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Urban Park Lighting Quality Perception: An Immersive Virtual Reality Experiment

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Abstract: Green areas and parks are increasingly important in improving citizens' physical and mental recovery. Lighting systems play a considerable role in affecting city park life and activities along with people's moods and behavior in the evening and at night. Immersive virtual reality laboratory experiments may support urban and lighting research by providing information on the combination of lighting setup and visual context of existing or new urban parks. Gaze behaviors obtained from eye-tracking recordings and self-reported measurements using the perceived outdoor lighting quality questionnaire were used to determine the factors affecting human perception, comfort, and cognitive load, as the overall illuminance levels of the scene and correlated color temperature changes. Results pointed out that overall illuminance level and CCT significantly affect the perceived strength and comfort qualities of lighting with a dominance of the first compared with the latter when subjects were free to explore the lit environment. Low CCT and intermediate or high overall illuminance levels can improve the sense of accessibility as well as minimize the cognitive load.

Keywords: virtual reality; urban park; outdoor illuminance level; visual perception; correlated color temperature

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1. Introduction

While urban green areas can be considered among the most important spaces of a city—as they affect not only the local microclimate and the aspect of the city but also the users' mental and physical health and social cohesion—their usability and quality perception of the spaces in the post-sunset hours depend on several characteristics that foster the frequentation of the park, one of this is its lighting [1]. Current guidelines related to outdoor lighting design emphasize objective measurements, including luminance distribution, illuminance levels, glare, the directivity of light, color appearance, and color rendering, and take care of various needs from different perspectives, including energy efficiency, aesthetics, and safety [2–4]. Most of them were set for the needs of visual accessibility and perceived safety in specific environments such as workplaces [5], sports places [6], and pedestrian paths [2,7]. The illuminance levels and the correlated color temperature (CCT) of the light affect outdoor spaces' appearance and usage [8]. In particular, the illuminance level affected the sense of safety [9] and the area's visual aspect and attraction [10]. At the same time, the light CCT influences the human perception of the environment and sense of safety [11,12], their emotions and the sense of exploration [13], and the fauna [14]. However, less is known about their applicability to urban parks. The main reason is that the luminous environments in urban parks are more complicated and dynamic related to their spatial attributes and functionalities. The main challenge of the lighting research in those places is to clarify the effects of overall lighting level on human perception and behaviors in the urban park during the nighttime while retaining the naturalness of the complex luminous environments with mimic lighting characters [15].

Conventional lighting design tools that consider only objective parameters are not enough to reflect the total quality of luminous environments. Using immersive virtual reality (IVR) technology makes it possible to improve the quality of the design process through controlled objective parameters and real-time subjective assessments in more realistic lit environments.

1.1. Immersive Virtual Reality for Outdoor Lighting Design

Several studies have tested the feasibility of immersive virtual reality (IVR) to reproduce realistic physical environments for outdoor lighting research. Chen et al. [16] contrasted the subjective reactions of people to physical lit space and its reproduction through photography, video, and immersive virtual reality. The results indicated that virtual reality is the best technology to reproduce lighting environments. Chamilothori et al. [17] proposed the use of rendered images obtained from physically-based software into IVR to carry out subjective investigations of daylit spaces. The results indicated high perceptual accuracy of daylit space in VR settings and few variations compared with real environments. Lee and Lee [18] built a virtual urban plaza in the Unreal Engine to explore the effectiveness of virtual reality simulation on the qualitative analysis of landscape lighting design. More studies were reviewed in the work of Scorpio et al. [8]. In 2022 [19] the same research group developed a methodology to use a game engine (Unreal Engine 4.22) to reproduce light distribution in a real indoor lighting environment. The results suggested good reliability of the Unreal Engine in reproducing the light distribution. Some researchers focused their effort on evaluating the effects of light level [20–22] and CCT values [20,23,24] by using virtual reality (VR). However, the combined effects of overall illuminance level and CCT are rarely investigated, and even fewer works refer to urban green parks [18]. More recently, Masullo et al. [13] investigated the effects that the combination of illumination intensity and CCT had on the most favorable psychological effects on users of urban parks. With this aim, nine distinct virtual scenarios were created by mixing various CCT and overall brightness levels and asking the participants to rate how much each scenario contributed to making them feel calm, nervous, energic, weak, happy, and sad. Additionally, how much each lighting setting affected people's motivation and feeling of safety was also observed.

The previous investigations are mainly focused on assessing the users' preferences, fostering more comprehensive knowledge and deeper insights from the user's perspective. These studies should be extended to evaluate urban park lighting.

1.2. Subjective Design Factors for Outdoor Lighting

Along with physical management of objective factors in outdoor lit environments, the human perception and reactions to the environmental lighting need to be also considered from a human-centric design perspective [25,26]. Flynn et al. [27] published a research report on the Illuminating Engineering Research Institute (IERI) Project 92, providing procedures for evaluating the subjective impression in lighting. According to their suggestion, two aspects of human behaviors should be answered in the effects on spatial illumination: the light effects on subject impression and attitude, as well as on performances and overt behaviors.

