realism [19,20], presence [21], and the "feeling of being" in the virtual world as if it were the real world [22]. The following key elements of IVR have been described by Burdea and Coiffet [23]: immersion, the capacity to isolate from the external world; interaction, the capacity to naturally exploring the virtual environment; and imagination, or individual aptitudes with mental imagery [24].

IVR has been used to investigate the multisensory interactions among auditory and visual [25] stimuli, in collaborative urban design [26], and to collect human preferences among different environment conditions and design solutions [19,27–29] for public motivation and satisfaction in urban decision-making processes. Although IVR is now used in many research and industrial sectors [30–35], the reliability of IVR as a tool for lighting design still has to be thoroughly investigated. Depending on the interaction degree between the user and the virtual environment, two categories of VR can be identified. The first category is composed of VR systems that use screens (desktop VR) [23] or smartphones (mobile VR) to reproduce the virtual environment that the user can only explore from a fixed position. The second category is composed of immersive virtual reality (IVR) systems that guarantee the immersion and the interaction between the user and the virtual environment by using a head-mounted display (i.e., Oculus at Menlo Park, California, USA and HTC Vive at Xindian, New Taipei, Taiwan) and motion sensors [18].

In this paper, the capability of VR for smart city lighting systems is investigated. The paper starts with a literature review aimed at both establishing the different city areas for which smart systems for lighting design are needed and identifying parameters able to characterise the quantity and quality of light and lighting systems. In particular, both parameters based on photometric units and parameters based on task-performance metrics, visual-comfort aspects, and emotional issues are considered. Papers focused on the use of the virtual reality for outdoor lighting design are also analysed in detail.

Finally, one of the most popular systems for immersive virtual reality is used to assess the features and limits of immersive virtual reality for city lighting systems design.

Therefore, the paper aims are to identify:

- the main outdoor urban areas;
- the objective and subjective criteria to consider in the lighting design of urban areas;
- the state-of-art in the use of virtual reality for outdoor lighting design;
- future opportunities and challenges for virtual reality in outdoor lighting design applications.

2. Smart Lighting for New Cities

Over time, city lighting systems have undergone a transition from a simple method to light spaces to very complex and smart systems able to affect the liveability and attractiveness of a city, as well as the perception and the well-being of people that live in that city (citizen, tourists, workers). Research has revealed that light strongly affects the life and behaviours of city users [36,37]. Then, city lighting systems have improved to meet the ever more demanding requirements of smart cities, becoming smart systems themselves. Consequently, the methodologies and parameters used to evaluate their performances have to be implemented. Traditional methodologies based on objective parameters, such as photometric units, need to be combined with those based on the subjective parameters (e.g., visual performances, perception and emotions) in order to meet people's expectations. Three main lighting systems applications, for which a smart design is required, were identified—road lighting, green area lighting, and architectural lighting. For each of them, the lighting design criteria are listed and described in the following subparagraphs.

2.1. Road Lighting

Road lighting represents a significant challenge for the light designer. To light a road means taking into account different visual tasks (recognizing vehicles, people, objects, or signals) and typologies of users (drivers, cyclists, and pedestrians). For these reasons, standards and laws were issued to define specific objective requirements, generally based on the minimum values of photometric requirements that road lighting systems have to guarantee. At the same time, recommendations and research [38–69] highlighted the need to consider additional benchmarks, mainly based on the subjective parameters to improve the visual performance, safety, and satisfaction of drivers, pedestrians, and residents.

Illuminance and luminance levels can be considered the most used control parameters. European standards [38–40] define the photometric unit to use and their minimum values as a function of the so-called light class series. The carriageway is subdivided into different lighting classes as a function of a combination of the road classification (motorway, urban, and extra-urban road), the intensity of the traffic, and the speed limits, defining three main lighting classes—M-series, C-series, and P/HS-series. The M-series is intended for drivers of motorized vehicles on traffic routes of medium to high driving speeds; the C-series is intended for all road users on conflict areas such as shopping streets, road intersections, or roundabouts; while the P/HS-series is intended for pedestrians and pedal cyclists on footways, cycleways, or other road areas, as well as for residential roads, pedestrian streets, parking places, and schoolyards. Mainly, lighting system performances are evaluated through the average luminance, the average illuminance values, and the luminance and illuminance uniformity. Some methodologies for the correct determination of the street lighting classes are available in the literature [41], since it affects both visual performance and energy consumption connected to lighting systems.

The presence of parked vehicles on the roadside is another crucial parameter that can affect the light distribution on the pavement and the visual task [42–45]. Parked vehicles, on one or both sides of a road, are considered as obstacles, increasing the general risk and causing some obstruction to drivers and pedestrians. According to reference [42], the presence of parked vehicles results in one step improved lighting class. Studies [43] underline the association between the presence of parked vehicles and the risk of accident/injury to pedestrians.

However, as suggested in reference [39], additional aspects such as facial recognition and the sense of safety should be taken into consideration to improve the visual performances and perception of road users outside during the night.

Researchers [46–49] identified additional lighting at pedestrian crossings as one of the most effective actions to improve the safety and visibility of pedestrians. Higher illuminance levels at such crossings can lead to a dual goal: to signal to drivers the presence of crossing and pedestrians and to persuade the pedestrian to use the crossing point. The relationship between the vertical illuminance levels and pedestrian visibility at a crosswalk is investigated in references [48,49]. The results point out that vertical illuminance values of 20 lux, measured at the height of 1.5 m from road level, can significantly increase pedestrian visibility.

Facial recognition concerns the ability of a cyclist or pedestrian to recognize the face of other road users and is considered as a critical parameter to get people to go out at night. Regarding the specific task of facial recognition, the European standard [39] defined the lighting class SC-series based on semi-cylindrical illuminance that have to be guaranteed at the height of 1.5 m from road level, suggesting the use of light sources with high values of the colour rendering index (CRI). Even though recommended by standards, only a few studies [50] advise the CRI as one of the usual lamp metrics to be able to predict the benefit of light on facial recognition. In general, facial recognition is associated with the spectral power distribution (SPD) of light, even if the scientific literature does not give a definitive conclusion about this relationship. Some investigations suggest that light SPD affects facial recognition [37,50–52], while others underline no or little effect [53,54]. Studies [37,50–52] indicate that white light (the metal-halide (MH) or LED lamps) as the best light for facial recognition, rather than yellow light (high pressure sodium (HPS) light). No connection with CCT was underlined.

Orientation is another aspect considered important for people's satisfaction. It is a complex task that especially involves pedestrians and depends on familiarity with the environment, visual memory, and the lighting system. For proper orientation, people need to be able to recognize obstacles and identify houses and façades [55,56], as well as see any potential hazards. In other words, people should be able to see approaching vehicles, obstacles, and street irregularities but also construction barriers and bicycle racks [57,58].

The sense of safety, together with the concept of security, is closely linked to the concept of orientation. Even if safety is associated with obstacle detection while security is associated with the people's perception of protection, studies generally identify both concepts with the concept of safety. According to several studies [59–62], increasing the light level improves the sense of security of people, especially in unsafe areas. The sense of safety is more important, considering that the sense of security affects the social life of people [52,60]. According to reference [59], with about 30 lx on the horizontal plane, people have the same safety perception that they have under daylight. Vrij and Winkel [61] also suggested that if people see the light on their surroundings (for example, by cutting back bushes), their sense of fear diminishes.

