



Pedestrians' Alertness and Perceived Environmental Safety Under Non-Uniform Urban Lighting

Richard Jedon¹ , Antal Haans¹ , Yvonne de Kort¹ 

[1] *Human-Technology Interaction, Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, Eindhoven, the Netherlands.*

Global Environmental Psychology, 2025, Vol. 3, Article e13019, <https://doi.org/10.5964/gep.13019>

Received: 2023-10-11 • **Accepted:** 2024-02-26 • **Published (VoR):** 2025-09-09

Handling Editor: Marica Cassarino, University College Cork, Cork, Ireland

Corresponding Author: Richard Jedon, Human-Technology Interaction, Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, IPO 1.17, P.O. Box 513, NL-5600 MB Eindhoven, the Netherlands. E-mail: r.jedon@tue.nl

Badges for Good Research Practices:  Code.  Materials.

Abstract

The influence of urban lighting on the visual tasks of pedestrians is well known and, in line with this, numerous studies have explored the relationship between urban lighting and pedestrians' feelings of safety. This earlier research has traditionally focused on minimal required illuminance for various visual performance tasks (e.g., obstacle detection and face recognition). However, this focus may have been too narrow, as other light-moderated factors, such as pedestrians' general attentiveness to the environment, may also be important for safety. Despite this, psychological concepts related to the individuals' attention, such as alertness, arousal and anxiety, have only rarely been considered in street lighting research to date. The current study takes a first step in this direction, by testing the sensitivity and direction of response of relevant metrics in a pilot study. We decided for a conceptual replication of a field experiment from 1916 and managed to partly replicate the findings ($n = 29$). Reaction speed (i.e., alertness) was fastest under lighting with lowest uniformity whereas perceived environmental safety was highest under uniform lighting. Concepts of energetic and tense arousal showed clear, opposite relationships with perceived environmental safety. Limitations of the present study, as well as implications for future research in this domain are discussed.

Keywords

urban lighting, alertness, perceived environmental safety, arousal, anxiety



Non-Technical Summary

Background

Artificial light at night has become a common part of our lives but it also has harmful effects on our environment. For example, the loss of the night sky or disruption of the lives of nocturnal species. There is a growing desire to reduce artificial light at night only to the required minimum. The problem is, we do not know what that required minimum should be.

Why was this study done?

Commonly, studies on understanding required minimum of lighting for pedestrians look into tasks such as how well we see objects or people in our surroundings or what kind of light we prefer in the setting. We suggest and try to investigate the inner psychological and physiological states of pedestrians that could have an impact on their experience of the environment.

What did the researchers do and find?

We measured the speed and accuracy of participants' responses to unexpected sounds and how safe they felt under different lighting conditions while walking down the street. We found out that they reacted fastest under the most non-uniform lighting but felt the safest under the most uniform lighting. We also found that the exact nature of how they felt, more excited or more stressed, had an effect on how safe they rated their surroundings.

What do these findings mean?

The psychological and physiological inner states we introduced seem to have an impact on pedestrians' experience of their environment. If we would be able to target these inner states with urban lighting design, it might give us a better idea of pedestrians' experience than when merely looking at how well pedestrians see a specific object. With such knowledge, we could move closer to finding the required minimum lighting for pedestrians.

Highlights

- We replicated an experiment from 1916.
- Reaction speed (i.e., alertness) was fastest under non-uniform lighting.
- Perceived environmental safety was highest under uniform lighting.
- Nature of arousal important for studying perceived environmental safety.
- We suggest a shift of urban lighting research perspective towards studying also psychophysiological concepts.

Urban lighting is essential for human functioning and sense of safety at night (Peña-García et al., 2015), for the economy and, although debated (Falchi et al., 2011; Farrington & Welsh, 2002), for crime prevention (Boyce, 2019; Davies & Smyth, 2018). Yet, urban

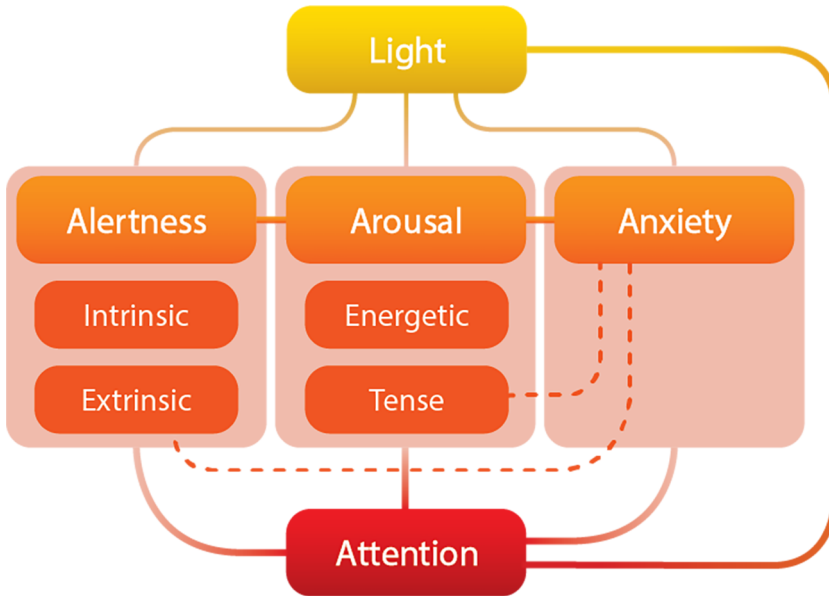
lighting can have negative effects on the environment and brings non-negligible financial expenses to municipalities (Davies & Smyth, 2018; Falchi et al., 2011; Hölker et al., 2010; Stone, 2021). Hence, a balance needs to be found, which includes determining the minimal required lighting for pedestrians' safety.

Unfortunately, current pedestrian lighting recommendations lack a solid empirical foundation (Fotios & Gibbons, 2018). Existing research on urban lighting for pedestrians has mainly focused on how lighting supports various visual performance tasks, such as obstacle detection or facial expression recognition (Fujiyama et al., 2005; Knight, 2010; Mao & Fotios, 2022; Yang & Fotios, 2015). Burt (1916), however, claimed that the mere range of individuals' sight is insufficient for their safety if they are not also attentive to their surroundings and able to react to possible dangers. In other words, to understand how lighting affects pedestrian safety – and thus to develop minimal lighting requirements – one must look beyond visual performance.

Figure 1 shows how, by focusing solely on the direct effect of lighting conditions on visual performance and subsequent attention, we could overlook the possible mediating effects of psychophysiological concepts of alertness, arousal, and anxiety. We understand alertness as a cognitive state of enhanced readiness and openness to incoming information (Brown & Bowman, 2002; Chandrakumar et al., 2019; Matthias et al., 2010; Petersen et al., 2017; Shapiro et al., 2006). This is reflected in faster and more accurate reactions to incoming stimuli (Brown & Bowman, 2002; Matthias et al., 2010). Arousal, the general state of both cognitive and physiological activation, can be distinguished in two dimensions (Thayer, 1978). One is an energetic dimension, ranging from feelings of vigour to drowsiness and tied in with circadian rhythms (e.g., sleep-wake cycle) and voluntary motor activity (e.g., exercise). A second dimension is labelled tense arousal and presumed to be connected with various negative emotions and stress reactions, notably with anxiety. Anxiety, as a reactive state of readiness to uncertain potential future threats, is negatively related to feelings of safety; the more anxious one is, the less safe one feels (Adolphs, 2013; Öhman, 2008). From an evolutionary perspective though, anxiety can also be considered a benefit to cognition as it facilitates physical readiness and faster detection of potential threatening information (Bateson et al., 2011; Eysenck et al., 2007). We can see that higher levels of alertness, arousal and anxiety could lead, through increased reaction speed and accuracy, to improved objective safety (i.e., obstacle detection, prevention of traffic collision) but could also influence perceived safety (e.g., absence of tense arousal and/or anxiety could mean higher feelings of safety). Therefore, we argue that it is not only the visual task performance that should be of interest in pedestrian lighting research but also other concepts, namely pedestrians' alertness, arousal and anxiety (Jedon et al., 2023).

Figure 1

The Triad Conceptual Framework



Note. Figure adapted from Jedon et al. (2023). All of the three interrelated main concepts – alertness, arousal and anxiety – are related to attention, and all may be affected by lighting (shown by the full lines). The dashed lines connect related concepts.