Various lighting research focused on outdoor lighting environments has assessed different subjective aspects of lit environments, including perceived quality [27], visual comfort [28,29], and psychological impression [27,29]. Flynn et al. [27] listed several rating scales that have been discovered to discern between lighted spaces in measuring perceived qualities referring to visual clarity, spaciousness, evaluative responses, social prominence, complexity, spatial modifiers, etc. Shikakura and Kikuchi [30] classified the subjective impression of outdoor lighting into three groups: brightness, comfort, and uniformity. Johansson et al. [31] investigated the potential predictors for the perceived visual accessibility and the perceived danger of an urban footpath. The perceived qualities, including light, unpleasant, colored, weak, concentrated, cold, evenly distributed, soft, focused, unnatural, murky, monotonous, bright, dimmed, and brilliant were used for subjective lighting assessments. There are also some works that brought the Attention Restoration Theory (ART) to the examination of lighting's role in psychological restoration [32,33]. Nikunen et al. [33] studied the link between the four attributes of ART (being away, fascination, extent, and compatibility) and perceived lighting (brightness, distribution, glare, color quality, feeling of safety, and pleasantness). However, no fixed relationship between those attributes and ART components was found. Kim and Noh [34] evaluated the Perceived Adequacy of Illumination (PAI) effect on walkers' nighttime experiences, including discomfort glare, willingness to stay, pleasantness, and liveliness. They found that spaces with a higher percentage of PAI were strongly correlated with the perception of pleasantness, liveliness, and suitability of spaces. Among all of the evaluation scales, Johansson et al. [35] addressed the quality of street lighting in two-side ways: technical environmental assessment (TEA) and observer-based environmental assessment (OBEA) in the perceived outdoor lighting quality questionnaire (POLQ). This questionnaire summarized most of the items in the works we mentioned above and could help us combine the objective descriptors and subjective indexes for a deeper investigation.

1.3. Eye-Tracking for Lighting Design

Besides subjective assessments, objective evaluations referring to human perception and cognition of luminous environments are also necessary for investigating lighting environments. Ocular behaviors recorded by eye-tracker are most considered for investigating human visual perception. Eye movements (such as fixations, saccades, and pupil dilations) reveal the sensory inputs from the external luminous environments and are controlled by the internal brain involving cognitive and affective processing. Two kinds of eye-tracking metrics were used for most of the vision research, including gaze metrics and pupillometry. Foulsham et al. [36] compared the gaze distribution of participants while viewing natural scenes in the lab and the physical environment. The data revealed that eye movements were more centralized in the real world, and locations around the horizon were selected with head movements. Using on-site captured gaze data in the real world could bring us more insights into landscape perception and evaluation. Cottet et al. [37] recorded in situ gaze data to study how the composition of a landscape affects how people see it. The findings showed that the rating, verbal, and gaze data were highly concordant (based on gaze fixations). The gaze data aided in classifying the effects of nature on urban inhabitants' perceptions and assessments of the landscape, as well as identifying landscape items essential in creating landscape valuation judgments. As for the application of eye-tracking in lighting study, Fatio et al. [38,39] used pedestrians' fixation data to address the importance of people and path visibility for lighting design. The walkers' typical distance and duration of fixation in the street night-lighting environments have been investigated. However, few studies have evaluated saccadic eye movement in VR scenarios, regardless of lighting research. Zhang et al. [40] proposed an integrated approach to cityscape design based on virtual reality and eye-tracking technology to reveal the salient cityscape features. Anderson and Bischof [41] examined the extent to which image content influenced eye and head movements in a VR environment. Haskins et al. [42] examined the effects of active and passive viewing circumstances on gaze behavior while participants explored new, real-world settings using VR technology and in-headset eye-tracking. They discovered that active viewers paid greater attention to areas of the scene that were semantically significant, indicating more exploratory, information-seeking gaze behavior. Kim and Kim [43] conducted eye-tracking experiments in a VR scenario through real-field panoramic image presentation and provided an empirical framework for quantitative visual data analysis in virtual environments. Using eye-tracking 'in the wild'—in real, naturalistic, and outdoor settings—poses logistical and methodological difficulties, including the gaze–object mapping and gaze behavior classification during the gaze–head co-locomotion, thus more and further studies are needed [44]. Except for the spatio-temporal features of ocular behaviors, pupil diameter measurements could reflect the intensity of the sensory inputs. The pupil size constricts with the increment of light intensity and dilates with the decrement of light intensity. However, there is also evidence indicating that the change in pupil size reflects high-level sensory and cognition processing, including high-level visual features detection [45], internal environment representation [46], attention [47], affection [48], and emotional memory [49]. The index of pupillary activity (IPA) developed by Duchowski's work is related to cognitive load to pupil oscillation after removing the effect of light reflex because the pupillary response increases at the increase of cognitive load [50]. Imaoka et al. [51] found the pupillary response in HMD display close to previous studies on 2D screen display. However, less is known about the contribution of light luminance and CCT in VR environments to those responses.

1.4. Aim of the Research

This paper explores the effects of overall illuminance levels and CCT of the lit environment of urban parks on gaze behaviors and subjective reports. To this objective, a detailed model of an existing city park located in the south of Italy was built into the Unreal Engine and experienced through a head-mounted display (HMD) at different lighting conditions. Users were asked to see the virtual scenarios and answer a questionnaire to evaluate the perceived outdoor lighting quality.

The novelties of this paper, in comparison to the current literature, are the use of IVR for the:

- Lighting management in urban green parks and the comprehensive investigation of human feeling in different lighting environments (limitations underlined in Section 1.1);
- Evaluation of the effects of light brightness and CCT on fixation behaviors and pupil changes measured by IPA indexes (limitations pointed out in Section 1.2);
- Investigation of the effects of brightness and CCT on the perceived quality of street lighting, fixation, and pupillary activity (in contrast to feeling sensations, motivation, and sense of safety analyzed in [13]).