In recent years, some researchers have suggested that both the colour and correlated colour temperature (CCT) of light mainly affect people's perception of safety outside at night, as well as the visibility of lighted targets on the roadway; white light helps to improve the sense of safety [52] and makes facial recognition easier [51]. Fusheng et al. [63] investigated the visibility of achromatic and coloured targets under high-pressure sodium (Ra = 26; CCT = 2321 K) and LED (Ra = 66; CCT = 4810 K) illumination. The results point out that LED lamps allow for better visibility of targets. Knight [64] presents the results of research carried out in three European countries aimed at investigating how light

SPD can affect the perception of people outside at night. Three different light sources, with different SPD and CCT equal to 2000 K, 2800 K, and 4200 K, as well as colour rendering index (CRI) equal to 25, 83 and 90, respectively, were used. The research highlighted that by using 2800 K or 4200 K lights, it is possible to increase the city users' perception of safety and comfort in comparison with the 2000 K lights.

The results reported in references [65,66] suggest that the position of luminaires along the road is significant. The locations of luminaire installation give information about the shape and the boundaries of the street (visual guidance) to the road user. The luminaires siting, the light colour, the mounting height, and/or the luminaire style increase the visual performance of users.

Weather conditions can be considered as the parameter that mainly influences the visual performances of road users. Rain modifies the road surface and its reflection properties, causing a marked change of the luminance distribution and the formation of very bright areas. On these areas, the luminance values can be 5–10 times higher than those in dry conditions [67–69]. Roads covered by snow exhibit higher average luminance values but luminance uniformities comparable with those in dry conditions [67,68]. Fog causes higher average luminance values and luminance uniformities, even though it may result in substantially decreased driver visibility [67].

Finally, according to reference [39], the following additional subjective parameters in the design and siting of road lighting installations and equipment should be considered:

- choice of supporting method—for example, columns with or without brackets, suspension wires, or direct mounting on buildings;
- scale and height of lighting columns or other suspension elements in relation to the height of adjacent buildings, trees, and other salient objects in the field of view;
- mounting height of the luminaire;
- the lit appearance of the complete installation.

2.2. Green Area Lighting

Urban green areas have become one of the most important components that affect the life of city users and the appearance of the city. Studies underline that green spaces allow for an increase in life quality, affecting citizens and workers positively, from both physical and psychological points of view [70]. Green areas are the place where people establish the connection among different parts of the city [71], where people develop social integration [72], and where people exercise, spend leisure time, and can relax. In this scenario, the green areas lighting system is one of the most important tools to guarantee people enjoy the city spaces at night. A proper lighting system design allows people to use green areas for as long as possible, maximising the efficiency of these areas. From this perspective, the green areas lighting systems have the main objective of encouraging the citizens to use these spaces at night, as well as during the day. The various activities that people can do in green areas (e.g., walking, talk, exercise, relax), as well as the presence of vegetation and animals, make the lighting design of these areas particularly complex. For these reasons, basing the green areas lighting design only on the photometric requirements may not be the optimal design approach. Studies have underlined that photometric measures are not enough for describing the user experience of the lighting system, and additional tools based on area users are needed [73]. Additionally, user perceptions in green areas involve psychological and vision features, so exterior lighting design is more challenging.

Many researchers agree that the most important aspects to guarantee in green areas are a sense of safety and security and that the lighting can significantly affect these aspects [74–80]. A proper lighting system can be the key factor in ensuring the success of a green area. People in a well-lit green area feel safer and more secure, thus using the space more. The presence of people in a green area improves the safe perception of the place, attracting more people to that area. This improves the overall feeling of security in both the green area user and the community. In some cases, light has been used to reduce gang-related violence and to strengthen individuals, families, and communities [81]. Generally, people judge safer spaces with higher illuminance levels, in which an optimal view of the environment is kept [82]. Despite this, using a constant high intensity of light could dwindle the appearance of the park and reduce its usage. The light intensity should be differentiated according to different areas and activities present in the park for providing an interesting visual aspect of the landscape and attracting people's attention [83,84].

Many studies agree that a successful green area lighting design is achieved mainly using a hierarchical approach to choose light types and intensity [85–88]. Using a hierarchical approach for lighting help user orientation, thus improving the recognition of the different activity areas of the park correctly. The main footpath and activity areas should be put at the top of the hierarchy, while unsafe spaces or areas that could be inappropriate for the night use should be put at the bottom of the hierarchy.

Together with the sense of safety and security, to ensure a good perception of space accessibility makes people more confident when entering the park after dark. According to reference [89], the perception of accessibility increases when increasing the perceived brightness of the lighting. The research also suggests that the extent of the visual field is the major contributor to the perceived visual accessibility. In addition, the results advise that the perception of the lighting as unpleasant, unnatural and monotonous is important to the perceived danger of a footpath.

The lighting system should prevent the occurrence of dark shadows and glare [61,74,90,91]. Glare reduces people's visual performances [82] and can be avoided using fixtures with a proper intensity distribution curve. Dark shadows affect the fear perception of the people. Studies [61] underlined that when people looking towards lighted areas have less fear than looking toward darker areas. By appropriately assessing the positions of trees, bushes, and lighting pole, as well as the height of bushes and luminaires, dark areas can be avoided.

Studies suggest that areas allowing for high visibility (to recognise distant objects) [84,92] and the ability of precise identification of the surrounding space [28,74,83,87] attract people, making the areas safer and more secure. From the lighting points of view, the concepts of visibility and surrounding identification are closely linked. Both objectives can be reached through a lighting system that avoids unlit areas or dark trees and bushes, increasing the visibility of the whole environment around the users. The paths, as well as elements along with them and trees between them, have to be lighted to provide more information to people. Moyer [83] states that people feel safe and secure when they can see the boundaries of the environment around them. In reference [28], Nasar and Bokharaei argued that the perception of the entire environment is a key aspect also for square users.

For a park, the choice of the correlated colour temperature of light is a particularly important issue. CCT affects not only the human perception of the environment and safety [63,64,78,79], but also the fauna [77,93]. Smith and C. Hallo in [78] demonstrated that park visitors prefer that the light CCT varies upon varying the area of the park. The participants in the research preferred 3000 K light (the warmest light available) for the comfort station and the amphitheatre but 4200 K light for the pathway. The participants indicated the 6000 K light as the most unwanted light for all locations. Regarding the lighting of trees and bushes, if on the one hand tourists prefer white light for creating a pleasant atmosphere to relax [79]; on the other, light with a CCT between 2200 K and 3000 K minimises the negative effects on birds [77]. Additionally, reference [77] advises to avoid cooler white light with CCT higher than 4000 K and to limit its use in areas where safety is particularly important. Greater care should be given to select products with specific spectral content to reduce possible impacts on any specific species of wildlife.

Regarding the CCT, it is important to remark that the light perception of humans, animals, and plants is strongly related to light SPD rather than CCT. This means that the use of light with different SPD could lead to different research results, even if lights are characterised by the same CCT value.

Additional issues to take into account in parks lighting design are [74,78,85,86]:

- the position of luminaires;
- the mounting height of the luminaire;
- the choice of luminaire;
- the luminaire supporting pole.

