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Footpath Lighting: Optical, Visual, and Perceptual Characteristics of the Social Light Field

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ABSTRACT
We studied how the characteristics of the light field, under varying real lighting conditions on footpaths at night, affect the appearance of a head-shaped light probe. A combination of physical light field measurements, image analysis, and a formal perception experiment using photographs was applied to understand how lighting characteristics affect the appearance of the face and environment. This empirical study was done in four different light configurations and for snowy and non-snowy conditions. We found that the resulting local light diffuseness, light vector, and vertical illumination correlated with the perception of friendliness, how well the faces were judged to be lit, and how comfortable the environment was rated. These local light qualities vary throughout the measured field, spatially and directionally, and showed a major effect of the presence of snow. This implies that managing and optimizing the actual light field characteristics or the spatially and directionally varying quality of the light in the three-dimensional space above the footpath is needed to fully capture its affordances such as walkability and its experiential values such as comfort in low light conditions. Extending architect Jan Gehl's idea of the "Social field of vision", to incorporate optical, visual, and perceptual aspects of human-centered lighting design, we propose the "The Social Light Field".

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1. Introduction

Artificial light at night has many benefits and has fundamentally changed how we spend our time outdoors. It prolongs the day, promotes increased activity after sunset, provides safety for pedestrians, reduces the fear of crime, beautifies the surroundings, and even enhances economic growth (Boyce 2019). In the current lighting practice, the overall quantity of light plays a pivotal role. Still, it is widely acknowledged that street lighting should not only be considered in terms of the presence or amount of light but also its quality. Further, the lighting designer has a responsibility to mitigate light pollution as it affects the natural dark sky (Bará et al. 2021; Kyba et al. 2017), and animals, by disrupting the natural signals conveyed by natural light (Gaston et al. 2015; Sanders et al. 2020). Lit footpaths are an essential feature of the general quality of neighborhoods, facilitating obstacle detection and visual orientation and enabling interpersonal judgment (Johansson et al. 2014).

According to Forsyth (2015), the more walkable the environment is, the more lively and sociable it is. Lighting is deemed important for establishing a sense of social security on footpaths, and various studies have looked at the role of lighting in facial expression recognition and reassurance (Fotios and Raynham 2011; Fotios and Yang 2013; Fotios et al. 2015; Yang and Fotios 2015; Fotios and Johansson 2019). Fotios and Johansson (2019) have also concluded that to support the exploration of changes in spatial distribution, further study is needed with three-dimensional targets – which is what the current study aims to address. We study the appearance of three-dimensional targets, face shapes, in real exterior spaces, relating the optical and perceptual effects to metrics for the light field in the empty space (Pont 2019; Xia et al. 2017a) in several ecologically valid lighting conditions. The need for visibility of the face is highly connected to a well-managed light distribution

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(Zaikina et al. 2015). For instance, the directional and spatial properties of different portrait lightings were found to significantly influence the perceived appearance of computer-rendered faces, where face lighting from under and with high contrast was rated more negatively on appeal, eeriness, and trustworthiness (Wisessing and McDonnell 2024), see also https://www.youtube.com/watch?v=6sgpeoWpO9w for an impressive artistic demonstration. Possibly for this reason, Bille and Sørensen (2007) stated that light is a powerful social agent in cities, as different aspects of light affect the experiences of the surroundings when people move around.

Gehl J. emphasized the importance of sensory-based design in city planning (Gehl 2010). Since much of our sensory stimulation happens through sight, lighting is crucial when observing forthcoming pedestrians. Gehl introduced the term "The social field of vision," related to social distances in city planning under daylight (Gehl 2010). In case of artificial lighting, the distance to other pedestrians is also important for interpersonal judgment and social security on footpaths (Caminada and van Bommel 1984; Fotios et al. 2015). In daylight conditions, facial expressions can be discerned at 25 m (Gehl 2010). At night, Fotios et al. (2015) suggest 15 m as an appropriate distance for interpersonal judgment in lit outdoor environments. Caminada and van Bommel (1984) found that semi-cylindrical lighting at face height, at 1 lux, is optimal for ensuring facial recognition at a 4-m distance (Fotios and Raynham 2011; van Bommel 2015). According to van Bommel (2015), face recognition is essential for assessing fellow pedestrians, while Fotios and Raynham (2011) propose that recognizing facial expressions serves as a means to assess other people's intent. The face is the most important visual cue for assessing the intent of fellow pedestrians as it provides cues to identity, emotion, age, and gender (Fotios and Johansson 2019). Consequently, in cases requiring facial recognition, additional criteria beyond the conventional horizontal illuminance need to be incorporated in light planning. Today, this involves vertical illumination and semi-cylindrical illuminance, as per the P-class guidelines outlined in the Norwegian standard NS EN13201–2:2015 (Standard Norge 2015a), based on the European standard.