2. Materials

2.1. Virtual Environment

A virtual environment reproducing an existing urban park in Aversa (Italy) was digitally modeled using the Unreal Engine 4 (UE4) software. The scene reproduced an existing layout including different elements: trees, grass, park pavement, some street furniture (i.e., street lamps, benches, dustbins), the sky, and other surrounding elements (buildings, walls, and roads). A fixed observation point inside the park was selected to simulate the perspective of a visitor sitting on a bench. Participants could rotate their heads and sight freely exploring at 360°, ecologically, the virtual environment of the park where they were immersed. The amount and quality of light emitted by each streetlamp were set at different luminous flux values and CCT. A total of 9 different virtual scenarios were obtained considering three luminous fluxes of the luminaires: 250 (low illuminance level), 500 (medium illuminance level), and 1000 (high illuminance level) lumen, and three CCTs: 2500 K (warm), 4500 K (intermediate), and 6500 K (cold). The nine lighting scenarios are shown in Figure 1.

An HTC Vive Pro Eye headset provided participants with immersive virtual reality experiences. This head mounted display (HMD) consists of two OLED screens (1440 × 1600 pixels each), offering a 110-degree field of view, and a refresh rate of 90 Hz. Unreal Engine 4.26 installed on a desktop computer (AMD Ryzen Threadripper 1950X 16-core processor 3.40 GHz, 2 NVIDIA Geforce RTX 2080 Ti, WINDOW 10 Pro 64bit) was used to control the HMD.

The lightness values were calculated from the panoramic image captured from UE4 in the CIE 1976 L*a*b* color space to evaluate the relation between the lighting distribution and gaze behavior using the built-in function rgb2lab in MATLAB [52]. A Difference of Gaussians (DOG) kernel was applied to each lightness image to simulate the lightness perception based on the work of Safdar et al. [53]. The semantic labels were manually labeled with the "Image Labeler" toolbox and "Color Threshold" toolbox in MATLAB, including the bench, grass, tree, road, sky, streetlights, infrastructure (direction board, dustbin), and others (surrounding buildings, walls, etc.). A color threshold was used to segment each label with the Color Threshold toolbox. Then, the Image Labeler toolbox was used to correctly handle each label (see Figure 2).

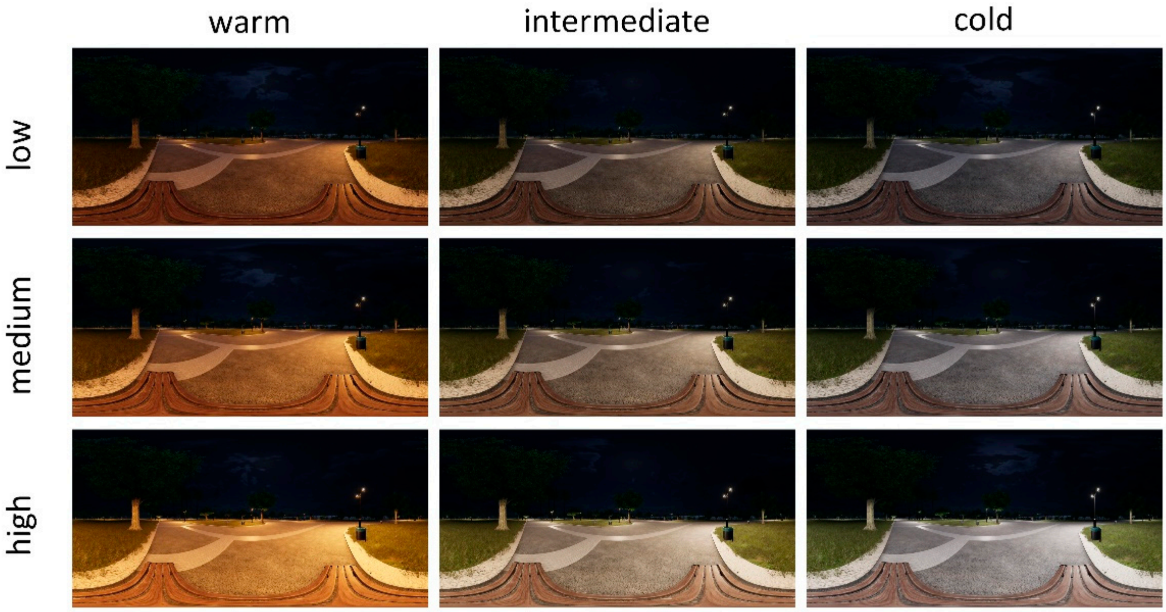

Figure 1. 360° images of the virtual environment across different overall illuminance levels and CCT conditions.

