Virtual Reality (2025) 29:8
https://doi.org/10.1007/s10055-024-01080-2

ORIGINAL ARTICLE

Street lighting environment and fear of crime: a simulated virtual reality experiment

Dongpil Son[1] · Boyeong Im[1] · Jaeseok Her[1] · Woojin Park[2] · Seok-Jin Kang[3] · Seung-Nam Kim[4]

Received: 1 February 2024 / Accepted: 1 December 2024
© The Author(s) 2024

Abstract
Nighttime activities have significantly increased in cities, underscoring the growing importance of nocturnal lighting in fostering emotional stability and comfort of people. This study utilized simulated virtual reality (SVR) technologies to investigate the relationship between lighting environment and fear of crime in narrow residential streets. We created virtual models replicating a typical low-rise residential area in Seoul, Korea, diversified into eight environments representing different times of day with corresponding lighting scenarios (natural light, streetlamps, and interior building lights). One hundred recruited young adult participants were asked to experience four randomly selected environments and rate their perceived level of fear of crime while wearing a head-mounted display. The ordinal logistic regression analysis demonstrated that fear of crime was influenced not only by natural light but also significantly by artificial lights on streets and inside buildings. Specifically, while a decrease in natural illuminance contributes to an increase in fear of crime in general (especially shortly after sunset), the role of natural illuminance was minimized immediately after streetlamp activation. After p.m. 8:30, when other light sources are relatively constant, fear of crime was significantly influenced by the proportion of interior building lights turned on. In residential areas where preventing light pollution is also crucial, a comprehensive strategy is necessary rather than solely focusing on improving illuminance levels to create safe and comfort lighting environment.

Keywords Fear of crime · Lighting environment · Virtual reality · Low-rise residential area · Streets

✉ Seung-Nam Kim
snkim@cau.ac.kr

Dongpil Son
dpson@auri.re.kr

Boyeong Im
byim@auri.re.kr

Jaeseok Her
jsher@auri.re.kr

Woojin Park
wjpark7@cau.ac.kr

Seok-Jin Kang
cpted@gnu.ac.kr

[1] Architecture and Urban Research Institute, Sejong 30116, South Korea

[2] Department of Urban Design and Studies, Chung-Ang University, 209-707, Seoul 06974, South Korea

[3] School of Architecture, Gyeongsang National University, Jinju 52828, South Korea

[4] Department of Urban Design and Studies, Chung-Ang University, Seoul 06974, South Korea

1 Introduction

As nighttime activities in cities have increased significantly, the importance of nighttime lighting environments has also grown (Boyce 2019; Cheon and Kim 2020; Liu et al. 2022; Mander et al. 2023; Wu et al. 2023; Zhang and Dai 2021). Well-lit spaces contribute to emotional stability and comfort, positively affecting physical and mental health (Boomsma and Steg 2014; Falchi et al. 2011; Zhang and Dai 2021). Adequate lighting levels also mitigate fear of crime (Ceccato and Nalla 2020; Cho et al. 2019; Fisher and Nasar 1992; Painter 1996).

Research on lighting effects has focused on on-site studies and virtual indoor experiments. While on-site studies offer accuracy, they are labor-intensive, time-consuming, and costly, with limited control over experimental conditions (Kim and Kim 2019; Kim and Lee 2022). Accordingly, as an on-site study alternative, studies have utilized photographs; however, controlling for experimental conditions remains limited. More recently, following technological

Published online: 12 December 2024

advancements, virtual reality (VR) technology has emerged as a viable alternative, enabling controlled experiments at lower costs and with greater flexibility. Moreover, this can be a useful alternative to on-site studies in situations such as the COVID-19 pandemic period, where social contact has to be avoided, as it allows for the efficient collection of several observations.

In VR experiments, it is critical to heighten the sense of presence of participants to enable them to feel that the VR environment is close to reality (Hong et al. 2019). Previous studies have validated sense of presence in VR experiments and found no significant difference between VR and physical environments (Abd-Alhamid et al. 2019; Heydarian et al. 2014, 2015; Hong et al. 2019). Additionally, the initial experimental method mostly used simulated VR (SVR), followed more recently by recorded VR (RVR), which achieves a higher sense of reality (Kim and Kim 2019; Kim and Lee 2022). However, RVR is based on live video footage captured using omnidirectional cameras, which makes it difficult to control for specific environmental factors. For instance, Son et al. (2023) used RVR to analyze the effects of measured illuminance on fear of crime; however, the illuminance levels were influenced by a combination of natural light, streetlamps, and interior lighting from buildings, making it difficult to pinpoint the specific factors that significantly affect fear of crime.