2.3. Architectural Lighting

Buildings are the essential elements of a city, being the places where people spend most of their time (living or working). They affect the shape and perception of the cities during the daytime and play a crucial role in space perception during the night. Artificial lighting plays a relevant role in the buildings and city perception since it can be used for both functional and aesthetic reasons [94]. Lighting building façades is a technique, known as floodlighting, that appeared at the beginning of the 20th century as a modern abstract art able to cross the boundaries between film, architecture, and painting [95]. The biggest challenge for architectural lighting is to design a decorative illumination that can give a building a different nature than the one it has in daylight, emphasizing its shapes and highlighting the characteristic details of the objects while hiding those that are less interesting [96]. The light is capable of "building" on its own, not only lighting or decorating, but making houses and facades visible, enhancing historic buildings, and emphasizing modern architecture. In recent years, the relevance of architectural light is changing since the change in habits of the city users. Lighted façades are becoming marketing factors and means of communication, improving the attractiveness of a space, enhancing tourism, arousing emotions, or being modern landmarks [97–99]. Due to the growing complexity of lighting design, field trials, that use real lighting equipment, can no longer be used. The design of complex lighting systems needs the use of smart simulation software that can provide a realistic virtual representation of the final results [96,100]. Studies observed that some factors, especially related to the subjective response of people, strongly influence the visual perception of lighted buildings.

The average luminance levels of the building façade are an objective parameter used in standards [101–103] to safeguard and enhance the night-time environment for people, flora, and fauna. Standards suggest maximum values of this parameter depending on the environmental zone where the façade is located, even if with slight differences. EN 12464-2 [101] recommends maximum average luminance levels equal to 0, 5, 10, and 25 cd/m^2, while the Commission Internationale de l'Eclairage(Vienna, Austria) recommends levels equal to 4, 6, and 12 cd/m^2 for floodlighting installations. These limitations are necessary to prevent physiological and ecological problems to the surroundings and people.

Another very important aspect of façade lighting is the position and directionality of the luminaires [96,104–107]. The luminaire position and the direction of the luminous flux emission modify the appearance of the façade and the light effect. Three different floodlighting methods can be identified—planar, accent, and mixed. The planar lighting is realised using large-wattage projectors placed away from the building. The result is a façade lighted as it would in daylight [108]. The accent lighting is realised using smaller luminaires, generally located on the façade or close to it. Combining the luminous flux coming from individual luminaires, it is possible to focus the observer's attention on some architectural detail instead of others. In the mixed lighting method, both the planar and accent lighting methods are combined [96,105,107,109]. For special occasions, specific projectors can be used to realise the dynamic lighting of the building, producing moving patterns or coloured light [105,110].

The luminous intensity distribution of the luminaire is a parameter closely correlated with the light effect on the façade. It can be used as an additional lighting design parameter that contributes, together with the arrangement and directionality of the luminaires, to emphasize the architectural details, and allows for a correct perception of the whole façade [100,104,106,107].

The correlated colour temperature of the emitted light can be used in architectural lighting for different purposes [100,104–106,111]. The light CCT can be used to align [100] or to differentiate [105] a building from its surroundings by using light with similar or different CCT in comparison to that used for the external lighting. The light CCT can also be chosen to accentuate the building materials [106]. Besides, the CCTs can be applied to underline dimensionality (for instance, using 5000 K for background surfaces and 3000 K for architectural details) [112] and create dramatic effects (such using 6500 K) or traditional effects (such using 2700 K) [111]. In this case, it is necessary to remark that the light perception of humans, animals, and plants is strongly related to light SPD rather than CCT.

The lighting of the building also affects people's perception of security, making visible the architecture and contours of the buildings even during the night [111]; some buildings are a landmark of the city, and their lighting helps to make them recognizable from afar as well as identify routes and places, facilitating the orientation of city users [55,56].

The architectural lighting has also been aimed at arousing emotions in people. Emotional aspects of the architectural lighting are influenced by the light CCT [111], the dynamic changes of the light [98], and the use of coloured light. Coloured light has a notable effect on people. Strong colours reinforce the nature of a busy area, while softer colours induce relaxation. Using different light sources or RGB, LED dynamic light can produce colour contrasts and distinguish two parts of a building or space [106].

In recent years, architectural lighting has evolved from a static instrument to light façades as a means of communication. Smart cities have increasingly encouraged human–computer interaction with a range of cutting-edge technologies. These days, smart media displays/façades provide a new means of communication and creative engagement in smart cities [97,113,114]. Combining the building skin with LED communication technology, the façades become "media-façades" able to display logos, text messages, and animations with the purpose of communication, advertisement, commerce, art installation, and social interaction [97,98,115].

2.4. Objective and Subjective Parameters

The objective and subjective parameters that emerged from the literature review for roads, green areas, and architectural lighting are listed in Table 1.

Table 1. Objective and subjective criteria used to design the lighting systems upon varying the area of the city.

Road lighting Design Criteria	Green Area Lighting Design Criteria	Architectural Lighting Design Criteria
Illuminance level	Illuminance level	
Illuminance uniformity	Illuminance uniformity	
Luminance level		Luminance level
Luminance uniformity		
Glare	Glare	
Traffic intensity		
Presence of parked vehicles		
Vertical illuminance (Pedestrian road crossing)		
Facial recognition		
Colour rendering index		
Correlated colour temperature	Correlated colour temperature	Correlated colour temperature
Spectra power distribution		
Recognition of obstacles		
Orientation	Orientation	
Sense of safety	Sense of safety	
Rain		
Snow		
Fog		
Luminaire supporting method	Luminaire supporting method	
Scale and height of luminaire supporting method		
Choice of luminaire	Choice of luminaire	
Mounting height of the luminaire	Mounting height of the luminaire	
Lit appearance of the complete installation		
Position of luminaires	Position of luminaires	Position of luminaires
	Hierarchical lighting approach	
	Accessibility	
	Avoid dark shadows	
	Visibility	
	See the boundaries	
		Directionality
		Luminous intensity distribution
		Emotional aspects
		Communication

3. Use of Virtual Reality for Lighting Design: State-of-Art

The use of immersive virtual reality as a tool for lighting design is a topic that is drawing great interest in the scientific community. IVR allows to overcome some barriers in carrying out tests in real environments, such as to control the luminous conditions, to change the visual conditions and safely investigate hazardous environments.

The studies carried out in this field suggest that renderings, photographs and virtual reality are suitable methods to investigate the effects of light and space on subjective impressions [116,117]. The key factor for using virtual reality environments as a substitute of a real one is the capability of reproducing a light environment perceived like the real thing, a correct light distribution from the photometrical point of view, and the perceptions that people experience in the real spaces. Some investigations [118] underline that (i) an accurate correspondence of the virtual environment from the photometric point of view is required for studies focused on the effects of lighting on perceptual impressions, such as interest or pleasantness of a scene, while (ii) interactivity and immersion of the users are essential for investigations focused on reproducing the human experience in real environments.

Sanchez-Sepulveda et al. [119] showed the result of a project aimed at creating a public space for people rather than vehicles, involving people in the design process. The virtual model of the area was realised in the game engine Unreal Engine 4 and shown to participants using wearables technologies and augmented reality in tablets. The study is focused on evaluating the participants' engagement, motivations, and overall experiences. The virtual reality allowed participants to explore the environment and propose some design solutions, seeing in real-time the effect of the changes. Regarding the lighting system, the participants could modify the CCT, intensity, and type of light for every street section. The results highlighted the possibility of using virtual reality to increase people's satisfaction and motivation in urban decision-making processes.