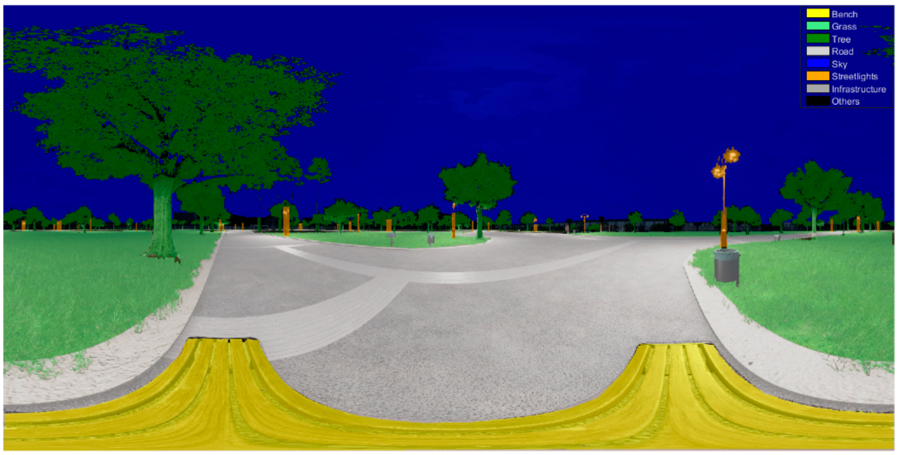

Figure 2. The semantic labels of the panoramic image in one of the VR scenarios.

The light amount received at the eye was evaluated at the eye's positions, acquiring the illuminance values through the CRI Illuminance Meter CL-70F (illuminance range: 0 ÷ 200 klux and accuracy: ±5% ± 1 digit of displayed value; CCT range: 1563 to 100,000 K and accuracy: xy = ±0.003 (at 800 lx)) placed in the HMD at 10 mm from the lens in a completely dark room [54,55]. The CCT values of the light reaching the participants' eyes were also acquired. The correct positioning of the measuring sensor was guaranteed using an ad hoc adaptor realized by 3D printing. Table 1 lists the values obtained by measurements in the right eye for each scenario. The measures on the left lens showed illuminance differences lower than 1.5 lux [5].

Table 1. Measured illuminance and CCT values at eye position upon varying the luminous flux and CCT of light in the virtual scenario.

			Virtual Scene CCT		
			Warm	**Intermediate**	**Cool**
Virtual scene Overall illuminance level	Low	CCT (K)	2890	5413	7912
		E (lux)	6.7	5.5	5.4
	Medium	CCT (K)	2727	4918	6922
		E (lux)	12.8	11.3	11.5
	High	CCT (K)	2871	4907	6629
		E (lux)	23.2	20.6	19.3

2.2. Questionnaire

The POLQ questionnaire [35] is a tool that laypeople can use to systematically capture the general public's view of outdoor illumination through two dimensions: (i) Perceived strength quality (PSQ) linked with the sense of brightness and light direction, and (ii) Perceived comfort quality (PCQ) linked with the light pleasantness and softness. In addition, high PCQ ratings are correlated with not perceiving danger, while high PCQ and PSQ values are related to highly experienced visual accessibility. The questionnaire was translated into Italian language and used to assess and compare the qualitative aspect perceived by the participants among the different scenes. A 7-point semantic differential scale question was assigned to each item (see the Supplementary Materials). The translation of each item was conducted and converged into one-by-one relationships by three field experts. The agreement of the translated items was also confirmed by a reversed translation conducted with ten native speakers from the students' group (see Table 2).

Table 2. The English items and Italian translation of POLQ questionnaire.

	English	**Italian**
Perceived strength quality (PSQ)	Clear–Drab	Chiara–Cupa
	Strong–Weak	Forte–Debole
	Unfocused–Focused	Uniforme–Concentrata
	Subdued–Brilliant	Fioca–Brillante
	Dark–Light	Scura–Luminosa
Perceived comfort quality (PCQ)	Mild–Sharp	Morbida–Netta
	Hard–Soft	Intensa–Soffusa
	Warm–Cool	Calda–Fredda
	Glaring–Shaded	Abbagliante–Non abbagliante
	Natural–Unnatural	Naturale–Innaturale

3. Methodology

3.1. Experimental Design

Each of the nine-light scenarios was presented to participants using the HMD HTC Vive Pro Eye after presenting a different view of the park to make them comfortable with the device. Before the formal experiment, subjects were seated in a non-swivel chair, and the built-in eye-tracking module of HMD measured their gaze movements and pupil diameters after they took the 5-points calibration procedure. The subjects were asked to free-view each visual scenario and answer the questionnaire on the perceived lighting quality from a rest-sitting view by oral reports [35]. After answering the questions, subjects would rest for a few seconds and turn to the next lighting scenario. The order of all conditions was randomized and balanced between subjects.

3.2. Participants

A priori analysis of statistical power and effect size was carried out to obtain enough statistical validity of the results. The power analysis was computed using G-Power software [56]. Pre-defined effect size (f = 0.25) and test power (1 − β = 0.95) were used to reach a significant level (α) of 0.05. The analysis pointed out the necessity to consider more than 22 subjects.

Twenty-six voluntary subjects (male: 16; female: 10; age: 29.72; s.d. = ±7.09) were recruited. The experiment took place in the test room of the SENS I-Lab of the Department of Architecture and Industrial Design of the Università degli Studi della Campania "Luigi Vanvitelli". All subjects were in good health, had normal eyesight, and had no color blindness or weakness. All subjects gave informed consent about their participation in the study after being told about the experiment's purpose and process.

3.3. Eye-Tracking Measurement

The built-in eye-tracker of the HTC Vive Pro Eye HMD provided gaze coordinates and pupil diameter data at a sample rate of 120 Hz. After the five-point calibration procedure of eye-tracking, the gaze data stream collected from VIVE SRanipal SDK with LSL API was transferred to a Lab Streaming Layer (LSL) [57] stream synchronized with lighting condition event triggers and 6-DOF head motion provided by a UE4 OSC plugin.