Curiously, these psychophysiological concepts have been scarcely considered in pedestrian lighting research. In one of the few such rare cases, Burt (1916) employed an auditory two-choice task (ATCT), a short memory task, and a motor coordination task in a field experiment to compare pedestrians' performance under different lighting conditions. In general, his findings suggest better performance on all three tasks under non-uniform lighting conditions than under more uniform ones. In Burt's study these positive performance outcomes may have been caused either by changes in the average intensity of illumination, or by the alternations between the illuminated areas under the lamps and the dark, unlit, regions in between them. However, Burt does not explain via what mechanisms the two lighting conditions could lead to such results. Through the lens of our triad conceptual framework (Jedon et al., 2023), we could offer potential explanations. The dark spots and reduced ability to see ahead might have caused higher tense arousal and/or anxiety, resulting in heightened alertness and attention, and hence better performance. Burt (1916) himself discusses that just the difficulty of seeing in the dark areas might have improved alertness; if one's vision is hindered one needs to be more attentive. Alternatively, such changes in alertness and attention may also

have been induced by positive increases in arousal, such as when the non-uniform lighting conditions would be perceived by the participants as novel and stimulating. Howbeit, finding a conclusive explanation for results like Burt's is difficult without first disentangling the relations between the psychophysiological concepts and the impact of light on them.

Research Aims

Burt's (1916) study, despite asking relevant research questions, received little attention. No replication of Burt's study, or its parts, has been done to our knowledge. Therefore, we conducted a conceptual replication of Burt's experiment using modern day measurement equipment.

We designed a quasi-experimental field study. Given the findings of Burt's (1916) experiment we had two main hypotheses on the possible effects of light. The first hypothesis was that responses would be faster and more accurate (i.e., increased alertness) on the streets with lower uniformity than on the streets with high uniformity of illuminance. Uniformity is rarely studied in pedestrian safety research (Boyce, 2014). Most of such research, with exceptions (Johansson et al., 2011), reports uniform lighting to be associated with higher perceived safety (Bullough et al., 2020; Fotios et al., 2019; Kimura et al., 2014; Narendran et al., 2016; Nasar & Bokharai, 2017; Portnov et al., 2020). Therefore, our second hypothesis was that the perceived safety would be lower on the streets with lower uniformity than on the streets with high uniformity of illuminance. For exploratory purposes, we were also interested in the sensitivity of, and the correlations between, the various measures used.

Method

Participants

Sample size was determined primarily with feasibility in mind. Only four participants could partake at the same time. Given that the experiment could only start in the last week of April 2021, we had a short window of opportunity before the late sunset would make it too troublesome for participants to come to the test site after dark. Based on this and considering possible days with poor weather conditions, we expected to run about 40 participants at best. A sensitivity analysis conducted in G*Power (Faul et al., 2009) for a within-subject ANOVA with 4 repeated measures (i.e., on each of 4 streets; see *Design*) and assuming a .50 correlation between repeated measures showed that with 40 participants we had 90% power to detect a small to moderate effect size of $f = .21$ at $\alpha = .05$.

Unfortunately, technical issues forced us to have three rather than four participants simultaneously per session. As a result, only a total of $n = 29$ people participated in

the experiment. An adjusted sensitivity analysis to this sample size showed that we had 90% power to detect a small to moderate effect size of $f = .25$ at $\alpha = .05$. Participants were recruited from the J. F. Schouten database of Eindhoven University of Technology (TU/e). Out of the 29 participants, 13 (44.8%) identified as female and 16 (55.2%) as male. The average age of the participants was $M = 23.1$ ($SD = 3.3$; range 19 to 30). Of the 29 participants, 12 (41.4%) and 10 (34.5%) indicated to be “very familiar” and “somewhat familiar” with the TU/e campus respectively. Of the remaining participants, 3 (10.3%) indicated to be “a bit familiar” with the campus and 4 (13.8%) to be “not familiar at all”. Participants received €10 as compensation for their participation.

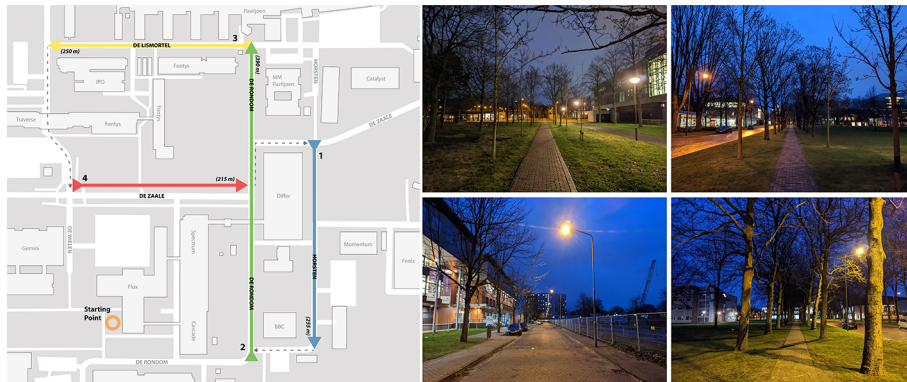
Design

We conducted a one-factor (4 streets), within-subject, quasi-experimental field study with response time (RTs) and accuracy in an ATCT as objective markers of alertness, and self-reports of sleepiness, arousal, safety and lighting appraisal as subjective outcomes. The experiment took place on 4 pre-selected streets that differed, amongst other things, in the uniformity of lighting (see Figure 2, Table 1 and Table 2). To reduce the time needed to move from one street to the other, and to keep the experiment manageable, we did randomize the starting street, but we did not fully randomize the order of the streets. Instead, Street 2 always followed Street 1, Street 3 followed Street 2, Street 4 followed Street 3, and Street 1 followed Street 4. During each 5 min walk participants engaged in two simultaneous tasks. We selected a dual task approach to increase perceptual load and reduce the chance that the slower and/or inaccurate responses were caused by boredom (Fotios et al., 2015). The primary task was walking along the street, following coloured ribbons that marked the path. An ATCT, which was adapted from the earlier study by Burt (1916) was the secondary task. Reaction times and accuracy to the ATCT were recorded. At the end of each walk participants completed a short survey.

The experiment took place on the TU/e campus during six days between 22nd of April and 5th of May 2021, at least 15 minutes after sundown. Each night consisted of one or two experimental sessions with maximum three participants each, starting between 21:00 and 22:45 hrs. Weather conditions were rather similar between days, except for May 5 when it rained. The average temperature was 9^o C. (range 3^o C. to 15^o C.).

Figure 2

Map and Photographs of the Streets on the Site of the Experiment



Note. Street 1 (top left), Street 2 (top right), Street 3 (bottom left), Street 4 (bottom right). Photographs were taken 20–30 minutes after sunset (civil twilight). The four test streets on the TU/e campus were reasonably free of traffic at the time of the experiment. They had an average length of 277.5 meters (range 215 to 390 meters). Each street was marked with coloured ribbons (corresponding to the colours on the map) that the participant had to follow. The streets differed in various aspects besides the lighting. On Street 2, for example, participants walked on the pedestrian pathway that was separated from the main road by a several meters wide strip of grass and trees. On Street 3, in contrast, the participants were asked to walk in the middle of the road as the pedestrian pathway directly next to the street was partly inaccessible due to construction work on an adjacent building.

Table 1

Extensive and Daily Illuminance Measurements Per Street

Extensive	Daily							
				Horizontal		Vertical		
	Street	E_h	E_v	U	E_h (SD)	Range	E_v (SD)	Range
	Street 1	2.72	1.19	0.18	3.50 (0.44)	2.93–3.85	0.93 (0.31)	0.38–1.20
	Street 2	1.20	0.60	0.17	1.11 (0.12)	0.90–1.25	0.41 (0.07)	0.33–0.55
	Street 3	13.60	6.32	0.46	16.3 (1.99)	13.4–17.83	5.75 (1.25)	3.48–7.25
	Street 4	4.15	2.30	0.07	5.29 (0.66)	4.45–6.00	2.02 (0.33)	1.70–2.55

Note. Average Horizontal Illuminance (E_h), Average Vertical Illuminance (E_v), Uniformity (U). Average horizontal illuminance (E_h), measured on the street surface, and vertical illuminance (E_v), measured at 1.5 m height in the direction participants were facing at the starting position, are reported. Uniformity (U), which was calculated as minimum E_h / average E_h , is also reported. Horizontal (E_h) and vertical illuminances (E_v) are in lux and measured with LMT Pocket-Lux meters (ILLUMINANCE METER LMT POCKET-LUX 2, n.d.). For each street, averages across all six days, their standard deviation (SD) and range are provided. The daily measurements reveal that inter-street differences in vertical and horizontal illuminance remained similar across the six days of experimentation. For further details see Appendix, Figure A1.

Table 2

Characteristics of Luminaires in Each Street

Street	Luminaire type	Height	SPD	
			CCT	WI
Street 1 ^a , 2, 3	PHILIPS SGS253 SON-T 70w	8 m.	1939	589
Street 4	PHILIPS SGS253 SON-T 150W DIM	10 m.	1918	588

Note. Luminaire type and height, Correlated Colour Temperature (CCT), and dominant wavelength (WI). For each street the luminaire type, height, Correlated Colour Temperature (CCT) and Dominant Wavelength (WI) are reported. SPD stands for Spectral Power Distribution. Measurements were taken with a JETI specbos 1211-2 spectroradiometer (Specbos 1211-2 Broadband Spectroradiometer, n.d.). Measurements for CCT are in Kelvin and for WI in nm. Spectral radiance measurements can be found in the Appendix, Figure A2.

