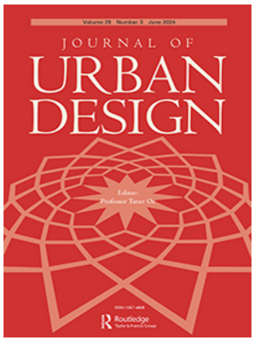

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Street luminance and night-time walking comfort: a new perspective for the urban lighting design

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ABSTRACT

A survey was carried out in Rome to investigate whether street luminance affects pedestrians' comfort, visibility and perception. Forty people walked five roads and assessed on a questionnaire their walking comfort, visibility of people and background, perception of lighting intensity and uniformity. Results indicated that walking comfort was affected by mean luminance of whole scene, of sidewalk, of lateral wall and of human body; luminance also influenced the perception of street lighting intensity and uniformity and, to a lesser extent, the visibility of other people and of background.

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Street lighting; walkability; pedestrians; city; lighting design

Introduction

One of the policies of municipalities to transform cities into sustainable cities is to promote walking. To walk improves urban sustainability under multiple aspects: being an alternative mobility to motorized traffic, it enhances the reduction of CO^2 emissions and improves the air quality of cities; to walk is also related to a healthy lifestyle that reduces the occurrence of some diseases related to the urban environment (Jackson 2003).

Among the several features of the urban environment that promote walking behaviour (Clifton, Livi Smith, and Rodriguez 2007), street lighting is an essential environmental feature for walking outdoors at night, since it illuminates the pathway and the urban landscape. Street lighting plays an important role in the plan of a contemporary city: it supports the use of cities by citizens and tourists, allowing them to walk at night for leisure purposes, for people working outdoors, for sports activities, or for travels from office to house and vice versa; urban lighting enhances social interaction and, in historical cities such as Rome, it also promotes enjoyment of the architectural and artistic beauties set in the urban environment (Casciani 2020).

The quality of street lighting design is crucial to allow people to enjoy the urban environment, since poor street lighting is one of the barriers that make it difficult for pedestrians to walk (Lavery et al. 1996). A recent study demonstrated that street lighting influences the route choice of pedestrians who prefer the brighter routes (Van Beek et al. 2024). Different street lighting affects the visual perception of the environment, the perceived quality of the environment, and the pedestrians' level of arousal, but not

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their walking speed (Rahm, Johansson, and Chen 2018). Jedon et al. (2023) suggest that urban lighting also influences attention and alertness of pedestrians.

Considering the influence of street lighting on walking comfort, illumination of the pathway allows the detection of obstacles, such as irregularities in the pavement or objects on the ground, avoiding trip hazards. The illumination of the environment surrounding the footpath enables visual orientation to recognize the place where people are walking and to find the correct way and it increases the visibility of objects such as insignia, street names, signs, signals and landmarks; illumination of other pedestrians' bodies and in particular their faces is required for seeing expressions, evaluating movements and judging other people's behaviour.

The lighting required for obstacle detection depends on the obstacle height: bigger objects are easier to see and the visual task needs low lighting levels, while smaller elements require higher lighting levels since they are more difficult to see. In cases of low illuminance level (0.2 lux), the ability to detect an obstacle depends also on the observer's age and on the spectral power distribution (SPD) of the light source that illuminates it (Uttley, Fotios, and Cheal 2017): young people (<35 years) showed better performance in the obstacle detection task than old people (>50 years); light sources having high scotopic/photopic (S/P) ratio enabled detection of obstacles of lower height with respect to low S/P light source.

The influence of lighting on pedestrians' orientation is a little investigated topic, while researchers posed much attention on legibility. For instance, Lindh and Annika (2021) suggested that spatial orientation can be favoured with the correct luminous contrast of vertical surfaces. The reading task is obviously more difficult with lower lighting levels (Pedersen and Johansson 2018); moreover, signs can be read at a greater distance when the luminance of the object is higher (Rahm, Johansson, and Chen 2018).

Studies on pedestrians' observation of other people (Fotios and Johansson 2019) indicated that face is a more relevant target than body only, since the time of fixation is longer (Fletcher-Watson et al. 2008) and the observation is more accurate (Burton et al. 1999). The semi-cylindrical illuminance measures at 1.5 from the ground was indicated by Van Bommel and Caminada (1982) as the appropriate quantity to measure the lighting amount on people's faces. When the level of illuminance increases, the ability to see facial expressions improves, while the spectral power distribution seems to be irrelevant (Li et al. 2023).

The investigation by Narendran et al. (2016) showed that a more uniform illuminance distribution improved people's ability to see surroundings and hazards, to distinguish people and ameliorate their judgement on the illumination quality. When the illuminance is more uniform the participant's ratings were higher even for low illuminance levels (Bullough et al. 2019; Narendran, Freyssinier, and Zhu 2016).

In Europe, some regulations guide the design of urban lighting. For pedestrian and low-speed traffic areas, the Technical Report CIE 115:2010 (Andersen, Larsen, and Takashi 2010) prescribes average and minimum horizontal illuminance levels at the ground to allow obstacles and hazard detection on the path; additionally, minimum vertical and semicylindrical illuminance levels are indicated for 'facial recognition'. Moreover, the notes advise that the average illuminance is lower than 1.5 times of the prescribed levels in order to guarantee lighting uniformity, and to adopt lamps having a high colour rendering index to enhance facial recognition. Luminance is a lighting criterion for prescriptions in roads with motorized traffic, but it is not considered in pedestrian areas. Similarly, the European regulation EN 13201-2 (2015a) prescribes horizontal and hemispherical illuminance levels for pedestrians' footways and streets; additionally, semi-cylindrical and vertical illuminance levels must be taken into consideration, respectively, to enhance security and feeling of security, and when the need to see vertical surfaces occurs. In this regulation, luminance and glare prescriptions are provided only for motorized traffic routes.