In reference [36], the virtual environments were used to present different outdoor lighting scenarios in urban spaces investigating the psychological effect of those scenarios on the participants. The lighting scenarios were presented using three representation methods characterised by different degrees of interaction and rendering quality. The Ludwigsplatz in Darmstadt was created in Photoshop, Relux Suite 2016 and Unity 3D and was shown to the participants using an LCD screen (Panasonic at Kadoma, Osaka, Japan, 56") and an Oculus Rift headset (Menlo Park, California, USA). A total of 19 lighting scenarios were created, modifying the light conditions of the square lighting brightness, as well as the façade, the trees, the seating cubes, and the fountain lighting. The 21 participants were asked to answer questionnaires on the lighting systems as a whole, the lights arrangement, the floor and façades visible brightness, and the height of the poles. The research results pointed out the possibility of using VR to evaluate lighting scenarios and compare different lighting systems. The participants could detect both the lighting quality and lighting technology.

Boomsma and Steg [62] investigated the effects of entrapment, lighting levels, and gender on the perceived social safety and acceptability. The study was conducted showing the participants four virtual environment movie-clips, through a 17" monitor placed inside a dark room; two lighting levels (assessed to be 17 lux and 12 lux) and two entrapment settings were considered. A road of about 20 m wide and another of about 5 m wide were used to reproduce a low and high entrapment setting, respectively. The light poles were also included in the scene. Seated alone at about 0.60 m from the monitor, each of the 88 participants was asked to see the movie clip and rated questions about the scene lit conditions, the easy to escape from the scene, the perceived safety, and the acceptability of lighting levels. The research results indicated that gender and entrapment have a significant impact on perceived safety and acceptability, and the effects of the lighting level are contingent upon the entrapment level. Low lighting levels were considered more acceptable for the low rather than the high entrapment setting.

Using immersive virtual reality, Tabrizian et al. [80] investigated the effect of the green space enclosure on the sense of safety. The images of two settings (urban park and urban square) were acquired and modified to include the vegetation spatial arrangement and permeability, for a total of

18 scenarios. The permeability was changed, varying the trees and shrubs number on each edge. Then, the modified images were converted into the six faces of a cube [35]. Using the World Vizard software, virtual environments of each scenario were built, from the cubes, and showed to the 87 participants through the head-mounted display (HMD) Oculus Rift CV1 (Menlo Park, CA, USA). The results demonstrated that the sense of safety does not depend on the enclosure levels; the research showed that it is in contrast to other research carried out on the urban environment.

Felnhofer et al. [69] used virtual reality to investigate the effects of different weather conditions in inducing specific moods in participants. The virtual models of five parks, each designed to induce different moods (joy, anger, boredom, anxiety, and sadness), were modelled with the software Blend 3D, while the real-time rendering was carried out using OGRE3D rendering engine. The virtual environments were displayed to the participant using a smartphone as an input device. The participants viewed the park in first-person and could walk inside the scene, while the scenario representing a grey and raining day was used to evaluate the ability of VR to induce sadness in the participants. A scenario with different park lighting conditions (light vs. dark) was used to cause a sense of anxiety. The results underline a satisfactory ability of the virtual environment in inducing the specific emotion in participants, as well as in producing emotions in people, by changing a few elements of the virtual environment design.

Nasar and Bokharaei in [28] investigated the effects of light brightness, uniformity and light position on people's impression of light, especially on the perception of safety. The simulation program 3DS MAX was used to create virtual environments representing two squares with different lighting scenarios—uniform and non-uniform lighting, more and less light, and a lighting pole placed overhead the square or along the edges. The images were then shown to 363 adult participants through an online survey. The uniform lighting scenario was realised by overlapping the light cones on the ground, while they were kept separated for the not-uniform lighting. The research underlined that the participants felt more comfortable and safer in uniform and bright light and in overhead light on the whole square.

The literature review revealed some limits that can affect the realistic perception of the sense of safety by using VR systems. The review underlines that the sense of safety is strongly influenced by visibility and the quality, quantity, and distribution of light. Visibility in the virtual environment can affect the correct perception of spatiality (and thus the sense of safety) since current VR technologies are characterised by limited values of the field of view in comparison to the human eye (for example, the HMDs field of view is equal to about 110 degrees). Regarding light, researchers have highlighted that the illuminance levels, quality of lighting, and light uniformity affect people's perception of the sense of safety. All these parameters are connected with the ability of VR systems to reproduce the light behaviour correctly from the photometrical point of view. Unfortunately, there is a lack of scientific literature in the assessment of VR systems accuracy in reproducing light distribution. The inaccurate reproduction of light distribution makes it very difficult to realise a light environment in virtual reality that corresponds to the real one. In the same way, a quantitative evaluation of the light uniformity and amount of light is not possible without an accurate reproduction of the light luminous intensity distribution in the VR. In addition, the limited values of contrast range and peak luminance of screens and HMDs make it difficult to reproduce glare effects and large variation of illuminance values. Finally, another parameter that changes the safety perception is the quality of light, intended as SPD of the light source used to light the virtual environment. At present, light with different SPD cannot be simulated in VR.

Basturk et al. [120] used virtual reality to reproduce a pedestrian area 150 m long in the calle San Jacinto (Seville, Spain). The research was aimed at taking advantage of virtual reality to involve the end-user in the design of public spaces by combining visual and acoustic stimuli; to create a reference scenario that was as realistic as possible, a model of the buildings and ground 3D was obtained from GIS data and satellite images and matched with real in situ photographs and rendered images. Finally, the sound sources recorded in situ were added and synchronized with the virtual scenes. Two scenarios were proposed concentrating on the variation of the lighting design as well as the luminaire and lamp types. Sodium-vapor-based luminaires (the warmer light) and LED-based luminaires (the cooler light) were reproduced.

The pedestrian behaviour at a street crossing [121] and visibility [122] were examined using VR during the daytime. Deb et al. [121] used virtual reality to investigate the efficacy of this technology for the examination of pedestrian behaviour at a street crossing. The Unity 5 game engine was used to recreate a traffic environment with a pedestrian crossing. To make the virtual environment more real, both visual and acoustic information was provided to the participants. A total of 60 trials were exhibited to the participants using the head-mounted HTC Vive (Xindian, New Taipei, Taiwan), while sensors were used to track the position and rotation of the user. During the experiments, the position and orientation of each participant's head were recorded. At the end of each experiment session, the 21 participants were asked to answer questionnaires about simulation sickness, presence in the VE, and the usability and user experience of the VR. The results confirm the validity of virtual reality to investigate pedestrian behaviour. The participants expressed a good feeling of presence and evaluated the simulation method as usable and realistic. The effects of visibility on the pedestrians' choice of the urban routes were examined by Natapov and Fisher-Gewirtzman [122] using virtual reality. For the research, an area of 1400 × 1800 m of the Tel Aviv central district was built in the simulation software 3D StudioMax. The virtual environment was shown to the participants using a 3D immersive theatre consisting of a 2.4 m × 7.0 m screen with a 75° field of view and three high-definition Projectiondesign projectors, arranged in a dark room. The 40 participants were asked to wear 3D glasses and, using a joystick, 'walk' through the same virtual environment. Sensors and tracking cameras were used to detect the road chosen by the participants. Then, the choices were associated with the environment visibility from the participant's point of view. The results hinted at a relationship between environment visibility and the participants' road choices. In addition, the findings stressed the benefit of the virtual reality laboratory as a tool for research on complex urban situations.