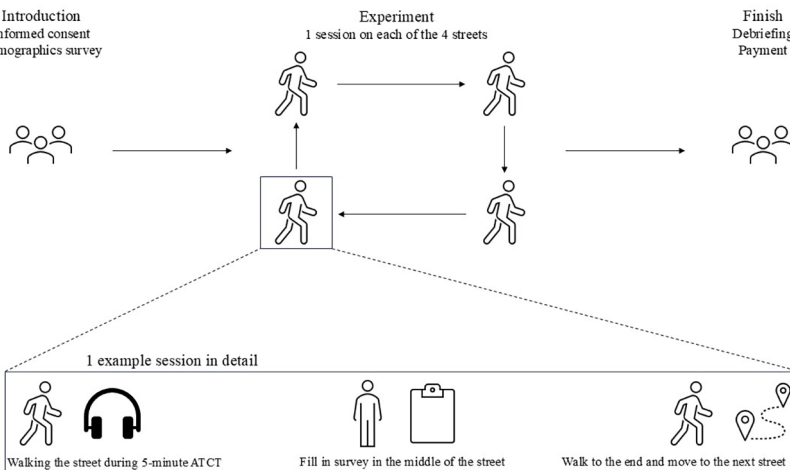
^aA small part of Street 1 was lit by different luminaires of the type HPS100 PLL 36W, height of 4 m. These had a CCT of 2812 K and a WI of 584 nm.

Procedure

After a short introduction to the experimental procedure, each participant was guided from the starting point to their respective first street. Here, they received a survey and pen attached to a clipboard worn around the neck. They completed the first page of the questionnaire (age, gender, and familiarity with the test site) and were then asked to wear a backpack carrying a laptop to which were attached a two-button response box and a pair of headphones (see Figure 3).

Figure 3

Scheme of the Experimental Procedure for Each Participant



In the first session, participants practiced 10 trials of the ATCT. They were instructed via a pre-recorded voice message to press as fast and as accurately as possible the leftmost green button in response to a high pitch sound, and the right most red button in response to a low pitch sound. During these trials they would receive feedback whether they had responded correctly, incorrectly or not fast enough. No feedback was given during the experimental sessions. When the participant started walking, the experimenters positioned themselves out of the participants' view. For five minutes the participant walked the street back and forth while following the coloured ribbons and performing the ATCT. After five minutes, the participant was asked, using a pre-recorded message, to walk to the middle of the street and to complete the remaining pages of the questionnaire. These consisted of the Stanford Sleepiness Scale (SSS; Shahid et al., 2012), the Activation Deactivation Adjective Checklist (ADACL; Thayer, 1986), three items for perceived environmental safety (PES; van Rijswijk et al., 2016) and six items for perceived lighting quality (PLQ; van Rijswijk & Haans, 2018).

When they completed the survey, they were escorted to the next street by another experimenter. After having walked all four streets, an experimenter escorted the participant back to the meeting location, where they were thanked and reimbursed for their participation.

Measures

Alertness and Attention

We used an auditory ATCT and derived three metrics from it: the reaction time (RT), the coefficient of variation in RTs (CV_{rt}), and the proportion of error responses (PE). Incorrect responses were excluded in the analyses of RTs as response errors may indicate that something (e.g., occasional passing car or other pedestrian) interfered with the process under investigation (Pachella, 1974). Missed responses were excluded in the calculation of PE. CV_{rt} was calculated by dividing the standard deviation of the reaction time (SD_{rt}) by the mean reaction time across each person and street (Flehmgig et al., 2007).

Although established methods such as the Psychomotor Vigilance Task (PVT; Loh et al., 2004) are typically used for this purpose, we wanted to use a response task that resembled most closely the method employed by Burt (1916). For stimuli, we used randomly presented, 500 ms long, low (220 Hz) and high (880 Hz) pitched sounds. The two stimuli were matched in loudness (Suzuki & Takeshima, 2004). The interstimulus interval was randomly varied between 2000 to 10000 ms, always in full thousands of ms. The participant was asked to give the correct response to each stimulus as fast and as accurately as possible. Participants had to respond within 2000 ms. Non-responses were treated as missing values. The total duration of the ATCT was 5 min. The ATCT was programmed in E-prime 3 (Psychology Software Tools, 2016) running on HP ZBook Studio G5 Mobile Workstations, and the stimuli were presented to the participants using Sennheiser HD 265 linear headphones. Responses were recorded using Millieky SV-2

response boxes (Labhackers, n.d.), where pressing the green button was the correct response for the high pitch sound, and the red button for the low pitch sound. Each participant was presented with 40 to 52 stimuli per street. Participants failed to respond to the stimulus in 50 (0.9%) out of 5361 trials, leaving 5311 responses for further analysis. The total number of responses per street across all participants ranged from 1325 to 1331.

Self-Reported Sleepiness (SSS)

Sleepiness was measured with the single item SSS (Shahid et al., 2012). Participants could answer using a 7-point response format ranging from “Feeling active and vital; alert; wide awake” (coded with a 1) to “Almost in reverie; sleep onset soon; lost struggle to remain awake” (coded with a 7). There were no missing responses.

Self-Reported Arousal (ADACL)

Self-reported energetic and tense arousal were measured using the ADACL (Thayer, 1986). Each type of arousal was measured with 5 items, in which a term is presented to the participant, such as “Active” (for energetic arousal) or “Fearful” (for tense arousal). We added Dutch translations to the English terms (i.e., “actief”, “nervuus”, “vitaal”, “gejaagd”, “krachtig”, “angstig”, “levendig”, “verward”, “pittig”, and “gespannen”). Participants were asked to indicate the extent to which they were feeling those terms. They could respond using a 4-point response format ranging from “Definitely feel” (coded with a 1) to “Definitely do not feel” (coded with a 4). All responses were reverse coded to ensure that a higher score means more energetic and tense arousal. We averaged the responses to each set of 5 items to calculate four scores per participant (i.e., one per street) for both energetic and tense arousal. These aggregated scores were used in the analysis. For energetic arousal, reliabilities (Cronbach's α) ranged from $\alpha = .74$ to $.88$ and for tense arousal, reliabilities ranged from $\alpha = .87$ to $.93$ across the four streets.

Perceived Environmental Safety (PES)

PES was measured using three items from van Rijswijk et al. (2016), for example “How safe or unsafe do you judge this environment?”. Participants could respond using a 5-point response format, ranging, for example, from “Very unsafe” (coded with 1) through “Neither unsafe nor safe” (coded with 3) to “Very safe” (coded with 5). Across all items, streets, and participants, there were 3 (0.9%) missing responses. By averaging across the three items, four scores were calculated for each participant, each corresponding to a street. These aggregated scores were used in the analysis. Here and in other self-report measures, a minimum of three responses per street and per participant were deemed sufficient to calculate a reliable aggregate score. For one person and on two streets no such reliable PES score could be calculated as this participant did not respond to all three items. Reliabilities ranged from $\alpha = .79$ to $\alpha = .91$ across the four streets.

Perceived Lighting Quality (PLQ)

PLQ was measured using the 6 items from van Rijswijk and Haans (2018), for example “How good or poor do you think the quality of the lighting in this nocturnal environment is?”. Participant could respond using a 5-point response format, ranging, for example, from “Very poor” (coded with 1) through “Neither poor nor good” (coded with 3) to “Very good” (coded with 5). These items were originally intended to measure the perceived darkness of the environment as well as the PLQ, but as in the research by van Rijswijk and Haans (2018), the two measures were found to correlate very highly with $r = .82$ and $p < .001$ (using within-subject correlations; Bland & Altman, 1995). Hence, we decided to calculate a single PLQ score across all six items. Across all items, streets, and participants, there were 7 (1.0%) missing responses. By averaging across the six items four scores were calculated for each participant, each corresponding to a street. These aggregated scores were used in the analysis. Due to missing responses, no reliable PLQ score could be calculated for one person on one street. Reliabilities ranged from $\alpha = .87$ to $.91$ across the four streets.

Results

Differences in Response Accuracy, Reaction Time and the Coefficient of Variation

Overall, participants gave the correct response in 5154 (i.e., 97.0%) of the 5311 trials. Based on a series of Shapiro-Wilk tests – one for each street – with $\omega \geq .97$ as the criterion for sufficient normality, the proportion of errors was not found to be normally distributed in any of the streets with $\omega \leq .88$. Using the Skillings-Mack test, we found no statistically significant differences between the streets on PE, with $SM = 1.0$ and $p = .800$ (see Appendix, Figure A3A; for descriptive statistics, see Table 3). There were no outliers (i.e., with standardized scores of $|Z| \geq 4$; Shiffler, 1988). Graphical summary of the results can be seen in Figure 4.