Recently, several limits of the previous street regulations have evidenced in the literature relatively to pedestrian lighting (Fotios 2020): in particular, the recommendations seem aimed at allowing drivers to see pedestrians, in order to avoid potential collisions, more than satisfying the pedestrians' needs. In fact, many of the parameters for selecting the road's lighting P-class in CIE 115:2010 (speed, traffic volume, traffic composition, parked vehicles) are related to pedestrian security. A similar consideration can be made for the European regulation: the EN 13201-1 (2004) grouped the lighting situations basing on the typical speed of the main user. This parameter calibrates the lighting condition to avoid traffic accidents more than to address the visual needs of pedestrians. Also, the street lighting levels indicated in the CIE 115:2010 and EN 13201-2:2015 regulations refer to people with a normal or corrected to normal vision and do not consider specific groups, such as elderly and visually impaired people, which require particular lighting conditions to walk at night (Guerry et al. 2019; Laurìa, Secchi, and Vessella 2019; Seetharaman et al. 2024).

To guarantee pedestrians' visual needs, regulations could take into consideration where the gaze is directed at night, so to prescribe adequate lighting conditions on surfaces and objects that are mostly observed. The survey of Davoudian and Raynham (2012) performed with the use of an eye tracker showed that people walking on the street at night look at the pavement for about 40% of the time, at other people for about 3.5%, at signs along the route and transient objects for less than 5% and for more than 50% of the time at houses, roads, and trees altogether. In general, pedestrians' fixation is directed to objects having higher luminance and greater saliency within the field of view, and this behaviour occurs more frequently at night than in the daytime (Jiang, Li, and Yang 2021). The CIE Technical Report 236:2019 (Fotios et al. 2019) provides several recommendations on pedestrian lighting based on a summary of actual knowledge on the pedestrians' four primary needs: reassurance, obstacles detection at pavement, judgement of other walkers, and visibility to drivers. For each of these tasks, optimal lighting characteristics are tentatively proposed on the basis of experimental results found in previous research, which can be used as a guide for future street lighting design.

Many of the studies carried out on pedestrian lighting focused on the role of illuminance, since, in general, more light allows a better vision and thus consents to easily execute visual tasks. Nevertheless, this approach can have the consequence of increasing the illuminance level in street lighting, with the undesirable effects of increased energy consumption and light pollution (Gălățanu et al. 2018; Leccese and Tuoni 2003); to enhance the illuminance uniformity seems to allow a reduction of street light levels while maintaining good visual performance (Narendran, Freyssinier, and Zhu 2016). An energy efficient method of lighting design that matches the road lighting level to the actual traffic volume both of vehicles and pedestrians, was proposed in Leccese et al. (2020).

Few studies investigated the role of luminance in the visual tasks of pedestrians, but the relevance of luminance for pedestrians was evidenced in Bierings and Jansonius (2019), which defined the relationship between people's ability to see when walking at night and pavement luminance level: the large survey campaign of this study indicated that people reported complaints with the vision of the walking place mainly for luminance levels below 0.01 cd/m^2, while people with visual impairment for luminance below 0.04 cd/m^2.

Luminance is the amount of light perceived by the human eye coming from other elements in the environment. Excluding light sources, the luminance of objects depends on their reflectance, which is the ability of surfaces to reflect light: light colours reflect much more light than dark colours, since they have higher reflectance. An environment containing elements with high reflectance will appear more luminous and brighter than the same environment with elements having low reflectance, even if it is illuminated with the same light source and illuminance level. At night, more than during daytime, luminance of elements present in the outdoor environment can affect both their visibility and the appearance of the whole environment.

Considering the previous literature, scarce attention was paid to the relationship between street luminance and pedestrians' comfort, but luminance can have an important role for walkability at night and for the experience of urban landscape. The aim of this paper is to investigate whether street luminance affects walking comfort of pedestrians, and in particular the role played by the luminance of some elements contained in the urban environment, such as the pavement, the building wall, the face and the body of other people. The results of this study will give indications to improve the actual urban lighting design theory, which will promote pedestrians' comfort and a new urban landscape appearance.

Method

To evaluate the impact of street luminance on walking comfort, a survey was carried out in the centre of Rome. Forty people (20 females and 20 males) of 19–36 years old (mean 27,11 ± 4,83) walked along five roads in daytime and night-time and evaluated their walking comfort, visibility and lighting conditions filling a questionnaire. They declared to have a normal or corrected to normal vision.

The survey was carried out in Autumn (September – November): the daytime walks took place about at 12:00 a.m., while the night-time walks about at 20:00 pm. The walk took approximately 45 min.

Roads and lighting conditions

Five roads (A, B, C, D and E) having similar features were selected for the survey (Figure 1): they have a one-way lane with car parking on one side and two lateral sidewalks; according with EN EN 13201-2:2015 the streets are classified in the C3 lighting class. Table 1 summarizes the dimensions of the roads.