Considering light quality, it is crucial to manage the light distribution when designing the lighting, as it directly influences visual aesthetics through its effects on appearance such as modeling. By light modeling, we refer to the way three-dimensional objects appear to observers, where contour, shape, and details are clearly visible (Zaikina et al. 2015), contrast/diffuseness over objects and people in the visual field, influencing how they are delineated, and providing depth cues affecting the perception of the three-dimensional space. This, as Cuttle (2010) discusses, represents a shift from a framework centered on sufficient surface illumination to a consideration of three-dimensional light and space perception. Pont (2019) describes a practical framework to describe, capture, visualize, and compose light spatially, in other words, the light field, connecting its optical, perceptual, and design properties. The light field was coined by Gershun (1939) and describes luminance as a function of position and direction. The light field framework was further developed into the Delft light framework (Pont 2019) and provides a scientific basis for lighting design principles. The light field framework was operationalized as the light (variations) in the three-dimensional space and its key characteristics as related to appearance, e.g. the light density, direction, diffuseness, spectral power distribution, and texture plus how those vary over space and time (Mury et al. 2008, 2009; Xia et al. 2017a, 2017b; Yu et al. 2023). These characteristics determine how a scene and the objects in it appear, e.g. the contrast, color, and modeling effects of light on objects, faces, and spaces, and affect the appearance of materials, surface structures, and spatial layouts (Kartashova 2018; Michel 1996; Xia et al. 2017b; Yot 2019; Zaikina et al. 2015; Zhang et al. 2019).

On a footpath, the distribution of light on a face varies according to the pedestrian's position to the light source (Fotios and Johansson 2019). The light distribution from the primary light sources is what lighting designers normally define. However, the reflected, scattered, and refracted light from the environment, including people and objects in it, also called the secondary and higher-order light sources, concerns the light we mostly observe (Pont 2019). The light field or actual light in a scene is composed of the light coming directly from light sources plus the indirect contributions from light reflected and scattered in the environment. This resulting light defines the appearance of oncoming pedestrians and the environment on the footpath. Snow-covered paths are good examples of how the reflectance of the road and surroundings can alter the light field if compared to the light coming solely from primary sources. To our knowledge, the effects of snow on the actual light on footpaths have hardly been studied, with some exceptions like a study looking at the energy-saving potential for snowy conditions (Juntunen et al. 2015) and a study where snow was found to affect only the perception of hedonic tone (Kuhn et al. 2013). The modeling characteristics of the lighting vary as a function of direction, diffuseness, and scattering from the environment (Xia et al. 2017b), e.g. by snow, which can contribute greatly to the light diffuseness. The normalized diffuseness describes the distribution of light around a point in space, ranging from fully collimated/directed light (with diffuseness 0) to completely diffuse (with diffuseness 1) light (Xia et al. 2017a, 2017b).

We aim to test if light field measurements can be used to assess the spatial and form-giving qualities of light that are relevant for face and scene lighting perception, relating to the social aspects of footpath lighting. Namely, how the direction, diffuseness, and intensity of the light on a walkway affect the appearance of the scene and the faces of oncoming pedestrians. The focus is on how the properties of the lighting influence the actual light distribution and the qualitative appearance of environments and a 3D-probe featuring a neutral face. Facial recognition is not included in this study. The scientific gap we address is the actual light evaluation in the space above the footpath, where an important visual task of assessing approaching persons takes place. We studied the lighting qualities 1.5 m above ground level, analyzing horizontal and vertical illuminances, flux density, and cubic light measurements. Simultaneously, we captured the appearance of a neutral face-shaped light probe via photography. In a lab setting, we assessed whether the perceived expression of the face appearance varied systematically with the spatial light distribution.

2. Materials and methods

2.1. Study design

In the current study, to ensure ecological validity when assessing face and environment, four footpaths were selected for light measurements and photography of face-shaped light probes (styrofoam heads; we use both terms "probe" and "head" henceforth) on the footpath. The faces were chosen to have a neutral face-form for evaluating the light distribution. A systematic set of photographs of the light probes was captured at footpaths with four different types of lighting installations, under snowy and non-snowy conditions. This resulted in eight configurations in total, see Fig. 1 and Table 1. The images were photometrically calibrated and used in a quantitative rating experiment in a lab, with 26 respondents. For each image, the corresponding cubic light fields were captured, providing the density, light vector, and diffuseness metrics at each position, as well as horizontal-, vertical-, and mean illuminance values. The cubic approach concerns a first-order approach in which the mathematical, physical, perceptual, and designerly approaches align, offering a coherent framework (Pont 2019). Cuttle (2003, 2014) defined simple ways to calculate its basic components, which, together with Xia's et al. (2017a) diffuseness metric gives a full description of this framework. Basic visual image measures (e.g., contrast and luminosity) were derived from the photographs. The data from the subjective rating experiment, objective optical light field measurements, and image analysis were examined separately and in combination to test whether there were systematic relationships between perceived affective judgments and lighting and disentangle the effects of light characteristics on appearance.