Reaction times ranged from 203 to 1996 ms. RTs did not meet our normality criterion, with $\omega \leq .84$ (for descriptive statistics, see Table 3). Therefore, we used the inverse of the reaction times (1/RT) or speed in the remainder of the analyses. After this transformation, the Shapiro-Wilk tests showed sufficient normality for all streets with $\omega \geq .98$. To test for differences in speed, we used a Mixed Linear Model with speed as dependent variable, street as fixed, and person as random factor. Residuals were found to be normally distributed with $\omega = .99$. We found a statistically significant effect of street with Wald $\chi^2(3) = 23.9$ and $p < .001$. Post-hoc paired comparisons revealed that people responded, on average, faster in Street 4 (473 ms) as compared to Streets 1 (490 ms), 2 (500 ms), and 3 (492 ms), with $Z \geq 2.93$ and $p \leq .003$ (see Appendix, Figure A3B). None of the other paired comparisons yielded a significant difference, with $|Z| \leq 1.80$ and $p \geq$

Table 3

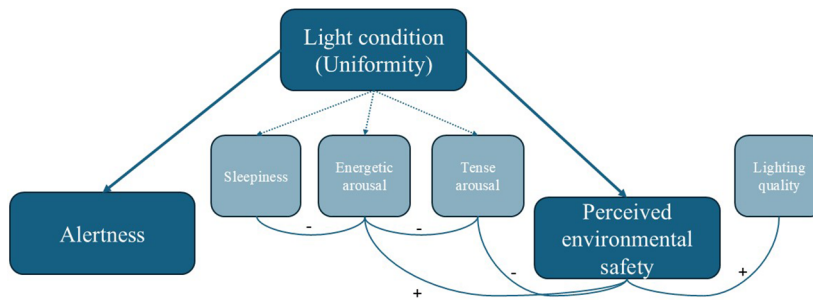
Descriptive Statistics: Means (M), Medians (Mdn), and Standard Deviations (SD) per Street on the Reaction Time (RT; in ms), Proportion of Errors (PE), Coefficient of Variation (CV_n), Sleepiness, Energetic and Tense Arousal, Perceived Environmental Safety (Env. Safety), and Perceived Lighting Quality

Street	RT (ms)	PE (%)	CV _n	Sleepiness	Energetic arousal	Tense arousal	Env. safety	Lighting quality
Street 1								
<i>M</i>	542	2.9	23.6	2.7	2.4	1.6	3.7	3.1
<i>Mdn</i>	492	2.2	23.0	3.0	2.6	1.4	4.0	3.2
<i>SD</i>	142	3.2	5.5	1.0	0.8	0.9	1.1	0.8
Street 2								
<i>M</i>	549	2.6	24.3	2.6	2.4	1.6	3.7	2.9
<i>Mdn</i>	516	2.2	21.2	3.0	2.4	1.2	4.0	2.7
<i>SD</i>	130	2.9	6.8	0.9	0.6	0.8	0.9	0.8
Street 3								
<i>M</i>	551	3.3	23.7	2.6	2.5	1.5	4.0	3.8
<i>Mdn</i>	533	2.3	23.5	3.0	2.6	1.4	4.0	4.0
<i>SD</i>	151	3.7	6.2	1.0	0.8	0.7	0.9	0.7
Street 4								
<i>M</i>	528	3	24.8	2.8	2.4	1.5	3.7	2.8
<i>Mdn</i>	499	2.2	24.4	3.0	2.6	1.4	3.7	2.8
<i>SD</i>	138	3.5	7.4	1.1	0.8	0.7	1.0	0.8

Note. Sleepiness was measured on a scale from 1 to 7; Energetic and tense arousal were measured on a scale from 1 to 4.; Perceived environmental safety and lighting quality were measured on a scale from 1 to 5.

.072. Removal of 27 outliers (i.e., with standardized scores of $|Z| > 3$; Shiffler, 1988) did not alter the interpretation of these findings. As Street 4 was the most non-uniform of the four streets, this finding is consistent with the findings of Burt's experiments on ATCT performance (1916), and thus in support of Hypothesis 1.

With $\omega \leq .95$, CV_{rt} scores did not meet our normality criterion in any of the streets, and hence the Skillings-Mack test was used to test for differences between streets on sustained attention. No statistically significant differences were found with $SM = 0.4$ and p (with ties) = .929 (see Appendix, Figure A3C; for descriptive statistics, see Table 3). There were no outliers (i.e., with standardized scores of $|Z| \geq 4$).

Figure 4*Conceptual Diagram of Relationships*

Note. Solid arrows indicate hypothesized relationships; dashed arrows indicate tested, yet not found effects curved lines indicate correlations with significance $< .01$.

Differences in Sleepiness and Energetic and Tense Arousal

Responses to the sleepiness item were found to have sufficient normality for all streets, with $\omega \geq .98$. There were no outliers (i.e., with $|Z| > 3$). A repeated measures ANOVA with sleepiness as dependent variable and street as factor, showed no differences in sleepiness between the four streets (see Appendix, Figure A4A), with $F(3,84) = 0.38$, and $p = .750$ (Huynh-Feldt corrected). Graphical summary of the results can be seen in Figure 4.

Energetic arousal was not found to be normally distributed in one street, with $\omega \geq .95$. There were no outliers (i.e., with either $|Z| > 3$ or $|Z| \geq 4$) depending on whether normality was met (Shiffler, 1988). Using the Skillings-Mack test, we found no differences between streets in self-reported energetic arousal (see Appendix, Figure A4B), with $SM = 1.7$ and p (with ties) = .580.

Tense arousal was not found to be normally distributed in any of the streets, with $\omega \leq .83$. There were no outliers (i.e., with $|Z| \geq 4$). Using the Skillings-Mack test, we found no differences between streets in self-reported tense arousal (see Appendix, Figure A4C), with $SM = 2.7$ and p (with ties) = .205. Descriptive statistics per street are reported in Table 3.

Differences in PES and PLQ

PES was not found to have sufficient normality in three of the streets, with $\omega \geq .94$. There were no outliers (i.e., with either $|Z| > 3$ or $|Z| \geq 4$ depending on whether normality was met; Shiffler, 1988). Using the Skillings-Mack test, we found streets to differ in PES to a statistically significant extent, with $SM = 6.3$ and p (with ties) = .033 (see Appendix, Figure A5A). Post-hoc paired comparisons revealed that Street 3 was perceived as safer ($M = 4.02$) as compared to Streets 1 ($M = 3.70$), 2 ($M = 3.70$) and 4 ($M = 3.75$), with $SM \geq 2.3$ and $p \leq .040$ (in support of Hypothesis 2). No other statistically significant differences

in PES were found between the other streets, with $SM \leq 0.6$ and $p \geq .444$. Graphical summary of the results can be seen in Figure 4.

PLQ was not found to have sufficient normality in three of the streets, with $\omega \geq .94$. There were no outliers (i.e., with $|Z| \geq 4$). Using the Skillings-Mack test, we found streets to differ in PLQ, with $SM = 31.3$ and $p < .001$. Post-hoc paired comparison revealed that Street 3 had better PLQ evaluations ($M = 3.79$) as compared to Streets 1 ($M = 3.07$), 2 ($M = 2.89$) and 4 ($M = 2.77$), with $SM \geq 15.2$ and $p < .001$ (see Appendix, Figure A4B). No other statistically significant differences in PLQ were found between the other streets, with $SM \leq 0.9$ and $p \geq .216$. Descriptive statistics per street are reported in Table 3.

Correlations Between Variables

We estimated all pairwise correlations using the within-subject method by Bland and Altman (1995). For this purpose, we calculated an average speed on the ATCT for each participant and each street. We found a moderate negative correlation between energetic arousal and sleepiness of $r = -.58$ (see Table 4). As expected, higher energetic arousal was associated with less sleepiness. Tense arousal also had a negative association with sleepiness albeit to a lesser extent with $r = -.25$. As expected, PLQ was positively correlated with PES with a moderate correlation of $r = .53$. In line with our expectations, we found a different association between PES on one hand, and energetic and tense arousal on the other hand. Whereas, as expected, tense arousal was associated with lower ratings of PES, with $r = -.43$, energetic arousal was found to be positively related to PES, with $r = .34$. Correspondingly, the two dimensions of arousal showed a dissimilar association with PLQ, with energetic arousal positively correlated, with $r = .29$, and tense arousal negatively, with $r = -.27$. We found a positive correlation between PE and ATCT speed (1/RT) which suggests the presence of a speed-accuracy trade-off. However, we found only very small and statistically non-significant correlations between ATCT speed and any of the self-report measures. Exclusion of outliers did not affect the interpretation of these correlations. Graphical summary of the results can be seen in Figure 4.