The roads are located in a residential neighbourhood in the centre of Rome with 5–6 floors buildings built at the end of the 19th Century; in general, the urban context presents low level of degradation. In addition to private houses, the other main buildings functions

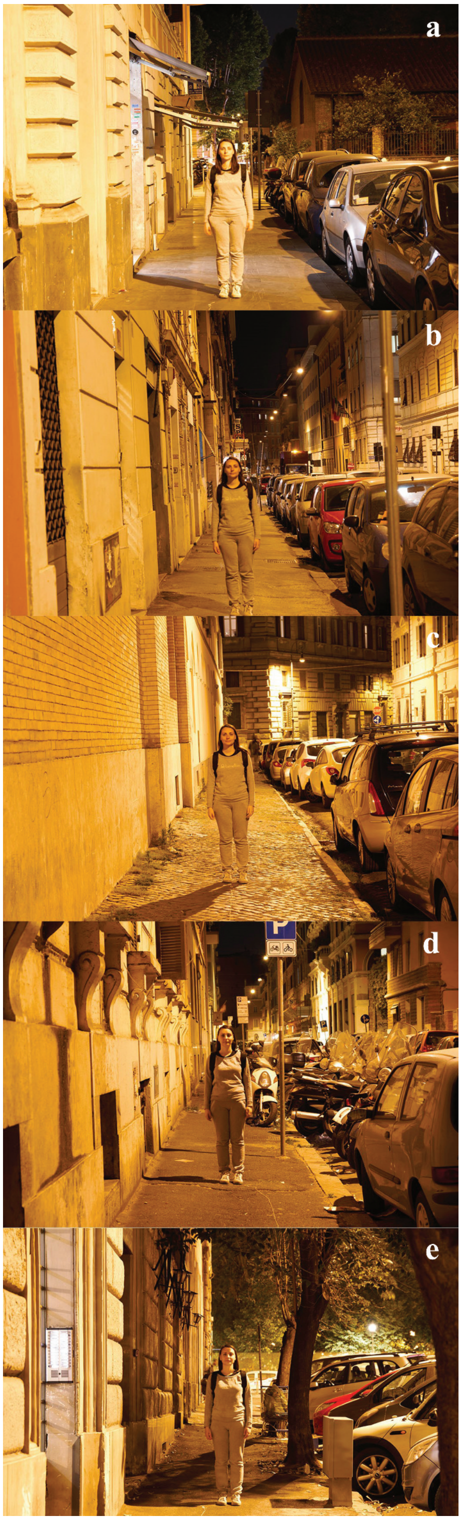

Figure 1. Pictures of the five streets.

Table 1. Characteristics of the five roads selected for the survey.

Road	Road length (m)	Road width (m)	Sidewalk width (m)
A	80	15.3	2.4
B	70	11.6	2
C	98	12	2.2
D	60	11.8	2.2
E	78	15	2.5

are offices, shops and restaurants; the neighbourhood is frequented by residents, workers and tourists.

The buildings walls are generally coated with external plasters, and many of the facades have the ashlar effect and/or plates of white marble at the base; few budlings have bricks on the wall. The pavements of the sidewalks are made of asphalt, porphyry cobbles or the traditional road paving of Rome called sanpietrini (see the picture C in Figure 1). One road (E) has a slight slope and small trees that shade the sidewalk, while the other roads are flat. Table 2 shows the average reflectance values of the sidewalk path and

Table 2. Reflectance values of the five roads 'materials.

Road	Element	Material	Reflectance (%)
A	Building 1	Plaster	11.7
		Marble	31.1
	Building 2	Plaster	34
		Plaster	20.3
	Building 3	Plaster	35.8
		Plaster	13
	Building 4	Plaster	33.7
		Marble	33.9
	Sidewalk	Porphyry cobbles	7.4
B	Building 1	Plaster	42.2
		Marble	42.4
	Building 2	Plaster	31.7
		Plaster	58.3
	Building 3	Marble	36.4
	Building 4	Plaster	39.3
		Plaster	41.3
	Sidewalk	Asphalt	6.2
C	Building 1	Brick	20.6
		Marble	46.2
	Building 2	Plaster	36.1
		Marble	35.7
	Sidewalk	Sanpietrini	8.8
D	Building 1	Plaster	13.4
		Brick	7.5
	Building 2	Plaster	13.7
		Marble	47.8
	Building 3	Plaster	25.7
		Plaster	19.8
	Building 4	Plaster	32.8
		Plaster	21.5
	Sidewalk	Asphalt	6.2
E	Building 1	Plaster	41.6
		Plaster	22.9
	Building 2	Plaster	23.2
		Marble	34
	Building 3	Plaster	11.2
		Marble	28.1
	Sidewalk	Asphalt	6.1

Table 3. Luminance values measured in the five roads.

Mean luminance (cd/m²)							
Road	Scene	Sidewalk	Wall	Side	Background	Centre	Face
A	0.9	0.9	1.7	0.4	0.8	0.6	1.4
B	1.6	0.6	2.4	1.2	1.4	1.2	1.7
C	1.8	1.4	2.6	1.2	1.3	1.7	1.6
D	1.2	0.9	1.5	1	1.1	0.9	1.3
E	0.6	0.5	0.9	0.4	0.4	0.4	0.8

Table 4. Illuminance values (lux) measured in the five roads.