2.2. Objective measurements

All data were collected at night, at footpaths in Oslo, Norway, at latitude 59.91°, in March for snowy conditions and in April and September for non-snowy conditions. The ecological conditions at this latitude are subject to seasonal and weather conditions like foliage on trees, cloud cover, snow, and large variations of the diurnal cycle over

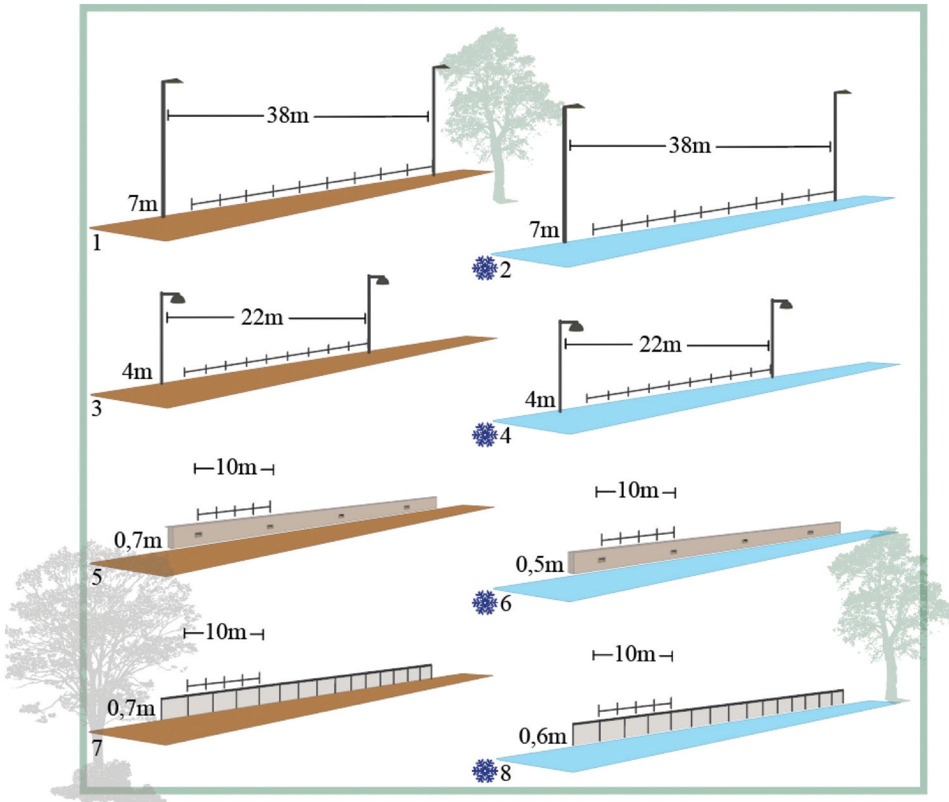

Fig. 1. The four different light configurations and two conditions (no snow left, snow right).

Table 1. Table of configurations for images and measurements.

Nr.	Configuration	Condition	Nr. of positions
1	Height: 7m (pole)/Distance: 38m	No snow	10
2	Height: 7m (pole)/Distance: 38m	Snow	10
3	Height: 4m (pole)/Distance: 22m	No snow	10
4	Height: 4m (pole)/Distance: 22m	Snow	10
5	Height: 0,7m (linear luminaire)/ Distance: 10m	No snow	5
6	Height: 0,7m (linear luminaire)/ Distance: 10m	Snow	5
7	Height: 0,7m (integrated luminaire)/ Distance: 10m	No snow	5
8	Height: 0,7m (integrated luminaire)/ Distance: 10m	Snow	5
Total amount of images/measurements			60

the year. It is important to note that between April 22 and August 21. The lighting conditions were unsuitable for this experiment, as the sun altitude in Oslo at night is less than 18° below the horizon ("astronomical night") and might interfere with measurements. A selection criterion for the sites was the absence of stray light from sources other than those on the path. Images and measurements were captured at moments with minimal cloud coverage and close to new moon, to ensure comparable lighting conditions.

To capture the light field, the cubic light meter (measuring in six directions) and head were positioned 1.5 m above the pavement, on the footpath, lit by the existing street lighting. The height was based on the standard NS EN13201–3:2015 for calculating semi-cylindrical illumination on footpaths (Standard Norge 2015b). The camera lens and light probe were set 2 m apart (see Fig. 2). The light probe was systematically positioned at five or ten locations, with the latter chosen for conditions featuring greater than 20 m distances. The locations were determined to stretch the distance between two luminaires in equal steps, to ensure comprehensive coverage of the changing light field. From these measurements, the metrics were derived according to the methods defined by Xia et al. (2017a).

To study different light settings, four lighting configurations were selected, with varying luminaire types, mounting height, and distance, and they were photographed under both snowy and non-snowy conditions (see Fig. 1 and Table 1).