Discussion

Findings

We managed to partially replicate Burt's (1916) findings about the positive effect of non-uniform lighting on pedestrian's alertness, indicated by their reaction speed. People responded, on average, faster on Street 4, which had the lowest uniformity. However, there were no differences in the accuracy of responses across the four streets. Similar to the results of Burt's experiment, we also found no clear relation between lighting uniformity and CV_{rt} . Regarding our second hypothesis, differences on self-reports were indeed in line with previous studies showing positive effects of illuminance levels and

Table 4

Within-Subject Correlations: Reaction Time (1/rt), Proportion of Error Responses (PE), Coefficient of Variation (CV_{rt}), Tense Arousal, Energetic Arousal, Perceived Environmental Safety (Env. Safety) and Perceived Lighting Quality

Correlation	PE	CV _{rt}	Sleepiness	Energetic arousal	Tense arousal	Env. safety	Lighting quality
1/RT	.29**	.01	-.08	.07	0.1	0.07	-0.01
PE		-.09	.18	-.23*	-0.1	-0.01	-0.02
CV _{rt}			.12	-.05	0.18	0.05	-0.02
Sleepiness				-.58***	-.25*	-.21	-.15
Energetic arousal					.13	.33**	.29**
Tense arousal						-.40***	-.27*
Env. safety							.52***

* $p < .05$. ** $p < .01$. *** $p < .001$.

uniformity on perceived lighting quality (PLQ) and perceived environmental safety (PES) (Boyce, 2014; Bullough et al., 2020; Fotios et al., 2019; Narendran et al., 2016; Peña-García et al., 2015; Portnov et al., 2020). Street 3, which had the highest horizontal and vertical illuminance values and highest uniformity, was perceived significantly safer and PLQ was rated significantly higher than the other streets. However, Street 4, which had the lowest uniformity, was not rated lower in perceived safety than the other streets. Hence, we did not manage to confirm our second hypothesis.

We succeeded in finding some insights regarding our proposed research framework (Jedon et al., 2023). The correlation between energetic arousal and Stanford Sleepiness Scale (SSS) is in line with our expectations as the energetic dimension is presumed to be linked with the sleep-wake cycle (Thayer, 1978; Thayer, 1986). However, SSS and energetic arousal did not vary between streets. We found no correlations between the ATCT and any of the other metrics. The lack of any correlation between RTs and either SSS or energetic dimension of arousal can be considered as a confirmation of the literature about sleepiness and alertness being two different constructs and captured through different metrics (Matthias et al., 2010; Shapiro et al., 2006). Alternatively, although RT tasks are commonly used as a measure of alertness (e.g., PVT, Go / No-Go) they might not be sensitive enough, or can be confounded by effort invested. This needs to be further investigated, for example by having more extreme conditions (e.g., very dark, very bright), a more demanding dual task (e.g., scanning the environment rather than walking), or the addition of effort measures. Using other metrics, namely the PE and CV, showed, although not always significant, slightly higher and more promising correlations with the self-reports and might be therefore of further interest in future research.

We found, as expected (Boyce, 2014; Bullough et al., 2020; Fotios et al., 2019; Narendran et al., 2016; Peña-García et al., 2015; Portnov et al., 2020), a correlation be-

tween PES and PLQ. Next, we found correlations of both dimensions of arousal with PES and PLQ but in different directions. The energetic dimension of arousal was positively correlated with both PES and PLQ. The tense arousal seems to have a reverse impact; the higher the tense arousal the lower were the ratings of PES and PLQ. Arousal is often measured only in its intensity. Our findings suggest that Thayer's (1978) categorization of energetic and tense arousal can bring more insights in research on urban lighting and pedestrian safety perceptions.

Limitations

The current study reintroduced attention towards concepts of alertness and arousal in the domain of urban lighting via a replication of a largely overlooked study (Burt, 1916). It tested the sensitivity of relevant metrics in a quasi-field experiment and managed to find effects of urban lighting conditions, potentially uniformity driven, on both perceived safety and alertness. Moreover, promising correlates of perceived environmental safety – energetic and tense arousal – showed opposing relationships with this outcome variable. The study combined both subjective and objective measures and exposed participants to real settings, instead of using proxies (e.g., photographs, videos).

One major limitation of the present study was that we, in contrast to Burt (1916), were not able to directly manipulate uniformity and illuminance. The streets differed in other characteristics as well, such as the presence of greenery, construction works or surrounding buildings. Hence, we cannot make any causal claims with respect to the effect of lighting on alertness and PES. In addition, and as in any field experiment, there were also momentary situational events that may have affected the results. A few examples include fireworks, passers-by (pedestrians, bicycles and cars) or the presence of animals. Furthermore, headlights from cars and uncontrolled lighting from surrounding buildings could have affected the lighting conditions at the time. These spontaneous events could not be captured in our daily measurements of lighting conditions as they were done after finishing the experimental sessions. The occurrence of these real-life events, however, also adds to the ecological validity of this study as all of these effects could possibly occur in daily life. Future studies should directly manipulate the light conditions within otherwise similar environments or otherwise attempt to measure and control for other (not necessarily light related) street characteristics (e.g., by measuring prospect, concealment, entrapment; van Rijswijk et al., 2016; van Rijswijk & Haans, 2018). Alternatively, one could employ day–night time comparisons (Fotios et al., 2019).

The sample of participants was rather homogenous in the manner of their familiarity with the site, as most of the participants were students from the university and knew the campus. This may explain why the PES ratings of all streets were relatively high and with little variation as familiarity with the environment is found to have a strong impact on its perceived safety (Crosby & Hermens, 2019; Day et al., 2003; Traunmueller et al., 2016). Hence, the streets might not have been perceived as unsafe at all because the

participants were familiar with the environment. If the streets would be unfamiliar to the participants, they might consider them as more unsafe and have different requirements from the surrounding lighting, in particular on its uniformity (Bullough et al., 2020; Fotios et al., 2019; Kimura et al., 2014; Narendran et al., 2016; Nasar & Bokharaei, 2017; Portnov et al., 2020). Future studies should try to use participants that are not familiar with the environment. Another solution would be to manipulate the environmental factors in a way to make the setting more unfamiliar and/or make them seem more unsafe (e.g., manipulate the factors of concealment and entrapment).

Another possible confounding variable that we did not take into account, was the walking speed of participants. Donker et al. (2011) found that lower illuminance levels lead to increased walking speed, but Pedersen and Johansson (2018) found the opposite relationship. However, walking could also be understood as a form of exercise. Hence, participants' speed could have an effect on the energetic dimension of arousal, as it is connected with the voluntary motor activity (Thayer, 1978). Moreover, Donker et al. (2011) proposed increased fear of the participants as an explanation for the faster walking speed under darker conditions. Walking speed could therefore be also an indicator of perceived safety, anxiety and/or tense arousal.

Last, the current field study does not allow us to attribute effects on alertness or safety perceptions to either visual or non-visual pathways. In fact, both may well play a part: for instance, alertness may be enhanced by visually perceived external cues (Matthias et al., 2010) as well as by non-visual pathways (Cajochen, 2007; Lok et al., 2018; Xu & Lang, 2018). As acknowledged earlier, our study does not even allow to conclusively attribute effects to lighting parameters per se. If, in future studies one would like to disentangle the underlying visual and non-visual mechanisms, one may have to make use of metameric light conditions. Such however, was not the goal of the present study. Our main aim was to explore and test, for the first time, methods and measurement instruments for disentangling the relationships between safety perceptions, anxiety, alertness, and arousal.

Conclusion

To uncover what pedestrians' needs are in respect to urban lighting, we suggest a shift of research perspective from a primary (or even singular) focus on visual performance tasks towards studying also psychophysiological concepts, such as alertness, arousal and anxiety. Our results show that these psychophysiological concepts, mainly energetic and tense arousal, are relevant when studying safety perceptions. However, more controlled experiments are needed to ascertain whether results such as ours were affected by lighting conditions or other environmental characteristics. Likewise, further research is needed to understand how exactly alertness, arousal and anxiety interrelate in the manifestation of the experience of safety.

Our findings about the impact of non-uniform lighting, its positive effect on the speed of responses without a negative effect on perceived safety, could be important for the discussion on minimizing the unfavourable effects of urban lighting. Positive effects of non-uniform urban lighting could be also welcomed by architects and lighting designers as these are more encouraging for creative and artistic lighting (Boyce, 2014; International Association of Lighting Designers, 2012; Jedon et al., 2022). However, due to the lack of experimental control and other confounds typical for field experiments we should not draw firm conclusions and should not attribute any effects found solely to the uniformity of urban lighting. It is impossible to make claims on the causal relationship between lighting characteristics, including uniformity, and RTs, in a quasi-experimental field study. Therefore, better controlled research is needed on uniformity of lighting.

Openness and Transparency Statements

The present article has been checked by its handling editor(s) for compliance with the journal's open science and transparency policies. The completed *Transparency Checklist* is publicly available at:
<http://doi.org/10.23668/psycharchives.21188>

Author Contributions.