Undoubtedly, to quantify the amount of light and its distribution represents a key problem in lighting design. This literature review underlines the wide use of quantitative criteria based on photometric units for evaluating lighting systems performances. In addition, correct reproduction of the light from the photometric point of view is required for research focused on the effects of light on perceptual impression [118]. Nonetheless, the reproduction of the real distribution of light and its realistic perception from the users is one of the critical aspects that strongly affect the usage of VR systems as a lighting design tool. To the authors' knowledge, the problem of the effective light distribution is a topic that has not yet been considered in outdoor lighting. Without research aimed at analysing the correct light distribution for outdoor areas, the first step should be to review the results made available by investigations carried out for similar applications. The aim of this review should be to obtain information about the available software and equipment, the best research methodology, and the parameters to take into account and those that can be analysed using VR. If the objective of the study is to evaluate the reproduction accuracy of the light distribution for outdoor virtual environments, the research on light distribution inside the indoor virtual environments can be considered as the best reference. Applying the necessary distinctions, environment typology (outdoor or indoor) does not affect how VR systems reproduce light distribution. Moreover, since at sunrise and sunset in the outdoor areas there is the contribution of both natural and artificial lighting, it is necessary to analyse the light distribution of both daylight and artificial light. In order to have an overview as wide as possible, studies focused on the distribution in VR systems of daylight [118,123,124], electric light [125], and their integration [126,127] were thoroughly reviewed.

Generally, daylight distribution inside VR is investigated [118,123,124] using head-mounted devices to display 360° immersive scenes realised by utilizing the physically based simulation software Radiance. Chamilothori et al. Reference [118] presented a new method aimed at obtaining immersive virtual environments starting from renderings in which the light behaviour was simulated in a photometrically accurate manner. A test room of about 20 m^2 with a window on the south-oriented wall, a grey floor, and white-painted walls and ceiling was taken as a reference. The physically based simulation software Radiance was used to generate six high dynamic range (HDR) perspective views of the test room. The six HDR images were then converted to low dynamic range and assembled to form an expanded cube. For the same light scene, two cubes with two viewpoints (one for each user's eye) were realised to create the perception of depth. The cubes were imported into the game engine Unity to produce an immersive virtual model of the test room and showed to users using an HMD Oculus Rift CV1 (Menlo Park, California, USA). Seven light scenes for clear and two for overcast sky conditions were rendered to analyse the perceptual accuracy, the users' physical symptoms using the HMD, and the presence perception of the users in the virtual room. The 29 participants were first asked to compare the real and virtual environments and to respond to some questions regarding their perception. Then, they were asked to respond to a questionnaire about their presence perception. The results underlined no substantial differences between the virtual and real test rooms in terms of the evaluation and physical symptoms of participants. Moreover, satisfactory responses were observed regarding the reported presence.

The possibility of reproducing the artificial light distribution by using virtual reality is examined in reference [125]. A real room (internal sizes of 4.35 m × 2.85 m and ceiling height 3.2 m) with white-painted walls and ceiling (reflectance equal to about 0.7 and 0.8, respectively) and floor reflectance equal to about 0.1 was considered as the reference environment. The virtual environment was recreated composing six fish-eye (180° in each direction) HDR images acquired from the same viewpoint in a 360° image. The 360° image was presented to the 20 participants using an HTC Vive head-mounted display (Xindian, New Taipei, Taiwan). The participants were asked to perform some visual tasks based on colour discrimination and contrast sensitivity in real and virtual environments. Finally, they had to make a judgment about the perception of the lighting appearance (brightness, CCT and distribution), visual-quality perception (details, contrast, and colours), room perception impressions (pleasantness, interest, complexity, excitement, and spaciousness), realness, spatial presence, and involvement. The results highlight no significant differences between the two environments, and similar contrast and colour appearance can be obtained through virtual reality. Differences came to light concerning colour, contrast, and detail perception.

Heydarian et al. [126] used immersive virtual reality as a tool to gather information on the effect of integration between daylight and electric light on the users' perception inside the virtual environment. Differently from other researches, the virtual environment was first built in Revit© 2015, then imported into 3DS Max© (where information about the furniture, material properties and lighting maps were added to the model), and finally imported into the Unity 3D game engine. In this study, a south-oriented private office of 50 m^2 in size was modelled, including three windows, each equipped with a manual switching system, and 12 luminaires (each with three fluorescent lamps). Each participant could see the virtual model through an Oculus DK2 HMD (Menlo Park, California, USA) while also having the ability to set the opening of each shading system and to turn on/off each lamp on each luminaire. The 89 participants were asked to select the preferred lighting condition from the 32 available, then reading a text, and finally to answer a few questions on text comprehension. To overcome the lack of VR game engine in providing illuminance values, the Unity 3D model was imported into Rhinoceros 3D and Grasshopper to carry out the lighting and environmental analyses. The results underline the suitability of virtual reality in collecting end-user lighting preferences and the benefits of its use in the buildings design stage to both improve energy saving and meet the users' expectations.

The above review allows the identification of some preliminary information useful to research the ability of VR systems in reproducing precisely the physical behaviour of light in outdoor virtual environments:

- calibrated 360° HDR images can be used to reproduce a correct light distribution;
- game engines can be used for correct reproduction of light distribution;
- HMDs are the best VR equipment for an exact perception of light distribution;
- game engines do not allow a direct evaluation of illuminance and luminance values;
- in VR a correct light distribution can provide an adequate level of space presence, lighting appearance and environment perception.

Table 2 shows the criteria analysed by using virtual reality.

Table 2. List of lighting design criteria analysed using virtual reality.

Lighting Design Criteria	References	Note
Illuminance level	[28,36,62,119]	Qualitatively evaluation
Illuminance uniformity	[28]	Qualitatively evaluation
Vertical illuminance (Pedestrian road crossing)	[121]	Daytime
Correlated colour temperature	[119,120]	
Rain	[69]	
Choice of luminaire	[119,120]	
Mounting height of the luminaire	[40]	
Lit appearance of the complete installation	[40]	
Sense of safety	[28,62,69,80]	
Position of luminaires	[28,36,120]	
Visibility	[122]	Daytime

The review reveals a general agreement that virtual reality can be considered a methodology capable of replacing the real world for investigations on the visual perceptions of people. It is well established that virtual reality, especially using head-mounted devices, can reproduce a realistic immersive environment with which the user can interact and have perceptions like in the real world. The review also indicates two different ways to use head-mounted devices according to the research objective. If the research is aimed at analysing the experiences, the mood, the psychological effects of light on participants, or to involve people in the lighting design, the virtual environments are usually built using a game engine and shown through HMDs to users. When the research is focused on the users' impressions assessment or the quantitative evaluation of the amount of light, HMDs, coupled or not with a game engine, are used to make immersive 360° HDR images taken in the real environment or rendered with physically based simulation software.

Generally, there is a lack of research assessing the possibility and accuracy of the game engine in reproducing the light distribution from a photometrical point of view. Game engines, calibrated from the photometrical point of view, could significantly improve the use of these tools in lighting design and research. The most significant benefit would be the possibility for users to walk through the scene and change their point of view.

4. Future Opportunities for Virtual Reality in the Lighting Field

The use of the HMDs coupled with a game engine could be beneficial for both lighting design and research. In contrast to other virtual reality systems, the game engines allow us to model virtual environments which are fully explorable by the user. Additional devices, such as position sensors or joysticks, can be used to univocally locate the user's position inside the virtual model, so that the user can explore the scene by walking through it, turning his or her head, or by changing his or her point of view. In addition, the user can interact with the virtual environment through the game engine, making changes, and viewing their effects in real-time.