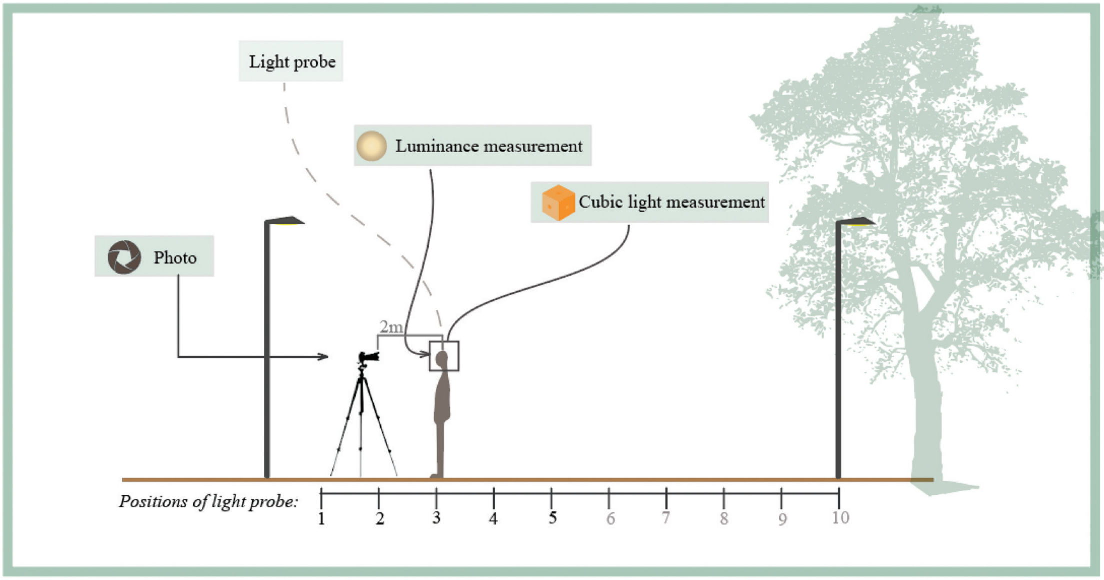

Fig. 2. The procedure of image/light measurement. A) photograph of the face-shaped light probe, distance 2m. B) luminance measurement at a vertically oriented middle grey surface in front of the probe. C) cubic light measurement, at the position of the light probe.

In configurations 3 and 4 (4-m light pole) the "non-snowy condition" was measured at another site than the "snowy condition" due to the unfortunate incidence of luminaires not working at the time of the second measurement. The conditions of 3 and 4 were, however, the same (luminaire type, pole height, distance, environment). Together 60 images of the light probe were captured in the different configurations and light probe positions (see Table 1).

2.2.1. Photometry

Lighting and photo capturing protocol at the site, which remained consistent across all light configurations and positions and resulted in 60 measurements/images:

- Photo of the light probe (h:1.5 m), 2 m distance between face and lens.
- Replace the probe with gray card. Luminance measurement at the gray card, (h:1.5 m), captured with the Hagner luminance meter, positioned 2 m in front of the gray card (same as camera lens).
- Replace the gray card with a cubic gauge. Cubic illuminance measurement at the position of the probe. Captured with the light spectrometer Spectis 1.0 Touch + Flicker, from GL Optics, with a Salli diffuser to allow measurements on low light levels. Oriented sequentially to all six directions of a gauge cube.

2.2.2. Photography

In each position the photos were captured with a Canon EOS 5D Mark IV, 2 m in front of the light probe, with the following camera settings: i) exposure mode: Aperture priority; ii) shutter speed: Automatic (Av Aperture priority); iii) aperture size: F8; iv) ISO: 100.

The RAW images were captured with 19 steps in exposure compensation each. It was planned to combine the images into one HDR image, but microscopic movements due to wind at the site rendered the image quality in the composed HDR-image too poor to use. However, based on analysis of the luminance distributions and contrast of single raw images, it was found that the image quality was sufficient for study purposes (that is, no severe under- or overexposure). The middle-value images from the 19 HDR-images were selected for all sets, allowing data comparisons between sets. A color chart was photographed prior to capturing the head photos, and the luminance on each patch was measured for further photometric calibration of the photographed images. Thereafter, the image was imported to Photoshop, and the luminosity of each patch on the color chart was checked. Luminance in the actual environment was plotted against luminosity on the screen, and these results were checked for linearity. The linearity was adequate, so images captured at the sites could be used without further linearizing. The lab screen on which the images were shown was calibrated with the Datacolor SpyderX Pro. To ensure a linear presentation of the images on the screen, the color chart was again used to measure the linearity of the luminance of the screen image and the actual color chart. The results confirmed correct linear presentation.

To prepare the images for presentation on a screen, the RAW images were adjusted with the program DCRAW, which adjusts settings as specified hereafter and saves the file in TIFF format. In DCRAW, the white balance was set to match the camera settings, the function for "clipping" was used to prevent re-adjustment of the dynamic range, and the color profile was set to sRGB with gamma 2.2 to match the sRGB color profile of the screen. Images were originally saved as 16-bit, and for the screen experiment transformed to 8-bit. The image size was originally 6744×4502, 300 dpi, but adjusted to 140 dpi to match the resolution of the screen and resized to 2360×1576 to show the face in the same size (visual angle) as in the real scene, that is, the styrofoam probe of 30 cm at a viewing distance of 200 cm, giving an imaged face of 6 cm on a screen at a viewing distance of 40 cm. The original images of the light probe mounted on a stick appeared quite eerie and made the distance and size of the head look ambiguous. To solve this, a simple black mask with the form of a neutral body matching the head size was superposed on the images (Fig. 3), using Photoshop, while other image parameters remained unchanged.