RICHARD JEDON: Conceptualization. Methodology. Software. Validation. Formal analysis. Investigation. Resources. Writing – original draft. Visualization. Project administration.

ANTAL HAANS: Conceptualization. Methodology. Resources. Data curation. Writing – review & editing. Visualization. Supervision. Project administration.

YVONNE DE KORT: Conceptualization. Methodology. Resources. Writing – review & editing. Supervision. Project administration. Funding acquisition.

Acknowledgments. The authors thank Doortje van den Bergen, Lorijn Jansen, Astrid Kolen and Iza Linders for their work on the experiment preparation and data collection and to Joost van Gennip for the technical support. Recognition also belongs to the Environmental Psychology Research group at the Department of Architecture and Built Environment, Lund University, for the discussions. This is an extended and improved version of a conference paper published in the conference proceedings of the 8th International Light Symposium: Re-thinking Lighting Design in a Sustainable Future (Light Symposium 2022) 21/09/2022 - 23/09/2022 Copenhagen, Denmark.
<https://doi.org/10.1088/1755-1315/1099/1/012010>.

Funding. This research was performed within the European Training Network LIGHTCAP (Project Number 860613) supported by the Marie Skłodowska-Curie Actions Framework H2020-MSCA-ITN-2019. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests. The authors declare no conflict of interest.

Ethics Statement. All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013), and the protocol was approved by the Ethical Review Board of TU/e (ID 1332). All participants that took part in the

experiment before April 29, the day the COVID19 evening curfew was dropped, received a curfew employer statement from the TU/e to be exempted from the curfew.

Data Availability. Data are available upon request via all authors or via the Ethics Committee (contact via ethicalreviewboardHTI@tue.nl). The data are not publicly available due to the informed consent form stating that data will be only available to other researchers in the Human-Technology Interaction group of Eindhoven University of Technology.

Supplementary Materials. The following table provides an overview of the accessibility of supplementary materials (if any) for this paper.

Type of supplementary materials	Availability/Access
Code	
Stata Syntax for: Pedestrians' alertness and perceived environmental safety under non-uniform urban lighting.	Jedon and Haans (2025b)
Material	
Research materials for: Pedestrians' alertness and perceived environmental safety under non-uniform urban lighting.	Jedon and Haans (2025a)

Badges for Good Research Practices.

Open data: NO.

Open code: YES.

Open materials: YES.

Preregistration: NO.

Diversity statement: NO.

Note: YES = the present article meets the criteria for awarding the badge. NO = the present article does not meet the criteria for awarding the badge or the criteria are not applicable.

References

- Adolphs, R. (2013). The biology of fear. *Current Biology*, 23(2), R79–R93.
<https://doi.org/10.1016/j.cub.2012.11.055>
- Bateson, M., Brilot, B., & Nettle, D. (2011). Anxiety: An evolutionary approach. *Canadian Journal of Psychiatry*, 56(12), 707–715. <https://doi.org/10.1177/070674371105601202>
- Bland, J. M., & Altman, D. G. (1995). Calculating correlation coefficients with repeated observations: Part 1—Correlation within subjects. *British Medical Journal*, 310(6977), Article 446. <https://doi.org/10.1136/bmj.310.6977.446>
- Boyce, P. R. (2014). *Human factors in lighting* (3rd ed.). CRC Press.
- Boyce, P. R. (2019). The benefits of light at night. *Building and Environment*, 151, 356–367.
<https://doi.org/10.1016/j.buildenv.2019.01.020>

- Brown, V. J., & Bowman, E. M. (2002) Alertness. In V.S. Ramachandran (Ed.), *Encyclopedia of the human brain* (pp. 99–110). University of Michigan/Academic Press.
- Bullough, J., Snyder, J., & Kiefer, K. (2020). Impacts of average illuminance, spectral distribution, and uniformity on brightness and safety perceptions under parking lot lighting. *Lighting Research & Technology*, 52(5), 626–640. <https://doi.org/10.1177/1477153519875171>
- Burt, H. E. (1916). The effect of uniform and non-uniform illumination upon attention and reaction-times, with especial reference to street illumination. *Journal of Experimental Psychology*, 1(2), 155–182. <https://doi.org/10.1037/h0071640>
- Cajochen, C. (2007). Alerting effects of light. *Sleep Medicine Reviews*, 11(6), 453–464. <https://doi.org/10.1016/j.smrv.2007.07.009>
- CEN. (2016). Road lighting — Part 3: Calculation of performance. EN 13201-3. https://standards.iteh.ai/catalog/standards/cen/3b3f153c-192f-486e-ba81-d0a6dbb114c4/en-13201-3-2015?srsltid=AfmBOoq0IOjqwutGNwf9ZBMcQOaHj4cj_Wl3AEM6n5HzNsuGa_TPI6td
- Chandrakumar, D., Keage, H. A., Gutteridge, D., Dorrian, J., Banks, S., & Loetscher, T. (2019). Interactions between spatial attention and alertness in healthy adults: A meta-analysis. *Cortex*, 119, 61–73. <https://doi.org/10.1016/j.cortex.2019.03.016>
- Crosby, F., & Hermens, F. (2019). Does it look safe? An eye tracking study into the visual aspects of fear of crime. *Quarterly Journal of Experimental Psychology*, 72(3), 599–615. <https://doi.org/10.1177/1747021818769203>
- Davies, T. W., & Smyth, T. (2018). Why artificial light at night should be a focus for global change research in the 21st century. *Global Change Biology*, 24(3), 872–882. <https://doi.org/10.1111/gcb.13927>
- Day, K., Stump, C., & Carreon, D. (2003). Confrontation and loss of control: Masculinity and men's fear in public space. *Journal of Environmental Psychology*, 23(3), 311–322. [https://doi.org/10.1016/S0272-4944\(03\)00024-0](https://doi.org/10.1016/S0272-4944(03)00024-0)
- Donker, S. F., Kruisheer, J., & Kooi, F. (2011, September 26–28) *Pedestrian walking speed as a tool to study environment-behavior* (pp. 71–77) [Conference presentation]. 9th Biennial Conference on Environmental Psychology, Eindhoven, the Netherlands.
- Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, 7(2), 336–353. <https://doi.org/10.1037/1528-3542.7.2.336>
- Falchi, F., Cinzano, P., Elvidge, C. D., Keith, D. M., & Haim, A. (2011). Limiting the impact of light pollution on human health, environment and stellar visibility. *Journal of Environmental Management*, 92(10), 2714–2722. <https://doi.org/10.1016/j.jenvman.2011.06.029>
- Farrington, D. P., & Welsh, B. C. (2002). Improved street lighting and crime prevention. *Justice Quarterly*, 19(2), 313–342. <https://doi.org/10.1080/07418820200095261>
- Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, 41, 1149–1160. <https://doi.org/10.3758/BRM.41.4.1149>

- Flehmgig, H. C., Steinborn, M., Langner, R., Scholz, A., & Westhoff, K. (2007). Assessing intraindividual variability in sustained attention: Reliability, relation to speed and accuracy, and practice effects. *Psychological Science*, *49*(2), 132–149.
- Fotios, S., & Gibbons, R. (2018). Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations. *Lighting Research & Technology*, *50*(1), 154–186. <https://doi.org/10.1177/1477153517739055>
- Fotios, S., Monteiro, A. L., & Uttley, J. (2019). Evaluation of pedestrian reassurance gained by higher illuminances in residential streets using the day-dark approach. *Lighting Research & Technology*, *51*(4), 557–575. <https://doi.org/10.1177/1477153518775464>
- Fotios, S., Uttley, J., Cheal, C., & Hara, N. (2015). Using eye-tracking to identify pedestrians' critical visual tasks, Part 1. Dual task approach. *Lighting Research & Technology*, *47*(2), 133–148. <https://doi.org/10.1177/1477153514522472>
- Fujiyama, T., Childs, C., Boampong, D., & Tyler, N. (2005, September 22–23). *Investigation of lighting levels for pedestrians: some questions about lighting levels of current lighting standards* (pp. 1–14) [Conference paper]. Walk21-VI, Everyday Walking Culture. 6th International Conference of Walking in the 21st Century, Zurich, Switzerland.
- Hölker, F., Wolter, C., Perkin, E. K., & Tockner, K. (2010). Light pollution as a biodiversity threat. *Trends in Ecology & Evolution*, *25*(12), 681–682. <https://doi.org/10.1016/j.tree.2010.09.007>
- ILLUMINANCE METER LMT POCKET-LUX 2. (n.d.). <https://www.lmt.de/illuminance-meter-lmt-pocket-lux-2/>
- International Association of Lighting Designers. (2012, May 20). Broken light in Rotterdam, Netherlands honored with IALD Radiance Award: Daglicht & Vorm shows that where light breaks, opportunities appear. <https://www.iald.org/News/Press-Room/BROKEN-LIGHT-IN-ROTTERDAM,-NETHERLANDS-HONORED-WIT>
- Jedon, R., & Haans, A. (2024a). *Research materials for: Pedestrians' alertness and perceived environmental safety under non-uniform urban lighting* PsychOpen GOLD. <https://doi.org/10.23668/psycharchives.14184>
- Jedon, R., & Haans, A. (2024b). *Stata Syntax for: Pedestrians' alertness and perceived environmental safety under non-uniform urban lighting* PsychOpen GOLD. <https://doi.org/10.23668/psycharchives.14183>
- Jedon, R., Haans, A., & de Kort, Y. (2022). Challenging current urban lighting policies: Case for a shift of focus to alertness. In E. Conticelli, G. Marzani & S. Tondelli (Eds.), *International conference proceedings: Shaping light for health and wellbeing in cities* (pp. 82–84). Università de Bologna, Bologna, Italy. <https://doi.org/10.6092/UNIBO/AMSACTA/6863>
- Jedon, R., Haans, A., & de Kort, Y. A. W. (2023). Proposing a research framework for urban lighting: The alertness, arousal and anxiety triad. *Lighting Research & Technology*, *55*(7–8), 658–668. <https://doi.org/10.1177/14771535221122139>