The azimuth angle ($Eye_{azimuth}$) and elevation angle ($Eye_{elevation}$) of each gaze position relative to the screen center was averaged for real gaze position account. Combined with the rotation data from head motion, such as roll ($Head_{roll}$), pitch ($Head_{pitch}$), and yaw ($Head_{yam}$), the gaze and head position in world coordinate, latitudes ($Eye_{Latitude}$), and longitudes ($Eye_{Longitude}$) on a sphere, were computed by the formula below:

$$Eye_{Latitude} = Head_{pitch} + (Eye_{elevation} \cdot \cos(Head_{roll}) - Eye_{azimuth} \cdot \sin(Head_{roll}))$$
$$Eye_{Longitude} = Head_{yaw} + (Eye_{elevation} \cdot \sin(Head_{roll}) + Eye_{azimuth} \cdot \cos(Head_{roll}))$$

Fixation classification in VR scenarios was difficult since it was combined with head motion. Based on the work of Agtzidis et al. [58], fixation without head pursuit and smooth pursuit with vestibule–ocular reflex (VOR) were extracted for analysis since both have a fixed gaze position in the VR world coordinates [59]. The duration of both indexes less than 100 ms were excluded.

The pupillometric data were pre-processed by the ET-remove-artifacts MATLAB toolbox for blinks and artifacts removal [59]. The onset of a blink is detected as the moment at which the velocity drops below a negative threshold (−5 mm/s), which reflects a rapid shrinking of the pupil due to the closing of the eyelid. The "reversal period" of a blink is detected as the moment at which the velocity exceeds a positive threshold (5 mm/s), which reflects a rapid reopening of the eye. The pupil size during the blink was interpolated using cubic-spline fitting. After data cleaning, one subject was removed because of too many missing values. Then, the average pupil diameters and the pupil diameter changes indicated by the indexes of pupillary activity (IPA) were computed. The algorithm of IPA computation was from Duchowski's paper [50]. A two-level Symlet-16 discrete wavelet decomposition of the pupil dilation signal by selecting a mother wavelet function $\psi_{j,k}(t)$ was used. Upon the wavelet analysis of the signal x(t), the resulting dyadic wavelet generated a dyadic series representation. Then, the process followed a multi-resolution signal analysis of the original signal x(t). A level was arbitrarily selected from the multi-resolution decomposition to produce a smoother approximation of the x(t) signal. Finally, the wavelet modulus maxima coefficients were assigned a threshold using a universal threshold defined by:

$$\lambda_{univ} = \hat{\sigma}\sqrt{2 \log n} \quad (1)$$

where $\hat{\sigma}$ is the standard deviation of the noise. The number of remaining coefficients represented the IPA reading for the given pupil diameter signal [60].

4. Results

4.1. POLQ Questionnaire Results

Two-way repeated-measures ANOVA analysis of overall illuminance level and CCT were conducted for each item in the POLQ questionnaire (sphericity assumptions were checked, and Greenhouse–Geisser corrections were used). The results are listed in Table 3.

Table 3. ANOVA results of POLQ items with all variables and their interaction effects.

POLQ Dim.	Items	Overall Illuminance Level			CCT			Overall Illuminance Level × CCT		
		F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
Perceived strength quality (PSQ)	Subdued–Brilliant	116.603	<0.001 ***	0.835	0.719	0.493	0.030	0.631	0.642	0.0027
	Strong–Weak	125.292	<0.001 ***	0.845	0.034	0.967	0.001	0.172	0.952	0.007
	Dark–Light	66.072	<0.001 ***	0.742	0.664	0.519	0.028	0.411	0.800	0.018
	Unfocused–Focused	1.251	0.296	0.052	0.652	0.525	0.028	1.479	0.215	0.060
	Clear–Drab	37.03	<0.001 ***	0.617	5.00	0.011 *	0.179	1.23	0.305	0.051
Perceived comfort quality (PCQ)	Hard–Soft	97.47	<0.001 ***	0.809	1.60	0.213	0.065	1.27	0.287	0.052
	Warm–Cool	0.089	0.915	0.004	47.151	<0.001 ***	0.672	1.003	0.410	0.042
	Natural–Unnatural	51.70	<0.001 ***	0.465	3.08	0.056	0.118	2.29	0.066	0.091
	Glaring–Shaded	87.767	<0.001 ***	0.792	0.488	0.617	0.021	1.301	0.276	0.054
	Mild–Sharp	43.10	<0.001 ***	0.652	1.41	0.255	0.058	1.94	0.111	0.078

* Means that p value was less than 0.05, while *** means that p value was less than 0.001.

In the perceived strength quality (PSQ) dimension, the subdued–brilliant item showed significant differences in overall illuminance level, as with the increment of the overall illuminance level, subjects felt the scene more brilliant, while there was no effect either from CCT conditions or the interaction effect between overall illuminance level and CCT. The same pattern also occurred in the strong–weak and dark–light items, as with the increment of the overall illuminance level, subjects more strongly felt the scene and with more light. The unfocused–focused item showed no significant effects on overall light level conditions, CCT, or the interaction effect between overall light level and CCT. The clear–drab item showed significant results both on the overall illuminance level and on CCT. In fact, with the increment of the overall illuminance level, subjects felt the scene clearer, while the results of the CCT condition showed a u-shaped trend of falling first and then rising with the increment of CCT only for the lower lighting level condition. No interaction effect was found (see left part of Figure 3).