2.3. Subjective measurements

2.3.1. Questions in the rating experiment

In the rating experiment, 60 photos of the light probe were tested and shown on an LCD-screen in a lab. The participants were asked four questions about the appearance of the light probe and the environment. The questions were explained briefly to ensure a congruent understanding of the tasks. The first two questions (Q1 and Q2) focused on assessing the appearance of the face-shaped probe: *Q1.) The face is well-lit*. The term "well-lit" in our context is not strictly associated with light intensity but rather with the aspects of visual appearance and light modeling. Its application resonates with Blöbaum and Hunecke (2005), where the term was employed in a contextual

Fig. 3. Example images showing the difference in face illumination in configurations 1, 7, 3 with the corresponding image for the non-snowy condition in configurations 2, 4 and 8 in the bottom row.

inquiry regarding location, and the term is also used in our Q3. It is used to describe the quality of the illumination and creates a coherence between questions 1 and 3. *Q2.) The face looks friendly*. Fotios and Raynham (2011) introduced a method for identifying emotion, where they propose friendly and non-friendly as categorization criteria. To understand how the perception and approachability of a face were considered in the specific light setting, the term friendly was included as a rating criterion. The latter questions (Q3 and Q4) allowed assessment of the environment and its influence on facial appearance: *Q3.) The environment is well-lit*. The question was adopted from Blöbaum and Hunecke (2005), as described above. Question *Q4) I would feel comfortable in this lit environment*. The term comfort was taken from Johansson et al. (2014), stating that public lighting should facilitate comfort (as well as obstacle detection and inter-personal judgment). The four questions were rated on a 7-point Likert scale, and participants were instructed to indicate their very first impressions of the image observed on the screen.

2.3.2. Participants

The research protocol was reviewed and assessed by the Norwegian Centre for Research Data. The participants (both University students and employees) were invited via e-mail lists. In total 29 participants, in the age between 20 and 70, with self-reported normal, or corrected to normal vision. The experimental setup was described to the participants, who were informed about their right to withdraw their consent without any explanation within 1 month after the trial and that all data would be published anonymized. Finally, they were asked to sign a consent form.

2.3.3. Rating experiment in lab

The experiment was performed in a dark room, where the computer screen was the only source of light. The measured vertical illuminance at the participants' face level was 8.2 lux and participants were adapted for dark conditions for 20-min prior to starting the evaluation. First, 10 sample images were shown, to establish an internal framework of the images used. Test trials were done with five images, to let the respondent get familiar with the questions. Finally, the experiment was performed where 60 images were presented in a random order (Figure S3). Four questions, to be rated on a 7-point Likert scale (1 - "strongly disagree," 4 - "neutral" and 7 - "strongly agree"), see Figure S1.

2.4. Control experiment

A control experiment was done to verify the results from the main experiment. In the main experiment, images with the middle value of shutter speed for the 19 HDR-images were used. In the control experiment, we tested if using the same shutter speed made any difference. Sixteen images (snowy and non-snowy) were selected, for their minimum and maximum ratings in Q1–4 in the main experiment and maximum difference in shutter speed between snowy and non-snowy conditions. These were evaluated by a new group of participants (14 individuals), and the same procedure, as well as questionnaires, as in the main experiment was applied.

3. Analysis

The cubic light measurements were analyzed in the Mathematica program to determine for each position and condition: light density E_{scalar}, light diffuseness D, mean illuminance, light vector (E_x, E_y, E_z) and its magnitude |E|, vertical illumination (E_{x+}), and horizontal illumination (E_{z+}) (see, for relationships with other frameworks and metrics and also for robustness tests (Kartashova 2018; Xia et al. 2017a, 2017b; Yu et al. 2023)):

$$E_{(x)} = E_{x+} - E_{x-} \tag{1}$$

$$|E| = \sqrt{E_{(x)}^2 + E_{(y)}^2 + E_{(z)}^2} \tag{2}$$

$$\sim E_X = \frac{E_{x+} + E_{x-} - |E_{(x)}|}{2} \tag{3}$$

$$\sim E = \frac{\sim E_X + \sim E_Y + \sim E_Z}{3} \tag{4}$$

$$E_{scalar} = \frac{|E|}{4} + \sim E \tag{5}$$

$$D = 1 - \frac{|E|}{4E_{scalar}} \quad (6)$$

- E_{x+} and E_{x-} = illuminance measured on the opposite sides of the cube
- $E_{(x)}$, $E_{(y)}$, $E_{(z)}$ = light vector components (defining the average light direction)
- $|E|$ = Light vector magnitude
- $\sim E$ = Symmetric illuminance
- E_{scalar} = mean illuminance in a point (light density)
- D = diffuseness

For the image analysis, the luminosity histogram in Photoshop was used to derive the brightness of the image. For each image, the mean, median, and standard deviation of the luminosity were determined. The values were recorded for the whole image and an oval selection of just the face.