Road	Average horizontal	Minimum horizontal	Uniformity	Cylindrical
A	18	6	0.3	10
B	27	21	0.8	7
C	30	7	0.2	10
D	33	10	0.3	10
E	11	3	0.3	5

of the buildings' walls placed to the side of the sidewalk walked during the survey. The reflectance measures were performed by means of the Spectrophotometer Konica Minolta CM-700d with the following measurement conditions: D65 illuminant, 10° observer eye, specular component included (SCI) and 3 mm aperture plate (SAV). Five reflectance measures were executed on each material of the lateral buildings and of the sidewalks.

The five roads were illuminated with High Pressure Sodium (HPS) lamps suspended at 10 m above the centre of the carriageway with a catenary. Luminance of the sidewalks was measured by means of a LMK video luminance metre: luminance images were taken every 10 m with the instrument placed at the centre of the sidewalk at 1,5 m above the ground. The instrument pointed in the same direction of the walking and focused on a person standing in the centre of the sidewalk at a distance of 3 m from the instrument. The luminance images were analysed, selecting the six areas of interest: Scene referred to the whole images, Sidewalk to the pavement, Wall to the lateral building wall, Side to the portion of the images with parked cars and road, Background to the space in the back of the person, Centre to the central part of the image containing the whole body of the person, and Face to the face of the person. Mean luminance (cd/m^2) levels of the selected areas for the five roads are shown in Table 3. Overall Luminance uniformity (Lmin/Lmed) was 0.1 in all the streets.

Also illuminance (E) levels were measured on the sidewalk according to the regulation EN 13201-4 (2015b) by means of the luxmeter Delata Ohm. Horizontal illuminances (Eh) were measured at ground level; vertical illuminances (Ev) were measured on the four vertical faces of a cube (300 × 300 × 300 mm) at 1.5 m above ground level. From these measurements the cylindrical illuminance (Ec) was calculated as the average illuminance on the four vertical faces. The illuminance values are shown in Table 4.

Procedure

Participants walked the five roads both in daytime and night-time following the same route, from road A to E. The researcher met the participant near the starting point and

Table 5. Questions presented in the questionnaire with relative answers.

	Question	Answers
Q1	Walking along this road was	very uncomfortable/very comfortable
Q2	To see clearly other people was	very easy/very difficult
Q3	To see far enough ahead was	very easy/very difficult
Q4*	The lighting along this road was	very dim/very high
Q5*	The lighting along this road was	Very uneven/very uniform

*Questions presented only at night.

explained the procedure, then drove her/him to the beginning of the road A. The participant walked alone the road and filled the questionnaire at its end; once completed this task the researcher reached the participant and drove her/him to the beginning of the successive road. The same procedure was repeated for all the roads.

The questionnaire presented one question about perception of environment (comfort) and two questions about visibility (of other people and far enough ahead); other two questions regarding the lighting conditions (light intensity and uniformity) was added to the questionnaire filled at night. Participants answered the question on an 11-points Likert scale ranging from 0 (very low evaluation) to 10 (very good evaluation). The English translation of the questions with the two extreme answers are reported in Table 5.

It is possible to expect that the luminance of the whole environment (Scene) affects the evaluations of all the 5 questions and that the perception of comfort is influenced by luminance of all the areas examined; the vision of other people should be mainly influenced by the luminance of their face and body, while the vision of the space far enough ahead by the luminance of the background; the perception of light intensity and uniformity should be affected by the luminance of the walls, of the sidewalk and of the lateral objects (Side).

Data analysis

The one-way independent measures ANOVA were performed separately on day and after dark ratings of each of the five questions, to examine whether differences exist in participants' evaluation of the five streets.

To analyse the participant's judgements, the answers to the questions Q1-Q3 were analysed with the day-night method, proposed by Boyce et al. (2000). This method focuses on the effect of lighting on participants' evaluations, minimizing the impact of other environmental variables: in fact, the main environmental difference between day and night is the lighting condition. According to this method the difference between daytime and night-time ratings has been calculated for each street: the result corresponds to how much the night-time condition differs from daytime, indicating the role of lighting in this evaluation. A previous work evidenced that the day-night participants' ratings showed higher levels of correlation with street lighting (illuminance) respect to the night-time ratings (Mattoni et al. 2017).

The questions Q4 and Q5, administered only at night as concerning the road lighting, were analysed calculating the mean rating of the answers for each road.

The correlation between answers given to different questions was calculated, since if two questions are highly correlated it is possible to suppose that they are addressing the same perception and only questions that are not strongly correlated should be analysed. For Q1, Q2 and Q3 the correlations were calculated on the mean value of the day-dark ratings, while for Q4 and Q5 the mean values of the after dark ratings were used: the correlations of answers to Q4 and Q5 with the answers to the other questions were not calculated due to lack of homogeneity between the two variables.

Then, for each question, the mean values of the evaluations of the 40 participants were plotted against mean luminance values of the streets, with the aim of assessing a correlation between the street lighting condition and participants' evaluation. In particular, ratings of question Q2 regarding the vision of other people, in addition to the mean luminance of Scene, were plotted against the mean luminance of Face and Centre and the mean luminance of Background: they are the areas referred to the body of the person standing on the sidewalk and the area where other people can walk respectively. Ratings of questions Q3 regarding vision of the space far enough ahead were plotted against mean luminance of Scene and also of Background, which correspond to the area in front of participants; ratings of the other questions were plotted against all mean luminance variables: Scene, Sidewalk, Wall, Side, Background, Centre and Face.