Thus, this study aims to investigate the relationship between the lighting environment and fear of crime in narrow residential streets using SVR, which has advanced in realism owing to technological innovations. In particular, this study examines the effects of various lighting sources in urban settings, including natural light, streetlamps, and interior lighting of buildings.

2 Literature review

2.1 Fear of crime and the role of the lighting environment

Fear related to people's perceptions of crime can be defined as perceived awareness of potential physical harm (Warr and Ellison 2000; Yin 1980). Ferraro and Grange (1987) classified fear of crime into personal versus general levels of crime, and crime perceptions into cognitive versus affective perceptions, subdividing the former into six types depending on whether judgments or values about crime were being measured. Fear of crime is greatly influenced by personal emotions, but the importance of physical and environmental characteristics has also attracted attention, with an increasing number of studies conducted on the effect of environmental characteristics on fear of crime (Jacobs 1961; Jeffery 1971; Newman 1972). According to Appleton's (1975) prospect-refuge theory, people feel safe and experience pleasure in environments in which open views and a sense of enclosure coexist. Thus, physical environments affect people's emotions and sense of perception, especially lighting environments, because they are critical for securing vision (Ceccato and Nalla 2020; Ferraro and Grange 1987; Fisher and Nasar 1992; Loewen et al. 1993).

Studies have been conducted on improvements in street lighting to prevent crime (Chalfin et al. 2022; Painter and Farrington 1997; Painter 1996; Xu et al. 2018); however, there is controversy surrounding the direct causal relationship between lighting environments and crime rates (Boyce 2019). Nonetheless, substantial evidence indicates a clear relationship between lighting environments and a reduction in fear of crime, especially among women and older adults (Boyce 2019; Ferraro 1996; Fox et al. 2009; Gibson et al. 2002; Kanan and Pruitt 2002; Painter 1996; Warr 1984). Particularly, Boyce et al. (2000) suggested that 30 lx is an adequate level of brightness at night for people to perceive safety, while Fotios et al. (2019) suggested a minimum of 2.0 lx for street safety.

Other factors influencing perceived safety include the uniformity ratio of illuminance, color temperature, and other lighting characteristics (Boyce 2019; Fotios et al. 2019; Kim and Park 2017; Peña-García et al. 2015). In addition, regional differences have been reported in the feeling of safety from lighting (Svechkina et al. 2020). The direct effect of lighting quality on safety perception is weaker than that of factors such as visibility, concealment, and escape routes, which have a significant impact on safety perception (van Rijswijk and Haans 2018).

2.2 Lighting environment and fear of crime in VR studies

The existing body of studies analyzing the effects of lighting on fear of crime has primarily, though not exclusively, focused on single sites owing to the limitations of on-site studies. This may be attributed to the challenges of setting up experimental environments in real urban spaces and conducting experiments with residents of those areas.

Lab-based studies have been conducted to overcome this limitation. Early lab-based research (Hanyu 1997, 2000) utilized photographs of the site, whereas later studies used VR simulations to control for various factors in a designed environment (Lee and Lee 2021; Nasar and Bokharaei 2017; Van Gelder et al. 2019; van Rijswijk and Haans 2018). VR simulations allow controlling for diverse environmental factors and repeating experiments to evaluate the effects of variables, such as lighting environments. Nasar and Bokharaei (2017) created a virtual space with varying levels of

illuminance and its uniformity ratio to analyze perceptions of safety. They designed six types of VR lighting environments (nonuniform/uniform, dim/bright, and peripheral/overhead) and assessed 62 participants' perceptions of safety and emotional responses. The results indicated that brighter and more uniform lighting led to higher perceptions of safety.