Additional objective data included in the analysis were the following: pole height, distance to the first pole, lighting configuration, and conditions type. The subjective perceptual data from the rating experiment on the screen included mean, standard deviation, and standard error values of the subjective responses to Q1–Q4 per image.

Two types of statistical analysis were done after initial descriptive statistics. Firstly, the dependent variables from the rating experiment (subjective perceptual data) were correlated with objective measurements, analyzing if the variations in actual light qualities could explain the perceived qualities. Pearson correlations were used for analyzing the responses to the Q1–4 and for diffuseness. In contrast, Spearman correlations were used for testing relations between the subjective responses to the same questions and light density, light vector magnitude, mean illumination, frontal illumination, and luminosity because of their wide-ranging values. Subsequently, t-tests were conducted to verify statistically significant differences between subjective responses and anterior/posterior light vector, snowy and non-snowy conditions, and corresponding diffuseness parameters.

4. Results

The rating overview for all images can be seen in Figure S1 (Supplementary Figure S1). It shows a strong variation in the responses for face appearance (Q1, *The face is well-lit* and Q2, *The face looks friendly*), and less variation between the two questions concerning the environment (Q3, *The environment is well-lit* and Q4, *I would feel comfortable in this lit environment*), indicating that the variation in light distribution on the face along the path affects how friendly and well-lit it appears. The responses to Q3 and Q4 are generally higher rated than those for Q1 and Q2 (Fig. S2).

Based on Pearson correlation results, Q1 and Q2 were found to be strongly positively correlated ($r(58) = 0.95$, $p < .001$), as well as responses to Q3 and Q4 ($r(58) = 0.94$, $p < .001$) (Fig. 4). This demonstrates strong connections within the two pairs of questions (Q1/Q2 and Q3/Q4). The same

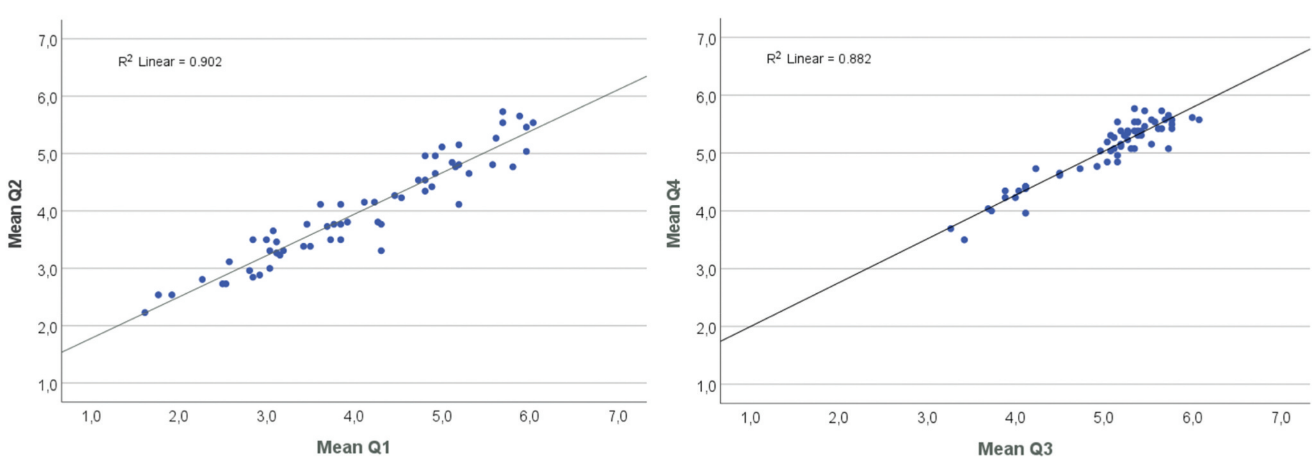

Fig. 4. Scatterplots of the pairs of questions, Q1 and Q2 related to face, and Q3 and Q4 related to the environment.

correlation analysis between Q1 and Q3, and between Q2 and Q3, did not demonstrate statistical significance, but did between Q1 and Q4 ($r(58) = 0.33$, $p = .010$) and Q2 and Q4 ($r(58) = 0.37$, $p = .003$). This indicates that participants judged the subjective feeling of comfort (Q4) at the footpath as better when faces were rated as well-lit and friendly, than when surroundings were well-lit (Q3).

An independent samples t-test relating the responses to Q1 with the light vector from the front (anterior) and back (posterior) of the face revealed that the anterior lighting received significantly higher ratings than the posterior lighting ($t(58) = 6.381$, $p < .001$). The Q2-ratings gave a similar result ($t(58) = 5.957$, $p < .001$). This suggests that lighting directed toward the front of the face is perceived more positively than lighting directed toward the back. No significant relation was found to Q3 and 4.