Results

The ANOVA analysis ($p < 0.05$) indicated that the daytime participants' evaluations of the five streets are significantly different for the questions Q1 ($p = 0.01$; F = 3.47), Q2 ($p = 0.03$; F = 2.77) and Q3 ($p = 0.01$; F = 3,27). A significant difference was found among the night-time participant's ratings of the five street for the questions Q1 ($p = 0.002$; F = 4.51), Q2 ($p = 0.0001$; F = 6.35), Q3 ($p = 0.001$; F = 4.75), Q4 ($p = 0.006$; F = 3.91) and Q5 ($p = 0.0007$; F = 5.27). As consequence of the statistical results, further analyses were performed on all the 5 questions.

Results of the correlations among answers given to different questions are reported in Table 6: it shows the variance of the relationship (R^2) between the mean values of answers given to two questions. Only the answers to Q4 and Q5 were highly correlated ($R^2 = 0.84$), but both the questions were further analysed, since the correlation level was not considered sufficiently high for establishing that they addressed the same perception.

Then, the mean luminance values related to the areas of interest of each of the five streets were plotted against the mean difference between daytime and night-time ratings of the 40 participants for Q1, Q2 and Q3, and against the night-time ratings' for Q4 and Q5. Differently from previous literature that showed exponential correlations (Mattoni et al. 2017), in this study the higher correlations values between participants' ratings and mean luminance levels were found for linear functions. For each question, the variance of the correlation (R^2) referred to the analysed areas of interest are shown in Table 7: the highest values of correlations ($R^2 > 0.75$) are evidenced in bold.

Table 6. Variance of the linear correlation (R^2) between participants' ratings to different questions.

Questions	Q1–Q2	Q1–Q3	Q2–Q3	Q4–Q5
R^2	0.45	0.36	0.62	0.84

Table 7. Variance of the linear correlation (R^2) between participants' ratings and mean luminance levels of analysed areas.

Variance of linear correlation (R^2)							
Question	Scene	Sidewalk	Wall	Side	Background	Centre	Face
Q1	**0.82**	**0.76**	**0.96**	0.54	0.62	**0.90**	0.63
Q2	0.36	–	–	–	0.65	0.17	0.61
Q3	0.37	–	–	–	0.55	–	–
Q4	0.56	0.05	**0.75**	0.40	0.72	0.38	**0.91**
Q5	0.44	0.16	0.65	0.10	0.36	0.25	**0.87**

Table 8. Variance of exponential correlation (R^2) between participants' ratings and mean illuminance levels (lux) of the sidewalk.

Variance of exponential correlation (R^2)	
Question	Mean illuminance
Q1	0.59
Q2	0.65
Q3	0.22
Q4	0.65
Q5	0.50

For completeness, the same participants ratings were plotted against the mean horizontal illuminance values measured at the sidewalk ground: according to the literature, the exponential correlations were considered (Table 8).

Comfort

Day-night ratings of answers to the question Q1 showed high correlations with mean luminance values of Scene, Sidewalk, Wall and Center. Moreover, lower correlations were found between participants' ratings and with mean luminance values of Side, Background and Face. These results indicate that, in general, the perceived comfort of participants increased with higher luminance values. In accordance with previous studies, a correlation was also found with the mean illuminance level at the ground, but its value is lower than those found with the luminance.

Figure 2 shows that increasing the luminance level, the day-night difference of subjective ratings of comfort decreases, meaning that for higher luminance levels the walking comfort at night approaches to the walking comfort during daytime.

Results indicated that increasing the mean luminance level of the whole setting improves the perceived comfort of the night walk; in particular, the comfort levels seem also to be associated with the luminance of the ground, of the lateral wall and of the body of other people walking on the sidewalk. Moreover, can be noticed that the perceived comfort of participants during the night-time walk is very similar to that perceived during daytime for mean luminance values corresponding to 1.8 cd/m^2 of the whole scene, 1.4 cd/m^2 of the pavement, 2.6 cd/m^2 of the lateral building wall and 1.7 cd/m^2 of the other people's bodies.

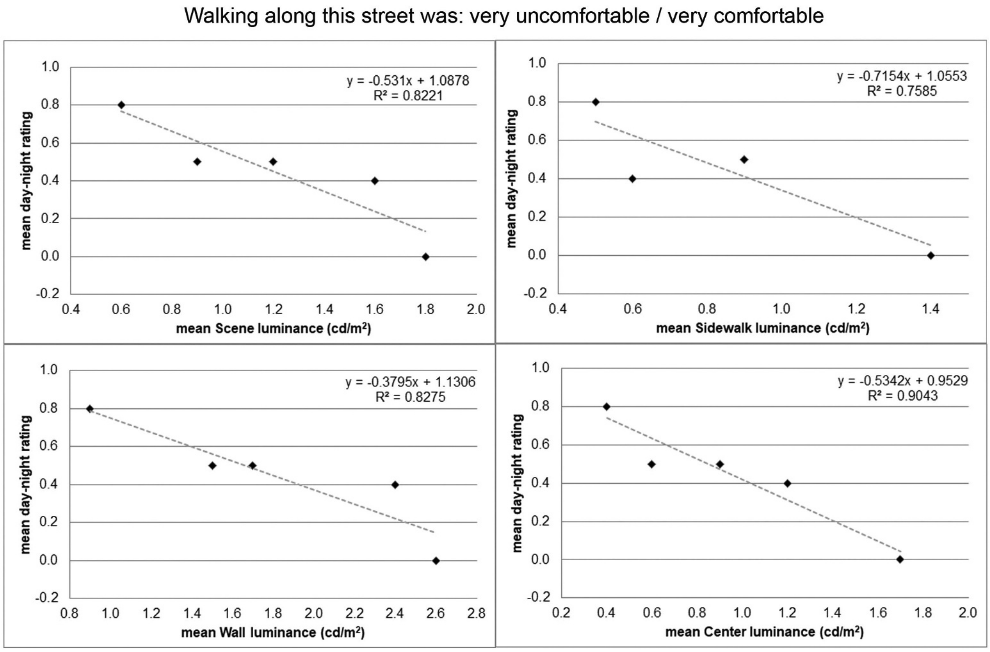

Figure 2. Question Q1: participants day-night ratings of the five streets respect to the mean luminance levels of Scene, Sidewalk, Wall and Center.