- Johansson, M., Rosén, M., & Küller, R. (2011). Individual factors influencing the assessment of the outdoor lighting of an urban footpath. *Lighting Research & Technology*, *43*(1), 31–43. <https://doi.org/10.1177/1477153510370757>
- Kimura, M., Hirakawa, S., Uchino, H., Motomura, H., & Jinno, M. (2014). Energy savings in tunnel lighting by improving the road surface luminance uniformity — A new approach to tunnel lighting. *Journal of Light & Visual Environment*, *38*, 66–78. <https://doi.org/10.2150/jlve.IEIJ120000487>
- Knight, C. (2010). Field surveys of the effect of lamp spectrum on the perception of safety and comfort at night. *Lighting Research & Technology*, *42*(3), 313–329. <https://doi.org/10.1177/1477153510376794>
- Labhackers. (n.d.). <https://labhackers.com/>
- Loh, S., Lamond, N., Dorrian, J., Roach, G., & Dawson, D. (2004). The validity of psychomotor vigilance tasks of less than 10-minute duration. *Behavior Research Methods, Instruments, & Computers*, *36*, 339–346. <https://doi.org/10.3758/BF03195580>
- Lok, R., Smolders, K. C., Beersma, D. G., & de Kort, Y. A. (2018). Light, alertness, and alerting effects of white light: A literature overview. *Journal of Biological Rhythms*, *33*(6), 589–601. <https://doi.org/10.1177/0748730418796443>
- Mao, Y., & Fotios, S. (2022). Lighting for pedestrians: Does multi-tasking affect the performance of typical pedestrian tasks? *Lighting Research & Technology*, *54*(1), 33–60. <https://doi.org/10.1177/14771535211002617>
- Matthias, E., Bublak, P., Müller, H. J., Schneider, W. X., Krummenacher, J., & Finke, K. (2010). The influence of alertness on spatial and nonspatial components of visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(1), 38–56. <https://doi.org/10.1037/a0017602>
- Narendran, N., Freyssinier, J., & Zhu, Y. (2016). Energy and user acceptability benefits of improved illuminance uniformity in parking lot illumination. *Lighting Research & Technology*, *48*(7), 789–809. <https://doi.org/10.1177/1477153515587959>
- Nasar, J. L., & Bokharai, S. (2017). Lighting modes and their effects on impressions of public squares. *Journal of Environmental Psychology*, *49*, 96–105. <https://doi.org/10.1016/j.jenvp.2016.12.007>
- Öhman, A. (2008). Fear and anxiety: Overlaps and dissociations. In M. Lewis, J. M. Haviland-Jones & L. F. Barrett (Eds.), *Handbook of emotions* (3rd ed., pp. 709–728). Guilford Press.
- Pachella, R. G. (1974). The interpretation of reaction time in information processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 41–82). Erlbaum.
- Pedersen, E., & Johansson, M. (2018). Dynamic pedestrian lighting: Effects on walking speed, legibility and environmental perception. *Lighting Research & Technology*, *50*(4), 522–536. <https://doi.org/10.1177/1477153516684544>

- Peña-García, A., Hurtado, A., & Aguilar-Luzón, M. (2015). Impact of public lighting on pedestrians' perception of safety and well-being. *Safety Science*, 78, 142–148. <https://doi.org/10.1016/j.ssci.2015.04.009>
- Petersen, A., Petersen, A. H., Bundesen, C., Vangkilde, S., & Habekost, T. (2017). The effect of phasic auditory alerting on visual perception. *Cognition*, 165, 73–81. <https://doi.org/10.1016/j.cognition.2017.04.004>
- Portnov, B. A., Saad, R., Trop, T., Kliger, D., & Svechkina, A. (2020). Linking nighttime outdoor lighting attributes to pedestrians' feeling of safety: An interactive survey approach. *PLoS One*, 15(11), Article e0242172. <https://doi.org/10.1371/journal.pone.0242172>
- Psychology Software Tools. (2016). E-prime 3.0 [Computer software]. <https://support.pstnet.com/>
- Shahid, A., Wilkinson, K., Marcu, S., & Shapiro, C. M. (2012). Stanford Sleepiness Scale (SSS). In A. Shahid, K. Wilkinson, S. Marcu & C. M. Shapiro (Eds.), *STOP, THAT and one hundred other sleep scales* (pp. 369–370). Springer Publishing.
- Shapiro, C. M., Auch, C., Reimer, M., Kayumov, L., Heslegrave, R., Huterer, N., Driver, H., & Devins, G. M. (2006). A new approach to the construct of alertness. *Journal of Psychosomatic Research*, 60(6), 595–603. <https://doi.org/10.1016/j.jpsychores.2006.04.012>
- Shiffler, R. E. (1988). Maximum Z scores and outliers. *American Statistician*, 42(1), 79–80. <https://doi.org/10.1080/00031305.1988.10475530>
- Specbos 1211-2 Broadband Spectroradiometer. (n.d.). <https://www.jeti.com/Products/Spectroradiometer/specbos1211-2>
- Stone, T. (2021). Re-envisioning the nocturnal sublime: On the ethics and aesthetics of nighttime lighting. *Topoi*, 40(2), 481–491. <https://doi.org/10.1007/s11245-018-9562-4>
- Suzuki, Y., & Takeshima, H. (2004). Equal-loudness-level contours for pure tones. *Journal of the Acoustical Society of America*, 116(2), 918–933. <https://doi.org/10.1121/1.1763601>
- Thayer, R. E. (1978). Toward a psychological theory of multidimensional activation (arousal). *Motivation and Emotion*, 2(1), 1–34. <https://doi.org/10.1007/BF00992729>
- Thayer, R. E. (1986). Activation-deactivation adjective check list: Current overview and structural analysis. *Psychological Reports*, 58(2), 607–614. <https://doi.org/10.2466/pr0.1986.58.2.607>
- Traunmueller, M., Marshall, P., & Capra, L. (2016). "... when you're a Stranger": Evaluating safety perceptions of (un) familiar urban places. *Proceedings of the Second International Conference on IoT in Urban Space* (pp. 71–77). <https://doi.org/10.1145/2962735.2962761>
- van Bommel, W. (2015). Calculations and measurements. *Road lighting — Fundamentals, technology and application* (pp. 205–220). Springer.
- van Rijswijk, L., & Haans, A. (2018). Illuminating for safety: Investigating the role of lighting appraisals on the perception of safety in the urban environment. *Environment and Behavior*, 50(8), 889–912. <https://doi.org/10.1177/0013916517718888>
- van Rijswijk, L., Rooks, G., & Haans, A. (2016). Safety in the eye of the beholder: Individual susceptibility to safety-related characteristics of nocturnal urban scenes. *Journal of Environmental Psychology*, 45, 103–115. <https://doi.org/10.1016/j.jenvp.2015.11.006>

World Medical Association. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *Journal of the American Medical Association*, 310(20), 2191–2194. <https://doi.org/10.1001/jama.2013.281053>

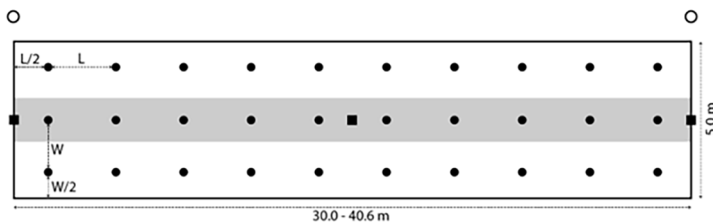
Xu, Q., & Lang, C. P. (2018). Revisiting the alerting effect of light: A systematic review. *Sleep Medicine Reviews*, 41, 39–49. <https://doi.org/10.1016/j.smrv.2017.12.001>

Yang, B., & Fotios, S. (2015). Lighting and recognition of emotion conveyed by facial expressions. *Lighting Research & Technology*, 47(8), 964–975. <https://doi.org/10.1177/1477153514547753>

Appendix

Figure A1

Illuminance Measurement Area (Black Line) Displayed Around a Footpath (Grey)



Note. Black dots represent the measurement grid for the extensive illuminance measurements. For each street section there were always 3 measurement points perpendicular to the walking direction, with distance $W = 1.67$ m. Distance L depended on the distance between the two lampposts (open circles). There were at least 10 measurement points parallel to the footpath with max. $L = 1.0$ m. Black squares show the three measurement points for the daily measurements.