Spearman correlation analysis of vertical illuminance at the face and responses to Q1 also revealed a positive correlation ($r(58) = 0.65$, $p < .001$), as expected, since the vertical illumination on the face is related to its anterior lighting. Similarly, an analysis comparing the luminosity of the faces (as determined through Photoshop) with responses to Q1 also showed a strong positive correlation ($r(58) = 0.71$, $p < .001$). As with Q1, vertical face illuminance positively correlated with Q2, ($r(58) = 0.67$, $p < .001$), and luminosity as well ($r(58) = 0.68$, $p < .001$), no relation was found for Q3 and 4. Also, for light density, a weak correlation was found for Q2 ($r(58) = 0.29$, $p = .023$). These findings indicate that both the objectively measured illuminance on the face and the luminosity of the face, as quantified using Photoshop, are positively associated with subjective assessments of face illumination and friendliness.

Subsequently, a Pearson correlation analysis was conducted between responses to Q1 (*The face is well-lit*) and Q2 (*The face looks friendly*) and the light diffuseness metric for each position of the light probe. The results indicated a positive correlation ($r(58) = 0.45$, $p = <0.001$) for both Q1 and Q2, no relation was found for Q3 and 4. The coefficient of determination, $R^2 = 0.20$, for both Q1 and Q2, suggests that 20% of the variance in the well-lit and friendliness factor can be attributed to the diffuseness of the light. The control experiment exhibits a stronger coefficient of determination, of 0.42 (Q1) and 0.25 (Q2), explaining 42% and 25% of the variance for these questions.

Further, a paired samples t-test was conducted to evaluate whether snow conditions, i.e. light reflected from the snow, affected responses to Q1. Here, a significant difference in the scores for non-snowy and snowy conditions was found ($t(29) = -2.066$, $p = .048$), indicating that in snowy conditions, the faces were perceived as better lit. Evaluation of the faces' friendliness (Q2) also varied for snowy and non-snowy conditions ($t(29) = -2.665$, $p = .012$), showing that faces were perceived as less friendly in non-snowy situations. For Q3 and 4, no significance was found.

In the case of Q4 (*I would feel comfortable in this lit environment*), a weak positive correlation was found with light density ($r(58) = 0.33$, $p = <0.011$) and mean illumination ($r(58) = 0.30$, $p = .019$), no significant results were found for Q3 (*The environment is well-lit*). For luminosity of the image, a positive Pearson correlation was found with both Q3 ($r(58) = 0.67$, $p = <0.001$) and Q4 ($r(58) = 0.59$, $p = <0.001$). No significant correlations were identified for Q3 and Q4 concerning the variables associated with the face appearance, like frontal light vector, vertical illuminance, face luminosity, diffuseness, and snow. This indicates that parameters such as mean illumination and light density play a more significant role in the evaluation of the surrounding environment, as opposed to those found to be related to the face evaluations, namely the diffuseness, snow, and the frontal light vector.

For the control experiment, the Pearson correlation between Q1 and Q2 was found to be positive ($r(58) = 0.87$, $p = <0.001$), although weaker compared to $r(58) = 0.95$ for Q1 and Q2 in the main experiment. For Q3 and Q4, a similar pattern was observed, with Q3 and Q4 showing a positive correlation of $r(58) = 0.59$, $p = .017$, compared to $r(58) = 0.94$ $p = <0.001$ for both Q3 and Q4 in the main experiment. Further, for the data related to the face perception, the control experiment exhibited stronger correlations for the two first questions, for vertical illumination (Q1 ($r(58) = 0.71, <p = .001$)) and Q2 ($r(58) = 0.68$, $p = <0.001$), luminosity in the face (Q1 ($r(58) = 0.94$, $<p = .001$) and Q2 ($r(58) = 0.72$, $p = .002$) and for diffuseness (Q1 ($r(58) = 0.65$, $p = .006$), Q2 ($r(58) = 0.50$, $p = .047$). For the data related to the environment perception, luminosity in the image showed similar results for the control experiment (Q3: $r(58) = 0.56$, $p = .023$), (Q4: $r(58) = 0.58$, $p = .018$) as for the main experiment. For Q4, the correlations with light density ($r(58) = 0.58$, $p = .019$) and mean illumination ($r(58) = 0.60$, $p = .013$) were stronger than in the main experiment, while for Q3 those correlations were found to be non-significant.

5. Discussion and conclusion

When designing footpath lighting, the perspectives of both the observer and the observed should be considered. On a footpath illuminated by light poles or bollards, the lighting conditions will change as the pedestrians move (Fotios and Raynham 2011). To investigate how this phenomenon influences the appearance of pedestrians, measurements of the objective and subjective appearance of a three-dimensional probe, as well as the actual light on it, were conducted at face height, and varying distances from the light source. Utilizing cubic light measurements on footpaths offered valuable insights into how light diffuseness, vector, and density relate to the visual appearance of objects above ground level.