Vision of other people

Day-night ratings of answers to the question Q2 showed correlations with mean luminance values of Background and Face. A similar correlation value was found also with mean sidewalk illuminance.

Figure 3 shows that increasing the luminance level, the day-night difference of ratings of people visibility tends to decrease: this indicated that for higher luminance levels the perception of people at night tend to ameliorate, approaching to the visibility of daytime.

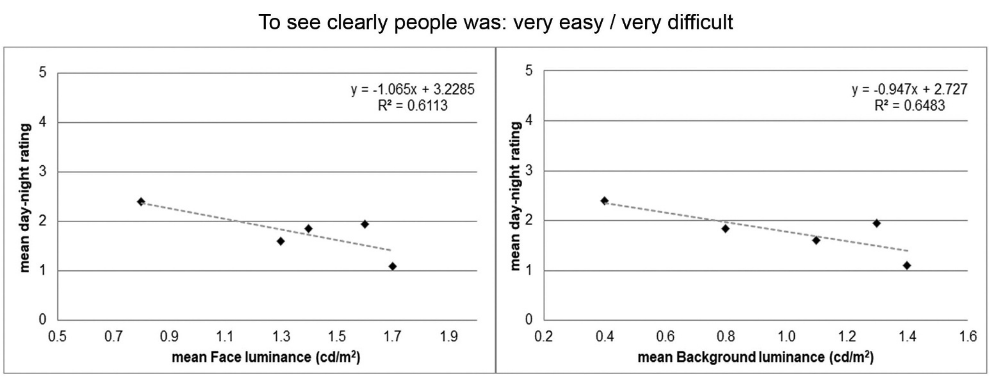

Figure 3. Question Q2: participants day-night ratings of the five streets respect to the mean luminance levels of Face and Background.

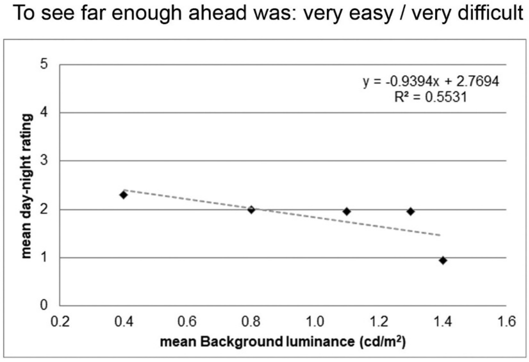

Figure 4. Question Q3: participants day-night ratings of the five streets respect to the mean luminance levels of Background.

Results of the survey indicate that with a luminance increase of 1 cd/m^2 on the other people's faces and in the background, the day-night difference of ratings halves and for the highest luminance levels the difference is about 1 point.

Vision of space far enough ahead

Day-night ratings of answers to the question Q3 has been investigated only respect to mean luminance values of Background and a correlation was found ($R^2 = 0.55$).

Figure 4 shows that increasing the luminance level of the background, the day-night difference of subjective ratings of visibility tends to decrease, indicating that for higher luminance levels the perception of background at night tend to ameliorate, approaching to the visibility of daytime.

Also in this case, results of the survey suggest that with an increase in mean luminance of 1 cd/m^2 on the background space, the day-night difference of ratings concerning the visibility of far enough ahead decreases more than half and for the highest luminance level the difference is about 1 point.

Lighting intensity

Nighttime ratings of answers to the question Q4 showed high correlations with mean luminance values of Wall and Face. Moreover, correlations were found between participants' ratings and mean luminance values of Scene and Background, and mean illuminance at the ground. These results indicate that, in general, where the surfaces were brighter participants perceived the lighting more intense. In fact, increasing the illuminance on a surface also its luminance level grows, and it is perceived more luminous.

Figure 5 shows that the night-time ratings of lighting intensity increase when the luminance level on the areas of Wall and Face increases.

Results shown in the two graphs indicated that the perception of the lighting intensity is mainly affected by the luminance of the lateral wall and of the other people's faces: in other words, the more the lateral wall and the faces are luminous, the more the lighting is perceived as intense. The influence is more marked for the people's faces: results