In the perceived comfort quality (PCQ) dimension, the hard–soft item showed significant differences in overall illuminance level, as subjects more strongly felt the scene with the increment of the overall illuminance level. No effect was found on CCT or the interaction. Similar results were carried out for natural–unnatural, glaring–shaded, and mild–sharp items. As with the increment of the overall illuminance level, subjects felt sharper, more unnatural, and glaring. The warm–cool item showed significant results on CCT but not on the overall illuminance level or the interaction effect (see Figure 3 right).

Table 4 reports the mean values (on a scale of 1 to 7) and the standard deviations of the two indices PSQ and PCQ of the POLQ for each of the light scenes investigated. Results show that PSQ values vary from 3.51 (high CCT and low overall illuminance) to 5.97 (high CCT and high overall illuminance), while PCQ values vary from 2.15 (high CCT and high overall illuminance) to 5.26 (low CCT and low overall illuminance).

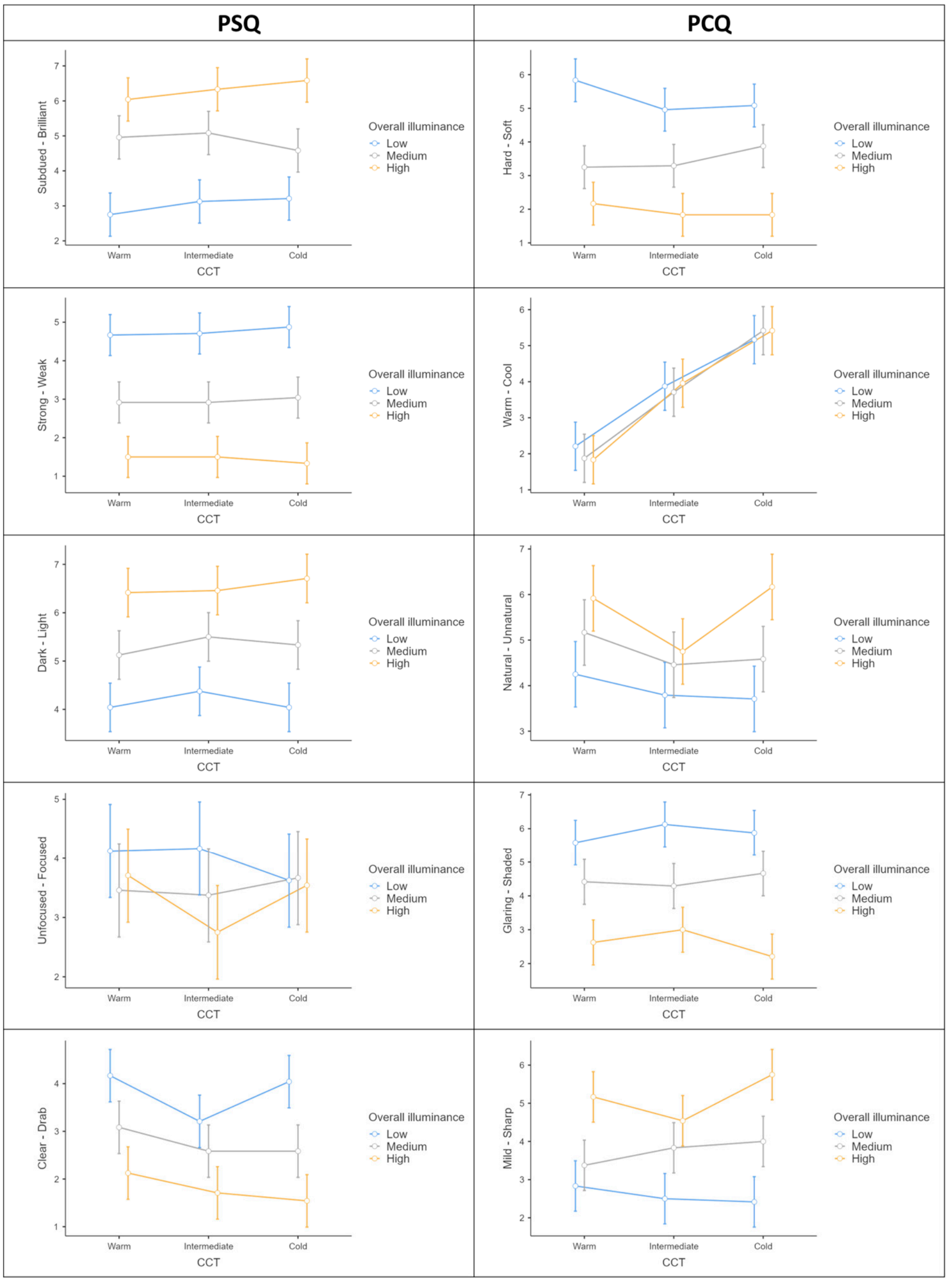

Figure 3. Results of POLQ items: PSQ dimension items (**left**) and PCQ dimension items on the (**right**).

Table 4. Average values of PSQ and PCQ indices (with standard deviation).