Our results indicate that light diffuseness, anterior light vector, and the directly related vertical illuminance play a significant role in the evaluation of a face's well-lit and friendly appearance. This was also observed in a previous pilot experiment with a higher "friendliness"-rating for faces illuminated slightly frontal and above and lower for hard contrasts (Wåseth et al. 2022). Hence, managing light diffuseness and light vector can be promising measures to increase the quality of the light at face level on footpaths. These metrics define the modeling properties (Pont 2013) and optimal modeling can increase the visibility of objects in the visual field (Zaikina et al. 2015). The light field framework can thus be useful for assessing the light modeling on footpaths. Vertical illumination of the face is correlated with the "well-lit" and "friendliness"-ratings, although, as van Bommel (2015) suggests, vertical illumination alone was found to not optimally support the impression of a three-dimensional face.

The control experiment showed weaker correlations between the pairs of questions (Q1/Q2 and Q3/Q4). This can be explained by that fewer images (16) were shown, and fewer respondents (14) participated. However, a more robust relationship was found between responses related to face (Q1 and Q2) and diffuseness, vertical illuminance, and face luminosity, and between Q4 and light density and mean illumination. This verifies the results from the main experiment, highlighting the importance of the three-dimensional light qualities. This also points to the importance of representing the visual qualities of the images shown in such an experiment with the actual visual experience as well as possible, although perfect mapping is not possible because of the fundamental difference in the dynamic range of a screen and a real scene. The slight improvements in the correlations in the control experiment, however, show that linearizing and anchoring the mappings are important for robust analysis of the relationships.

The environment was rated more robustly over the different positions, compared to the faces, whose appearance changed more according to the position relative to the light pole (see S1). The face ratings for well-lit and friendly correlated with the perceived comfort of the environment (Q4) but not to the well-lit-ness of the environment (Q3). This implies that designing the light field above the footpath, where f.i. the modeling effects at face level are rendered, hold greater potential to influence the comfort of walking than solely the horizontal illuminance level at the pavement surface. It is also important to acknowledge the significance of the environment reflecting properties of the spatial light qualities and the appearance of objects (faces). Our findings showed that faces were perceived as friendlier under snowy conditions. This effect can be attributed to the snow's ability to scatter and thereby diffuse the actual light, altering the spatial and form-giving light qualities. The diffuseness of light determines its "modelling" power (Xia et al. 2017a, 2017b; Zaikina et al. 2015). These effects point to the importance of taking factors like luminance and light diffuseness into account in exterior light(ing) studies and planning, which is not common practice yet.

One limitation of our face-formed light probe is its white color, which does not accurately represent the variety of human skin tones. Consequently, the light reflected beside the nose and within the eyes might have been more pronounced than it would be with typical skin colors. The color contrast between eyes and skin was also not captured in our experiment. Gaze direction is another perceptually meaningful factor (Palmer et al. 2020), which was also ignored in our study. It was chosen to use a face with a male appearance, as females often appear more approachable than males. In this study, the participant gender data was not collected, but this can be analyzed in future studies, as gender difference may potentially affect face perception. The angle at which the heads were observed deviates from the typical perspective of facial observation on footpaths, where heads are predominantly viewed from a slightly lateral angle. Additional limitations include conducting parts of the experiment in a controlled laboratory setting, which does not fully replicate real-world conditions, like the face illumination varying temporally while moving. Furthermore, the wide age range of participants (20–70 years) might affect the results, given that the eye's response to light varies with age. However, the mean values of the responses were found not to differ significantly for respondents over and under 50 years. However, this broad age range was intentionally chosen to include a diverse group of pedestrians. Finally, walking on footpaths, movement is evident in both subjects and the surroundings, as well as the clothing and gaits of the meeting pedestrian. This was not captured in our study; we captured the changes to the spatial distribution of light in the face over the different positions. It needs to be investigated whether full cue dynamic conditions outside will confirm our results.

Contrary to previous studies that concentrated on the light levels on faces for recognizing facial expressions (Fotios et al. 2015; van Bommel 2015; Yang and Fotios 2015), our current study emphasizes the modeling qualities of light, demonstrating their impact on the interpretation of facial expressions. The directional light prevalent in modern light sources often results in harsh contrasts in objects' faces. Our findings highlight the need to prioritize the use of optical equipment that enhances and metrics that capture, the modeling qualities of the light. Further, include this in the design process, to support the design of the three-dimensional appearance in the third stage of the lighting profession (Cuttle 2010). Enhancing the modeling properties of lighting on footpaths can improve the assessment of approaching pedestrians, facilitating interaction between the observer and the observed, thereby contributing to positive social values like improved walkability and aesthetics, supporting the "Social Field of Vision" (Gehl 2010) at night, thus creating what we term the "Social Light Field of the Footpath."

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Data availability statement

The data that support the findings of this study are openly available in Figshare at http://doi.org/10.23642/usn.25816975.

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