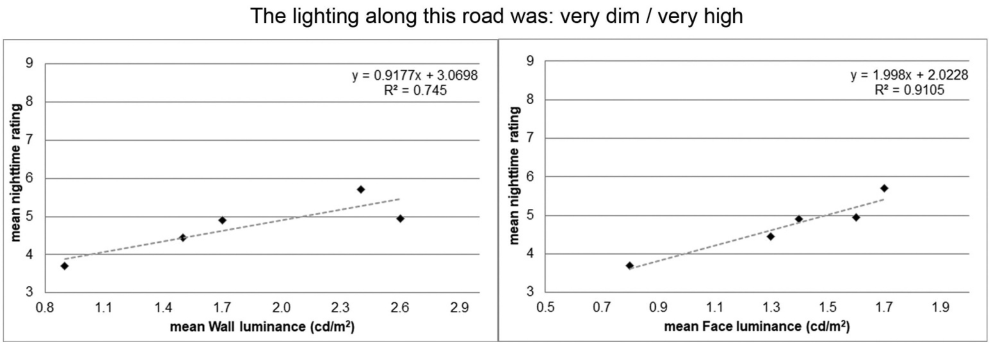

Figure 5. Question Q4: participants nighttime ratings of the five streets respect to the mean luminance levels of Wall and Face.

indicated that when the mean Face luminance increases of about 1 cd/m^2, the mean rating of perceived lighting intensity grows from 3.7 to 5.7. Considering that the evaluation scale ranges from 0 to 10, it can be said that the perception of lighting intensity changed from low intensity to medium intensity.

Light uniformity

Nighttime ratings of answers to the question Q5 showed high correlations with mean luminance values of Face. Moreover, a low correlation was found between participants' ratings and with mean luminance values of Wall and a very low correlation with mean illuminance at the ground. Differently as expected, no relevant correlation was found with areas in which the contrast of luminance is frequent in outdoor settings, such as the whole Scene, the Side area referred to the carriageway with parked cars or the Background, since they comprehend many different elements.

Figure 6 shows that the night-time ratings of lighting uniformity increase when the luminance level on the area of Face increases.

Results indicated that when the mean Face luminance increases of about 1 cd/m^2, the mean rating of perceived lighting uniformity grows from 3.7 to 6.0. In this case too,

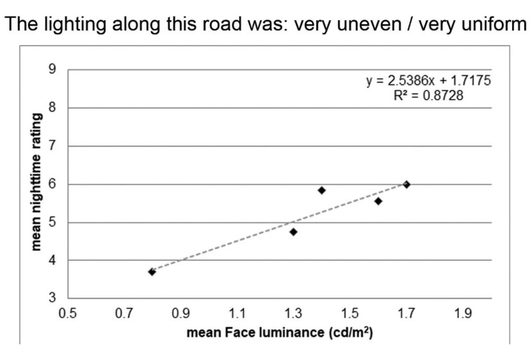

Figure 6. Question Q5: participants nighttime ratings of the five streets respect to the mean luminance levels of Face.

considering the 11-point evaluation scale, the participant's perception of lighting passed from low uniformity to medium uniformity.

Discussion

To support and increase the use of contemporary cities at night, one of the aims of the urban lighting design should be to improve walking comfort by enhancing the appearance of some environmental elements. This study focused on luminance, a lighting quantity not considered before in literature and with scarce consideration in the regulations regarding street lighting, but having a high impact on the appearance of the landscape and for this influencing the visual perception of the environment. Illuminance was also considered: the results, in accordance with previous studies, indicated that higher illuminance at the sidewalk increases walking comfort; anyway, in this study the effect of illuminance had less relevant results than the results produced by illuminance, since lower levels of correlation (R^2) were found with illuminance respect to luminance. On the other hand, in questions regarding the visual perception it is possible to expect to find a closer relationship with luminance than with illuminance since luminance is the metric expressing what the eye sees.

Street lighting regulations are based on the horizontal illuminance of the streets since they are finalized to drivers, cyclists, and pedestrians' safety, so they prescribe the minimum light level requested to avoid accidents but give scarce relevance to walking comfort. Luminance is related to human perception, as it indicates the effect that light produces on the eye, and for this, it is the lighting quantity that better expresses the issues of comfort: as consequence, this study investigated the effect of luminance more than illuminance.

This survey indicated that luminance could influence pedestrians' walking comfort around the city at night. For higher luminance levels walking comfort at night was evaluated similarly to daytime: in fact, the results showed that increasing the luminance level, the night-time participants' ratings of walking comfort increased, approaching the daytime ratings. These results are valid considering the mean luminance of the setting (Scene), as well as the mean luminance of the lateral building wall, of the body of other people and of the sidewalk, and, to a lesser extent, by the mean luminance of other people's faces, of background and of the street with parked cars. As expected, the comfort of participants was affected by the luminance of all the areas analysed since, in general, increasing the luminance of the environment and of the objects, the pedestrians' perception of walking comfort at night seems to ameliorate.

The obtained results indicated that the luminance level also affects the perception of street lighting intensity and uniformity and, to a lesser extent, the visibility of other people and of the background. The perception of street lighting intensity appeared to be correlated with the mean luminance of the lateral wall and with mean facial luminance, while the perception of street lighting uniformity was mainly correlated with the mean luminance of people's faces. Differently from what was expected, the perceptions of light intensity and uniformity were not influenced by the luminance of the sidewalk and of lateral environment (Side). Grater perceived light intensity and uniformity are desirable as they are related to a comfortable vision and are useful to realize a more sustainable street lighting design, since a previous study (Narendran, Freyssinier, and Zhu 2016) demonstrated that they allow to achieve good visual performances with lower illuminance levels, and then with lower energy use.

As expected, the visibility of the space far enough ahead is correlated with the mean luminance of the background, while the clear visibility of other people is correlated with the mean luminance of the background and with the mean facial luminance, but not with the mean luminance of other people's bodies. The mean luminance of other people's bodies did not affect the visibility of other people: this is in accordance with a previous study indicating that the gaze of pedestrians is directed mainly to the face of other people and less to their body (Fotios and Johansson 2019).