	PSQ				PCQ		
	Warm	**Intermediate**	**Cold**		**Warm**	**Intermediate**	**Cold**
low	M = 3.62 (SD = 0.87)	M = 3.89 (SD = 0.87)	M = 3.51 (SD = 0.99)	low	M = 5.26 (SD = 0.84)	M = 4.98 (SD = 0.9)	M = 4.75 (SD = 0.81)
medium	M = 4.79 (SD = 0.98)	M = 4.88 (SD = 0.95)	M = 4.82 (SD = 0.93)	medium	M = 4.18 (SD = 1.23)	M = 3.89 (SD = 0.91)	M = 3.75 (SD = 1.07)
high	M = 5.72 (SD = 1.05)	M = 5.6 (SD = 0.77)	M = 5.97 (SD = 0.43)	high	M = 3.15 (SD = 0.98)	M = 3.13 (SD = 1.23)	M = 2.15 (SD = 0.74)

4.2. Eye-Tracking Measurements Results

From the average data of pupil diameter, the normal pupillary light reflex was triggered by all lighting conditions matching the bright environment (varying from 2 to 4 mm), as with the increment of light intensity, the pupil size became narrower (F(2.46) = 74.938, $p < 0.001$ ***). The CCT did not show a significant result (F(2.46) = 0.064, $p = 0.852$) (see Figure 4 left part).

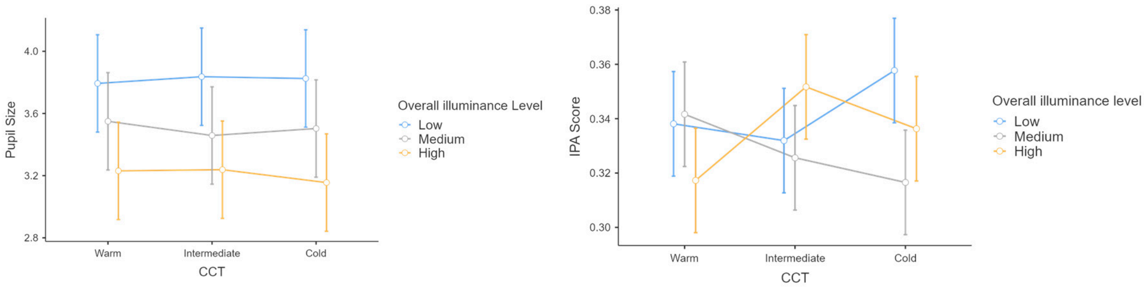

Figure 4. The results of pupil diameter (**left**) and IPA index (**right**) for all conditions.

The IPA results did not show any significant differences among overall illuminance levels (F(2.46) = 0.909, $p = 0.410$) and CCT conditions (F(2.46) = 0.126, $p = 0.882$). However, interaction effects between CCTs and the overall illuminance levels were observed (F(4.92) = 2.629, $p = 0.039$ *) (see Figure 4 right part).

From the generalized linear model results, neither dwell time nor fixation counts of each area showed significant linear relationships with overall illuminance levels and CCT conditions. Most eye-fixed areas were others (including surrounding buildings and walls), road, tree, and grass areas, as reported in Figure 5. The generalized linear model analysis indicated the effects of overall illuminance levels with interactions with CCT in fixation duration for each fixation along with the lightness of each fixation position. The area of light, trees, and others (including surrounding buildings and walls) had a more linear relationship with fixation duration. No differences were found in smooth pursuit with VOR behaviors between different lighting conditions (see Table 5).

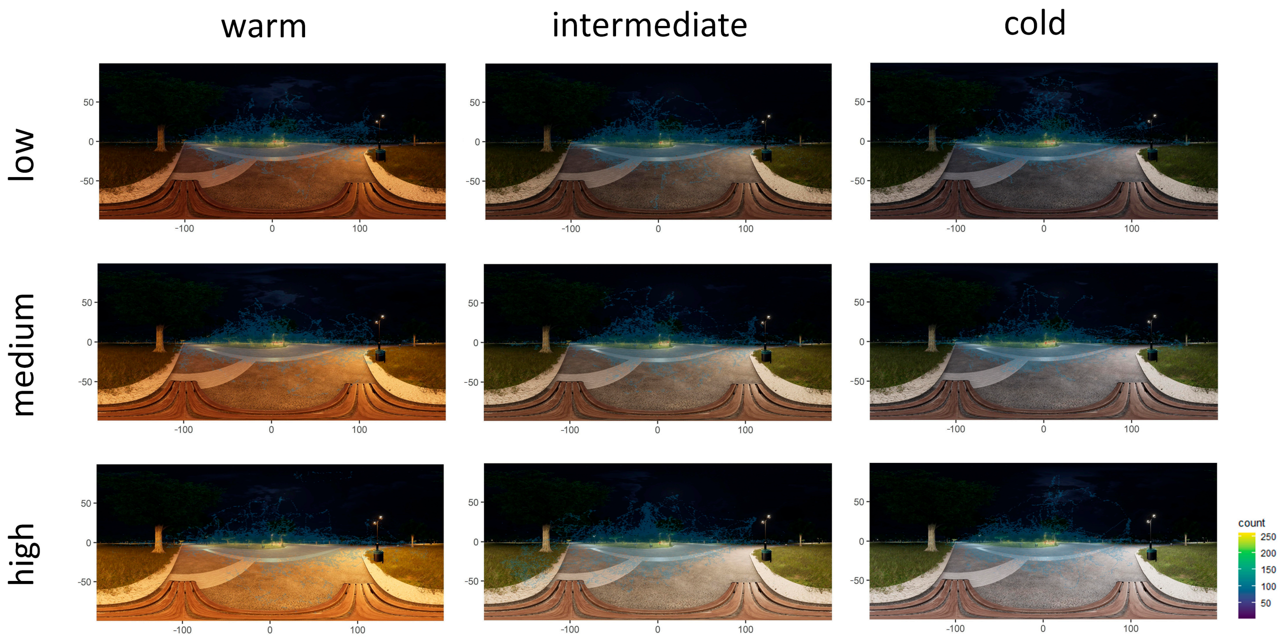

Figure 5. The gaze maps for all conditions.