The extensive measurements (see Table 1) were obtained on the night before the first experimental trial. Horizontal and vertical illuminance was measured in each point of – depending on the distance between the poles – a 3 by 10 or a 3 by 14 measurement grid as recommended in European road lighting standards (CEN, 2016). The measurement area that was representative for that particular street and its length was determined by the distance between two consecutive lamp posts and varied between 30.0 to 40.6.

Daily measurements were taken every day of the experiment using three measurement points (black squares). To keep measurements comparable across street sections, the width of the measurement area was the same for all street sections: 5 m. This was based on the width of the road of Section 3, where the walking path was most constrained due to the construction works. The daily measurements for Eh and EV were calculated by taking the weighted average of the three measurements giving 0.5 weight to the two outermost measurements and a weight of 1 to the middle one (van Bommel, 2015).

Figure A2

Spectral Radiance Measurements of Luminaires for Street Sections 1, 2 and 3 (Panel A), for Street Section 4 (B) and Small Part of Street Section 1 Lit by Different Luminaires (C)

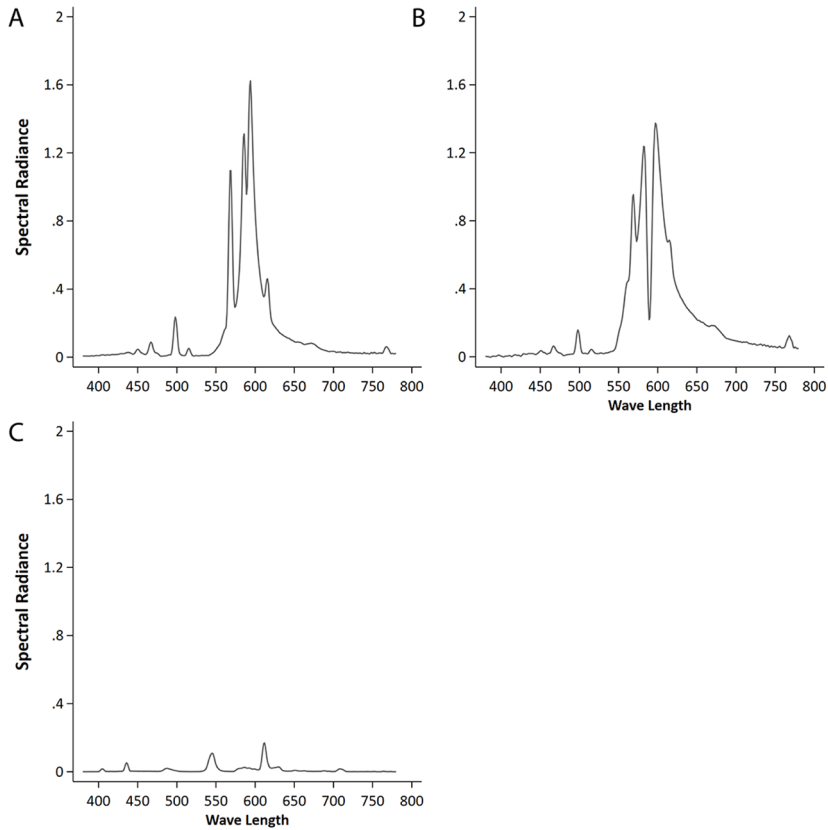


Figure A3

Violin Plot for Proportion of Error Responses (PE; Panel A), Marginal Estimated Mean Speed and 95% CI (B) and Violin Plot for Coefficient of Variation (CVrt; C) for Each Street

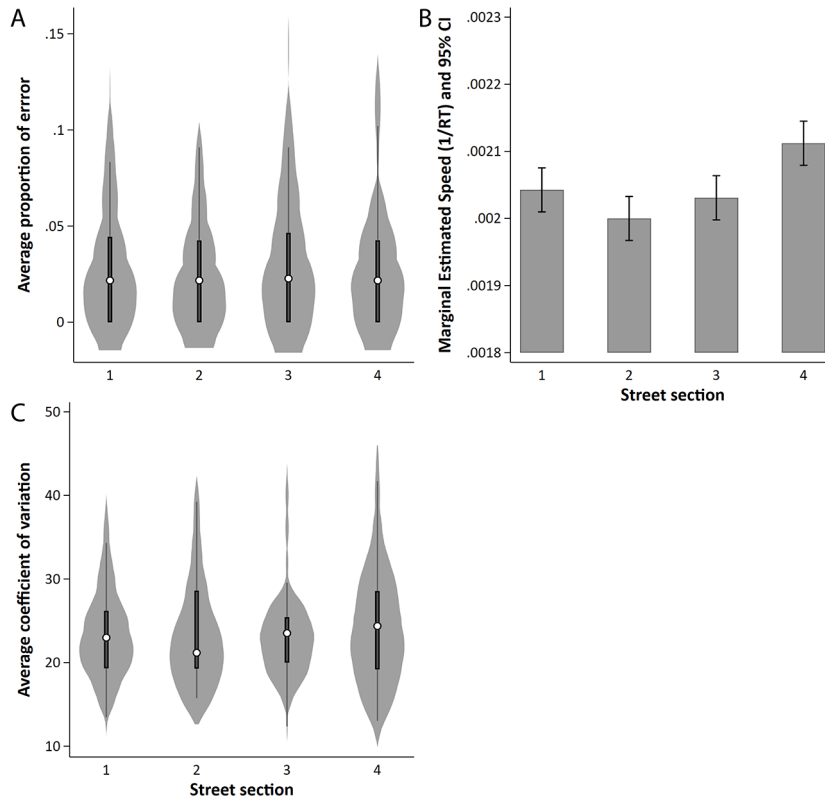


Figure A4

Violin Plots for Subjective Sleepiness (SSS; Panel A), Energetic (B) and Tense Arousal (C) for Each Street Section

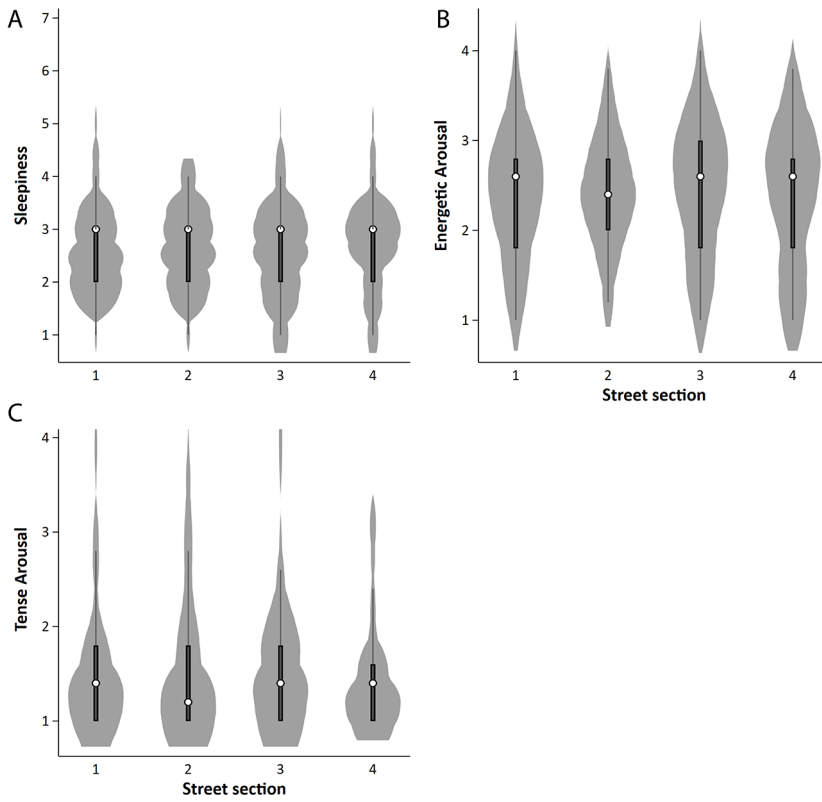


Figure A5

Violin Plots for Perceived Environmental Safety (Panel A) and Perceived Quality of Lighting (B) for Each Street Section