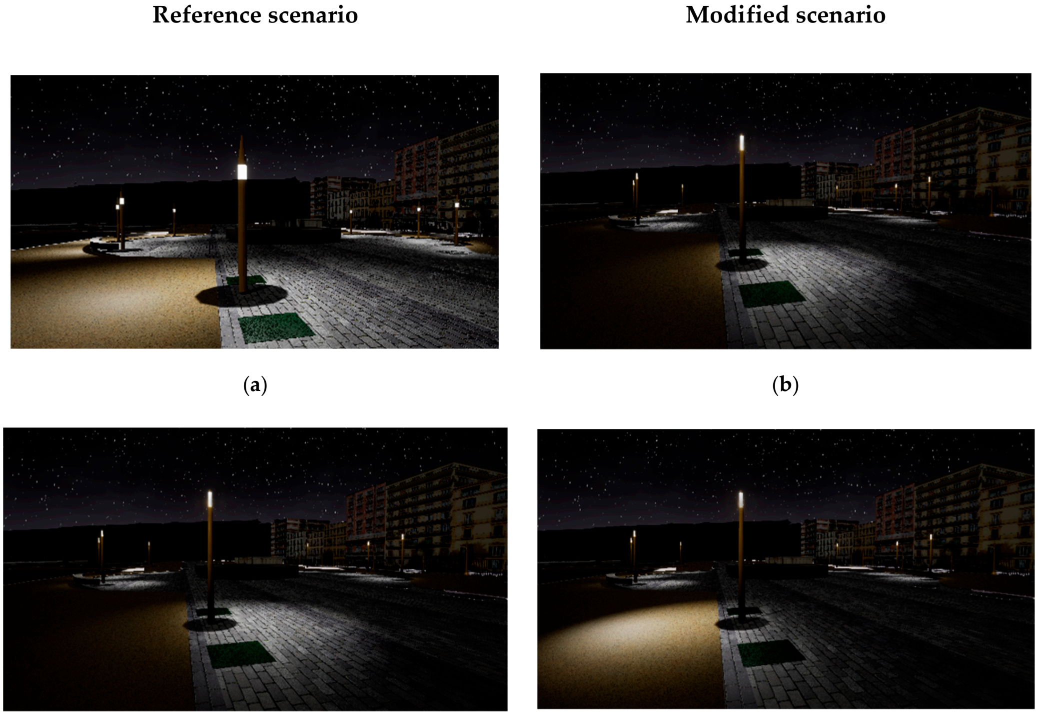
With the aims to verify the possibility of reproducing a specific criterion and encourage the use of virtual reality for both lighting design and research, an assessment of the feasible modifications to be made to a virtual scenario for reproducing a specific lighting design criterion was performed. For this purpose, the virtual model of the Villa Comunale of Naples (southern Italy) [128,129] was built in Unreal Engine 4. Technical draws and field surveys were used to make the virtual model as realistic as possible. City roads, materials, light, and trees from the real environment were reproduced in the virtual one. Figure 1 shows two views of the Villa Comunale.

Figure 2 shows illustrative images of the modified scenario in comparison with pictures of a reference virtual using the Unreal game engine [130]. Unreal Engine 4.24.3 [130] was used, coupled with an HTC Vive Pro Head-Mounted Display (Xindian, New Taipei, Taiwan), which is characterised by 1440 × 1600 pixels per eye resolution and a 110 degree field of view. The comparison between the criteria listed in Table 1 and those reported in Table 2 highlights that many criteria have not yet been investigated in previous studies. In this section, the results of the analysis performed for these unvetted lighting design criteria are presented. It is important to note that the object of the present study is not to validate the usability of virtual reality in the evaluation of its effectiveness in reproducing specific lighting design criteria but to indicate if and how they could be simulated through the Unreal game engine. For each criterion, further and specific investigations will be needed to evaluate the effectiveness of virtual reality in inducing the desired emotions in the users.

Figure 1. Views of the Villa Comunale of Naples.

4.1. Scale and Height of Luminaire Supporting Method, Luminaire Supporting Method and Luminous Intensity Distribution

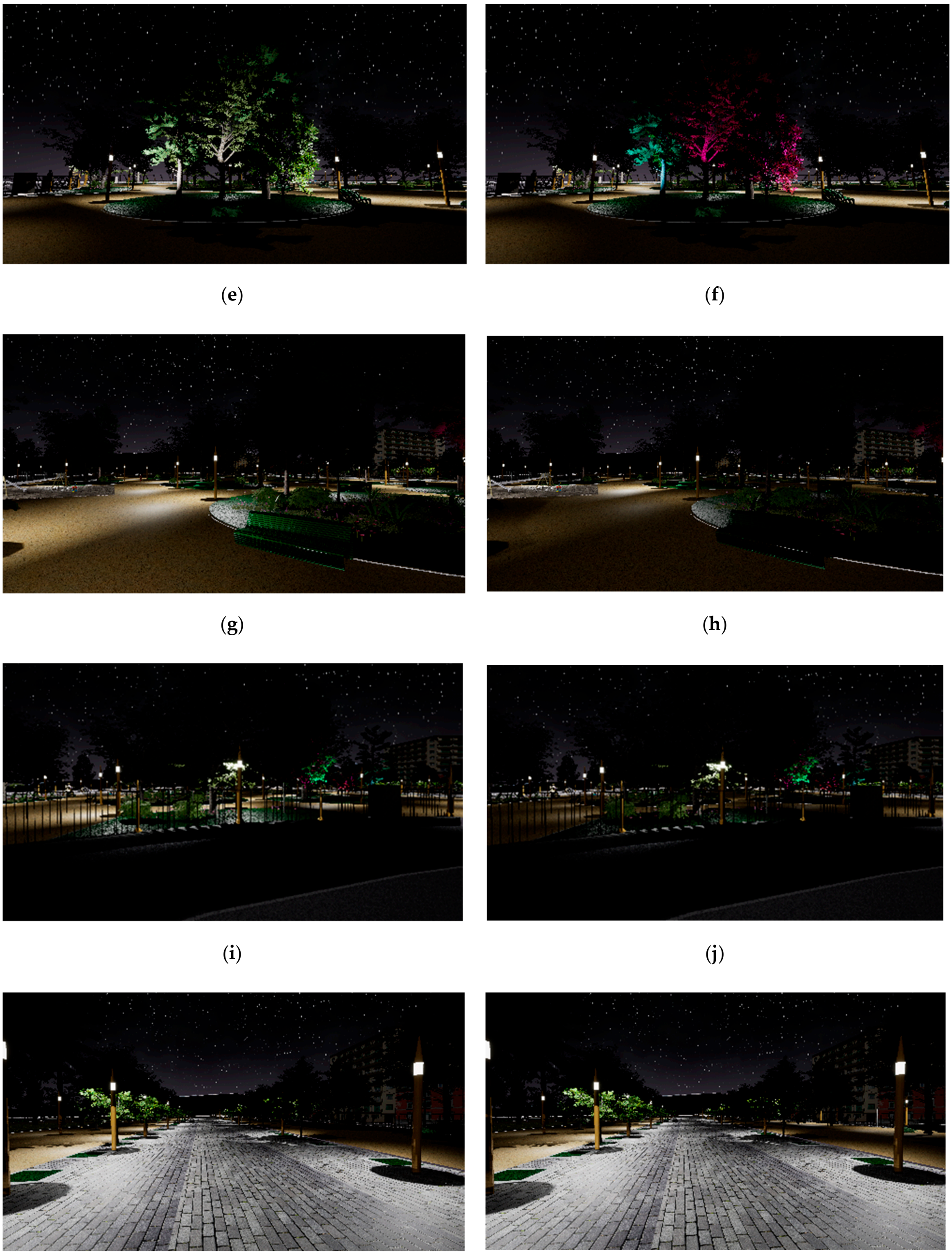
The parameters 'Scale and height of the luminaire support method', 'luminaire support method', 'directionality', and 'light intensity distribution' were analysed in Figure 2a,b; the central part of the 'Villa Comunale' of Naples was taken as reference.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. *Cont.*