Table 5. Generalized linear model results of fixation duration with independent variables.

Variables	Generalized Linear Model		
	X^2	df	p
Overall illuminance level	14.5058	2	<0.001 ***
CCT	0.0619	2	0.970
Labels	149.6701	7	< 0.001 ***
Lightness	s64.1997	1	<0.001 ***
Overall illuminance level × CCT	10.6036	4	0.031 *

X^2 means Chi-square coefficient, df means degree of freedom, * means that p value was less than 0.05, while *** means that p value was less than 0.001.

5. Discussion

The POLQ used for the observation-based environmental assessment tool differentiated between lighting conditions of different overall illuminance levels more than CCT in our IVR outdoor environment. The PSQ dimension was used to explain the variance in visual accessibility, while the PCQ was used to explain the failure to perceive danger in the environment [35]. The overall illuminance level influences most aspects of PSQ and PCQ except for unfocused–focused and warm–cool, while the CCT only showed differences between clear–drab and warm–cool items in our study, which were different from the previous findings from the work of Johansson et al. [35]. They showed PSQ was positively related to brightness and less connected to color temperature, and PCQ was negatively associated with color temperature [35]. The overall illuminance level in our VR lighting influenced the brightness perception also with the feelings related to pleasantness, hedonic tone, and softness, which have been reflected by the PCQ dimension from previous studies [31,61]. CCT influenced very limited items from PSQ and PCQ. The results are consistent with the works of Davis & Ginthner [62], Fatios [63], and Yang & Jeon [64]. Results also indicate that low CCT and intermediate overall illuminance can maximize the sense of accessibility, while, surprisingly, decreasing overall illuminance values—mainly due to the increase of the softness, mildness, and shadowiness—should be related to a failure to perceive danger. This last result, in contrast with previous studies. highlights a possible difficulty in using the PCQ dimension to explain the perception of danger in a virtual lighting environment. This aspect should be deeply investigated, especially in order to understand the level of detail and complexity (e.g., presence of an individual, sounds) of virtual scenes to elicit complex emotions like those related to the perception of danger in the visitors.

The lightness of each fixation position could predict the fixation duration within street lights, trees, and surrounding building areas. Rahm et al. [65] showed how the level of urban flora and street lights influenced people's decisions about their routes after dark. Avoidance was aided by entrapment brought on by untidy flora and gloom, whereas human presence may have the reverse effect. The results indicated that urban greenery and street lighting interact with the neighborhood's perceived safety and walkability. Our results also support the idea that more light could help the visual accessibility of greenery areas and street paths.

While previous studies have investigated the effects of illuminance and CCT of light on alertness, task performance, emotion [66], and mood [67] in indoor environments, the contribution of illuminance level and CCT on cognition in the outdoor environment has remained unknown. Zhang and Dai [68] used virtual reality scenarios to investigate the night light comfort of pedestrian space in urban parks. They found CCT influenced subjective light comfort while the average horizontal illuminance affected physiological fatigue, indicated by electroencephalogram signals. They offered a range of average horizontal illuminance and CCT for the light comfort zone in urban park pedestrian spaces. The interaction of overall illuminance level and CCT of cognitive load shown in our study indicates different influences of CCT settings in different overall illuminance level conditions.

6. Conclusions

The overall illuminance level influences various aspects of perceived outdoor lighting qualities more than CCT. The illuminance level affects most items of PSQ and PCQ except for unfocused–focused and warm–cool, while the CCT only showed differences between clear–drab and warm–cool items.

As the two POLQ indices were associated with the sense of accessibility and sense of danger, our results indicate that designing urban park lighting plants with low CCT and intermediate overall illuminance levels leads to maximizing the sense of accessibility, while the counterintuitive results emerged from the PCQ index suggest further and deep research on the use of VR environments to investigate the association between PCQ and not dangerous situations.

Fixation durations of subjects when free viewing the VR scenario have been found to be a close relationship with the lightness of each fixation area. A more complex interactional effect between overall illuminance level and CCT emerged from the IPA index, linked with the cognitive load. In particular, lighting systems with low CCT and high overall illuminance levels or with high CCT and medium overall illuminance levels may minimize cognitive load in the visitors.

While previous results can give some advice for urban park lighting design with a new human-centered and experiential perspective, the use of immersive virtual reality also confirms several important limits and issues of the applied lighting research. The most important is related to the fact that current HMDs can only reproduce a limited range of luminance compared with real lighting conditions, and that the reproduction process of the lighting scenes, from the software to the different HMDs, is still not fully well-known.

Moreover, further specific physiological issues related to the visual interaction between the subjects and the immersive virtual environment, as reproduced by HMDs, need to be deeply investigated.

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