Results indicated that the luminance level of two areas are particularly relevant for walking at night: the lateral building wall and the face of other people. In fact, the mean luminance level of these areas is correlated with the mean participants' rating of all the questions investigated; moreover, the highest correlation levels (R^2) were found for Wall (0.96) and Face (0.91).

In this study, a linear correlation was found between participants' mean ratings and mean luminance levels. This is not in contrast with previous works where exponential correlations were found (Mattoni et al. 2017) since the lighting metric investigated was not the same: here luminance was used as variable instead of illuminance. The linear correlation implies that the best luminance level can be found where the trend line reaches the value zero of the day-night difference ratings, or where it reaches the central value between the two extreme points of the night-time ratings (in this case 6 is the central value between 0 and 10). Anyway, the results of this study do not pretend to indicate optimal levels of street luminance, but they highlight the relevance of the luminance parameter for pedestrians' walkability at night.

Previous works on pedestrians' perception of outdoor environments at night focused on illuminance (Boyce et al. 2000; Mattoni et al. 2017; Pedersen and Johansson 2018; Peña-García, Hurtado, and Aguilar-Luzón 2015; Portnov et al. 2020; Svechkina, Trop, and Portnov 2020; Uttley, Fotios, and Cheal 2017), the lighting quantity indicating the amount of light on a surface: results of these studies indicated that increasing the street illuminance levels (within a certain range) the pedestrians' evaluations get better. Similar results were also obtained in this study, but the correlations (R^2) found with illuminance were generally lower than those found with luminance. The disadvantage of using illuminance as a reference metric is that a higher lighting amount should be provided to improve the walkability at night. The consequence can be a rise in energy consumption for street lighting, provided refurbishing the actual street lighting installations (Beccali et al. 2018) with light sources having higher power, and an increase in municipality costs (Cellucci et al. 2015). In addition, an increase in illuminance level can produce light pollution, a harmful phenomenon for plants and animals, including human beings (Hölker et al. 2010; Owens et al. 2020).

This study indicated that luminance should be taken into account for the lighting design of pedestrian streets to ameliorate walking comfort at night. Moreover, the design of the street lighting should be strictly related to the design of the street environment. Acting on materials and colours of the surfaces, the luminance level of the environment increases without increasing the lamps' power. Using high-reflecting and light-coloured materials in the urban contest, the overall brightness of the environment increases: this could improve the perception of the outdoor environment and enhance pedestrians' comfort, without increasing the luminous emissions of street lighting. This solution implies that urban lighting energy consumptions and costs do not rise to produce higher comfort for pedestrians.

Anyway, the urban designer should carefully consider the street light design to avoid unwanted consequences. Street materials must be carefully selected since high reflective materials, in particular glossy materials, can produce glare, not only during the night but also under sunlight; this can impair pedestrians' vision and produce discomfort. Also, it is important to guarantee the luminance contrast that allows people to correctly perceive the path, the lateral front, the background, and objects on the pavement; otherwise, pedestrians could encounter orientation problems and accidentally fall.

Conclusion

Results of this study indicated that luminance is a relevant metric for walking at night, influencing in particular pedestrians' comfort, but also affecting visibility of other people and background, as well as perceived lighting intensity and uniformity. From this study emerged that walkability comfort is influenced by the luminance of the whole environment, since increasing the luminance levels of the whole scene, as well as of defined areas, night-time participants' ratings approach to daytime evaluations of comfort. Since the most relevant areas for walkability at night resulted in the lateral building wall and people' s face, it is particularly important to consider the luminance of vertical surfaces.

The results obtained in this study highlight that to improve pedestrians' walking comfort at night it is necessary to consider the luminance. From an energy point of view, the benefits to people's walking comfort can be obtained without increasing the luminous flux and the energy emitted by the lamps, but only by acting on street materials. Using light and high reflective materials imports an overall change in the city landscape: the whole street environment will be brighter, the night-time appearance of the landscape will be more similar to daytime and all its elements will be better perceived. When planning the urban lighting, the designer should adopt the luminance to address the pedestrians' needs influencing walking comfort, such as easy orientation, vision of other people, visibility of the urban elements and detection of obstacles at the ground. Moreover, the design of the street lighting should be deeply integrated with the design of the urban landscape, in order to define the materials used in the streets, their colours and finishing, and to control the effect produced by the street design at a visual level.

This study presents some limitations that can be solved in future research. It considered only five roads with mean luminance levels of the whole scene ranging between 0.6 and 1.8 cd/m^2, and they do not cover the wide range of luminances that could to be found in locations different from the centre of Rome: for this reason this work can be considered a pilot study and many other roads having a wider range of luminance levels should be investigated to define a more precise trend line. The study could be limited by the fact that participants walked the streets in the same direction and in the same order, so different routes should be investigated. The number of participants is adequate for this survey, but a larger number of people is required in order to define adequate luminance levels in outdoor environments for the night-time period. Moreover, the results of this study are limited to street lighting in the city centre, but other settings such as green urban areas, residential neighbourhoods, suburbs, and extra-urban zones are still to be investigated. In fact, results can differ according to the setting.

The results of this study indicated that the luminance impacts both on people's walking comfort and on the perception of the environment, and for this reason it should be considered in the design of the street lighting to improve the night-time experience of pedestrians within the city.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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