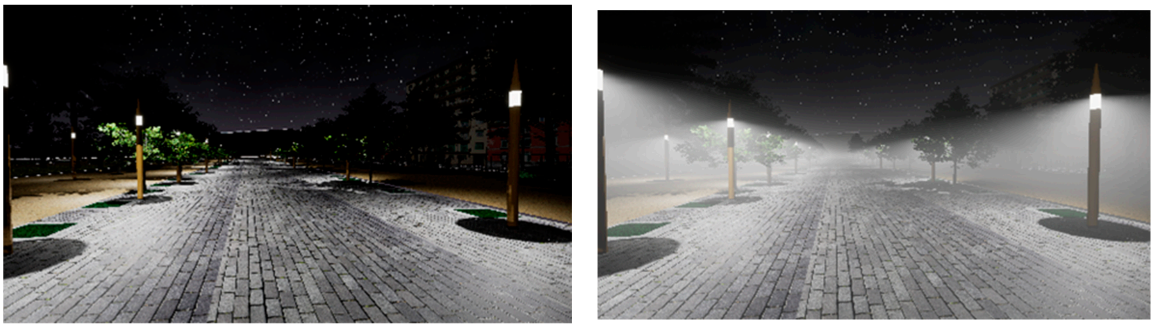
(**e**) (**f**)

(**g**) (**h**)

(**i**) (**j**)

(**k**) (**l**)

Figure 2. *Cont*.



(**m**) (**n**)

Figure 2. Representation of lighting design criteria in the virtual environment: (**a**) Reference image of lamps used in avenue, foreground, and square; (**b**) Luminaires taller and thinner with different light intensity distribution in comparison to that of Figure 2a; (**c**) Reference image with lamps characterised by the same luminous intensity distribution with respect to Figure 2b; (**d**) Lamps rotated in comparison to that of Figure 2c; (**e**) Trees illuminated by using white light; (**f**) Trees illuminated by magenta and green lights; (**g**) Lamps in park characterized by the same luminous flux value; (**h**) Dimmed lamps from secondary areas; (**i**) Exterior view of the park with lamps characterized by the same values of luminous flux; (**j**) Exterior view of the park with lamps characterized by two luminous flux values; (**k**) Main tree-lined avenue without the presence of luminaires along the park edges; (**l**) Main tree-lined avenue with the presence of luminaires along the park edges; (**m**) Demonstration of lighting effect without fog; (**n**) Demonstration of lighting effect with fog added (using 'Exponential Height Fog Actor').

Figure 2a shows the reference image, in which the lamps used in the avenue, in the foreground, and in the square are the same from both geometrical and photometrical points of view. They are characterized by the same shape, height, and emission of light. Regarding the luminous intensity distribution, Unreal Engine allows us to define the light emission following two different methodologies. In the default setting, the light is considered emitted according to a cone. By varying the aperture angle and luminous flux values, it is possible to change the distribution of light as well as its intensity. In the second method, it is possible to insert the IES file of the luminous intensity distribution as 'IES Texture'. In this case, the light emission follows the profile described by the IES distribution, while the light intensity can still be changed.

Figure 2b exhibits the same scenario in which the lamps were different from the first ones from geometrical and photometrical points of view. The luminaires of the square are taller and thinner and have a different light intensity distribution.

As the figures show, all modifications regarding the luminaire supporting methods, the shape and height of the poles, or the luminous intensity distributions are perceptible in the virtual model.

4.2. Directionality

The parameters 'directionality' was analysed in Figure 2c,d. In particular, the lamps used in the avenue are characterised by the same luminous intensity distribution, but the lamp in Figure 2d is rotated in comparison to that of the Figure 2c. Comparing the two figures, it is possible to notice the ability of the virtual model to make noticeable the variation in light orientation.

4.3. Light Spectral Power Distribution and Emotional Aspects

The criteria 'light spectral power distribution' and 'emotional aspects' were analysed in Figure 2e,f. Regarding the quality of light, Unreal gives us the ability to use both white or coloured light, setting its RGB values in the Unreal setting 'Light Color'. White light is obtained by setting the RGB values to 255, 255, 255, while coloured light is obtained changing the RGB values, the range of which can vary from 0 to 255. For white light, the CCT can also be changed, as reported in previous studies [119,120].

Figure 2e shows trees illuminated by using white light, for which the Unreal 'light color' was kept at its default value, while in Figure 2f, magenta and green lights were used instead of white light. Comparing the two figures, it is possible to notice the effects of RGB value variation on the appearance of light and the ability of Unreal Engine to change the colour of a surface according to the colour of the light that illuminates it. In addition, as the colour of the light changes, the luminance value of the lit surfaces also varies. Unfortunately, the current version of Unreal does not give us the ability to set the light source type (e.g., LED, fluorescent).

Finally, based on the ability of Unreal to reproduce light with different colours, it should be possible to create very suggestive scenarios designed to arouse different emotions, such as excitement or astonishment, making a simple walk less boring and more amazing. After all, previous works [69] used light in virtual reality to induce specific emotions in participants.

4.4. Hierarchical Lighting Approach, Visual Orientation, Dark Shadows, and Recognition of Obstacles

Figure 2g,h show the use of a hierarchical approach for lighting in a single scenario with different areas. Figure 2g shows a scenario in which all the lamps in the park are characterized by the same luminous flux value, while in Figure 2h, the lamps of the secondary areas were dimmed in comparison to the lamps in the main avenue and the children's play area.

These figures show that it is possible to recognize the differences in light intensity, resulting from the diversification of the luminous flux value for the different areas to assist the users in recognizing different park activity areas correctly and in orientation. In this way, different lighting systems could be compared with the objective to find out the one able to satisfy both the citizens' needs and the reduction of the energy consumption associated with the lighting system.

Controlling the lighting systems is now considered the best way to achieve energy savings. The review results underline that, in general, an increase in lighting amount does not translate directly to an increase in people's satisfaction, and that the correct amount of light should be guaranteed for each visual task. For these reasons, different lighting control strategies and systems have been developed [131–136]. In general, these strategies are aimed at dimming or switching off the lighting system in the absence of vehicles or people and reducing the amount of light at night in very low traffic and brightening when presence is detected.

According to reference [131], energy savings in the range of 25–45% can be achieved using remote-control lighting systems. Sedziwy and Kotulski [136] proposed a control roadway lighting system with which is possible to reduce energy consumption by up to 70%. Jägerbrand [132] mapped synergies and trade-offs between sustainable development and energy efficiency and savings regarding exterior lighting. From the energy point of view, it should be noted that VR systems do not allow energetic analyses. However, it is possible to show people different scenarios, with varying amounts of light, and then different energy consumption. Asking people to select which solution they prefer, it is possible to identify the optimal solution that will be able to assess both energy savings and people's acceptance.

Furthermore, the two figures show that dark shadows can be avoided by changing, for example the value of the lamps' luminous flux. Indeed, the software takes into account the amount of light coming from various lamps and changing the intensity of the shadows accordingly. Thanks to the possibility of modifying the shadows' intensity, the virtual environment appearance and the ability of users to recognise obstacles can be varied.

4.5. Accessibility

Exterior lighting addresses specific needs and uses, as welcoming people to a park with a dedicated walking path and entry lighting, providing views from the interior to the exterior of a building (and vice versa), and allowing for easier and more secure night-time activities. Figure 2i,j shows a view of the park from the outside, considering two lighting conditions. Figure 2i shows a scenario where all the lamps are characterized by the same values of the luminous flux, while in

Figure 2j, two luminous flux values were considered—a higher one for the main park areas and a lower one all other areas.

The reduction of the luminous flux and, consequently, the energy consumption and waste of light leads to a reduction of the environmental impact and the light pollution caused by the lighting of urban centres. At the same time, the usability of city spaces at night can only be improved if people feel safe enough to live in the area. The critical factors in achieving these objectives are the quality of light (not the quantity), the width of the visual field, and the perception of the lighting [89]. As the pictures show, Unreal Engine can be used for comparative evaluation among virtual environments with different lighting conditions. In particular, based on the light quality (colour and CCT), the field of view (how much space is visible), the orientation, and the pleasantness, users can suggest the lighting design that raises their sense of safety or the one that they simply prefer.

4.6. See the Boundaries and Visibility (by Night)

Figure 2k,l show the main tree-lined avenue of the 'Villa Comunale'. Figure 2l differs from Figure 2k by the presence of luminaires along the railings at the park edges. The presence of the lamps allows the user to have a wider and deeper field of view. The software allows the creation of a virtual scenario to verify the influence of lighting along the park boundaries on people's perception in terms of visibility and safety.

4.7. Fog

In Figure 2n, thanks to the use of the 'Exponential Height Fog Actor', it was possible to recreate the fog within the scenario. It is possible to modify several parameters of this actor—for example the 'Fog Density', which can be thought of as the fog layer's thickness, and the 'Fog Height Falloff', which controls how the density increases as height decreases. Besides, each light's contribution amount to the scene can be controlled by adjusting some light details, such as the 'Volumetric Scattering Intensity' that controls how much each light will contribute to the 'Volumetric Fog'.

4.8. Facial Recognition

Facial recognition strongly affects people's perception of safety. Studies underline that pedestrians' sense of safety rises if they can recognize oncoming people by a distance of 4 m [50]. Generally, facial recognition investigations have been carried out both in the field [50,64,73,89] and in the laboratory [37,51,53,137,138]. Using different targets, such as dummies, real persons, or images, the distance at which participants are able to recognise gender, identity, facial features, or facial expressions is measured. A common approach for field tests is to place the target under a lamp, while participants are asked to see the target from a distance and express judgments about the target's recognisability. Tests can be performed by varying the distance between the participants and the target while asking some questions about the target recognisability or by making the participants walk toward the target and asking them to stop when they recognise the target. Light condition (different vertical illuminance levels on target or lamp type) and/or the observation time can be varied to analyse their effects on the participants' judgment.

Generally, laboratory tests are carried out using images as the target and following two different setups. In the first setup, a large room with black walls is used to simulate a piece of a road [37,51]. The target images and lamps under investigation are placed at one end of the simulated road, while the participant is on the other. Then, the tests follow the same analysis methodology used in field tests. In the second setup, the target images are shown to participants by means of apparatus [53], screens [137], or projectors [138]. Participants are then asked to express judgments about their ability to recognise faces identity, facial expression, facial emotion, or matching faces.

The review highlights two important outcomes—(i) the effects of lighting conditions on facial recognition can be effectively investigated showing test images to participants by means of projectors or screens and (ii) some characterising parameters are common to all investigation methods. In particular, parameters that mainly affect the field and laboratory investigations are the (i) relative position among lamp, target, and participant; (ii) illuminance level on the target image; and (iii) lamp type. Also, in reference to the Unreal game engine, by comparing the parameters which can be adjusted in the software with the parameters which mainly affect the facial recognition tests, it is reasonable to expect the possibility of using Unreal for that kind of analysis. Indeed, the relative position between the player and target can be exactly defined and know in Unreal, either by setting the distances in the geometrical model or by identifying the position of the player through the motion tracking system. As previously described, the illuminance level on a surface can be changed by modifying the luminous flux or the luminous intensity distribution of the light source. As reported above, Unreal allows us to change the CCT and colour of light, while it is not possible to modify the light SPD. Regarding the target, researchers can either import high-quality images into the virtual environment, or they can create virtual characters with very detailed facial expressions.

4.9. Glare

Glare is one of the most relevant parameters used to identify physical discomfort caused by a non-proper light distribution. Generally, two different types of glare were identified—(1) discomfort glare, caused by high luminance levels in the field of view, and (2) disability glare, caused by light reflected in the eyes, thus reducing visibility [111]. With the aim to quantify the discomfort glare, different indices have been proposed over the years [139]. With the current technology of HMDs, it is almost impossible to reproduce the effect of glare. Indeed, standard HMDs are characterised by limited values of contrast range (generally 100:1) and peak luminance (100–160 cd/m^2). Consequently, the magnitude of glare in the eye produced by the display light cannot be compared with that produced by a real light source. Nevertheless, the reproduction of the sense of glare is one of the major challenges for VR that some researches try to overcome by adding glows around the light source in order to mimic a kind of glare sensation [140] or by suggesting new methods for the realistic visualization of lighting conditions [141].

5. Conclusions

This paper is aimed to underline the current state of use of virtual reality for outdoor lighting design. With this aim, in the first part of the article, a comprehensive review of the lighting design criteria to consider for lighting design of three city areas was carried out. In particular, the review was focused on the road, green area as well as architectural lighting. The review identifies a total of 22 lighting design criteria for road lighting, 15 for green area lighting, and seven for architectural lighting. Considering that some criteria are common to different city areas, a total of 31 lighting design criteria are identified. The state-of-art of the virtual reality use for the outdoor lighting design is then established. Papers focused on this issue were thoroughly reviewed in order to understand if and how the virtual reality is currently used as a lighting design and research tool. The review underlines that, until now, only 11 lighting design criteria have been investigated using virtual reality (with some limits).

In general, researchers agree on considering virtual reality, especially coupled with HMDs, to be a promising methodology for investigating people's visual perception thanks to its ability to reproduce the real world. In addition, the review points out a research gap in assessing the accuracy of game engines in reproducing light distribution properly; therefore, immersive virtual reality could be used much more for light design. With the aim to verify the possibility of reproducing a specific criterion and encourage the virtual reality use for both lighting design and research, the Unreal game engine is used to assess the IVR ability in reproducing each of the lighting design not yet investigated by the current literature. For this purpose, the Villa Comunale in Naples was built in Unreal Engine. Starting from a reference scenario, modifications were made to evaluate if and how each unvetted lighting design criterion could be reproduced. In addition, IVR can be used to identify the optimal lighting design solution that is be able to assess both energy savings and people's acceptance.

The analysis results emphasize the effectiveness of Unreal in simulating almost all (except facial recognition and glare) of the found lighting criteria, even if specific investigations will be needed to evaluate the efficacy of Unreal Engine in inducing the desired emotions in the users. In particular, future research should be devoted to investigating the accuracy in reproducing light distribution, a methodology to verify the illuminance and luminance values, the effects of different climatic conditions, the reproduction of glare, the sense of safety, facial recognition, and emotional aspects.

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