Although it is critical for virtual environments to enhance the sense of presence, there are limitations to replicating the sense of presence in actual environments. To address this, research has used RVR to analyze the effects of external factors on people's emotions, perceptions, and crime psychology (Kim and Lee 2022; Lee and Kim 2021; Mouratidis and Hassan 2020). For example, Van Gelder et al. (2019) compared written and VR scenarios to analyze the decision-making processes involved in violent crime. The scenarios were set in bars, with participants being male and aged 18 years or above. The experiment used footage from a 360-degree camera and audio narration to enhance sense of presence. The VR scenario had a higher level of immersion than the written one, demonstrating VR's usability in research on crime decision making. Using an RVR experiment, Son et al. (2023) analyzed the relationship between measured illuminance levels and fear of crime using illuminance metrics from prior research, such as the average horizontal and vertical illuminance levels, and the uniformity ratio of illuminance. The results demonstrated that illuminance levels affected fear of crime; however, the illuminance levels involved a combination of natural light, streetlamps, and interior lighting from surrounding buildings, making it difficult to extrapolate the impact of specific factors.

With advancements in VR technology and equipment, numerous studies have compared real and virtual environments, thereby demonstrating VR's potential as an effective alternative to on-site research. Virtual environments provide a sufficient sense of presence, showing no significant differences from physical settings. Recently, although RVR research has utilized actual footage to enhance the sense of presence, it remains challenging to test and isolate the effects of individual environmental factors using RVR. Therefore, this study employed SVR to segment various lighting environment factors, such as natural light, the presence of streetlamps, and interior lighting from surrounding buildings. This approach allows for a more detailed analysis of the effects of light levels compared with previous studies.

3 Methods

3.1 Experiment design and virtual environment simulation

Figure 1 outlines the experimental design and analysis framework. Initially, SVR environments based on narrow streets in Seoul were constructed using Unity, a popular 3D game engine. The lighting environment was designed to incorporate natural light, streetlamps, and building interior lights. We then recruited 100 adults in their 20 s and 30 s and conducted the SVR experiment in the following sequence: pre-questionnaire, pilot test, main questionnaire ('fear of crime questionnaire'), and post-questionnaire. Finally, the impact of the lighting environment on fear of crime was analyzed using an ordinal logistic regression model.

The SVR environment was constructed to enhance realism by referencing an actual street location: 43 Sangdoro 45-gil, Dongjak-gu, Seoul, a typical narrow street in a densely populated low-rise residential area in Seoul, South Korea. This site was one of four streets analyzed in the study by Son et al. (2023), allowing us to design the virtual environment based on the physical dimensions measured in the previous research. The simulation included typical housing types and specifications for a residential street in Seoul, with the street designed to be 6 m wide without sidewalks. Residential options were limited to walk-up apartments and single-family houses, each with a front façade width of 10 m. Each side of the street featured five buildings (Fig. 2).

The simulated virtual environment controlled for all variables except lighting conditions to replicate the physical

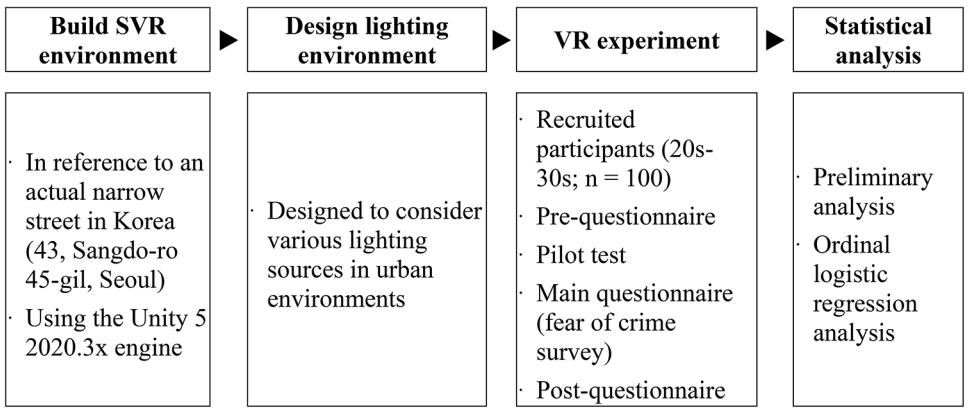

Fig. 1 Study flow

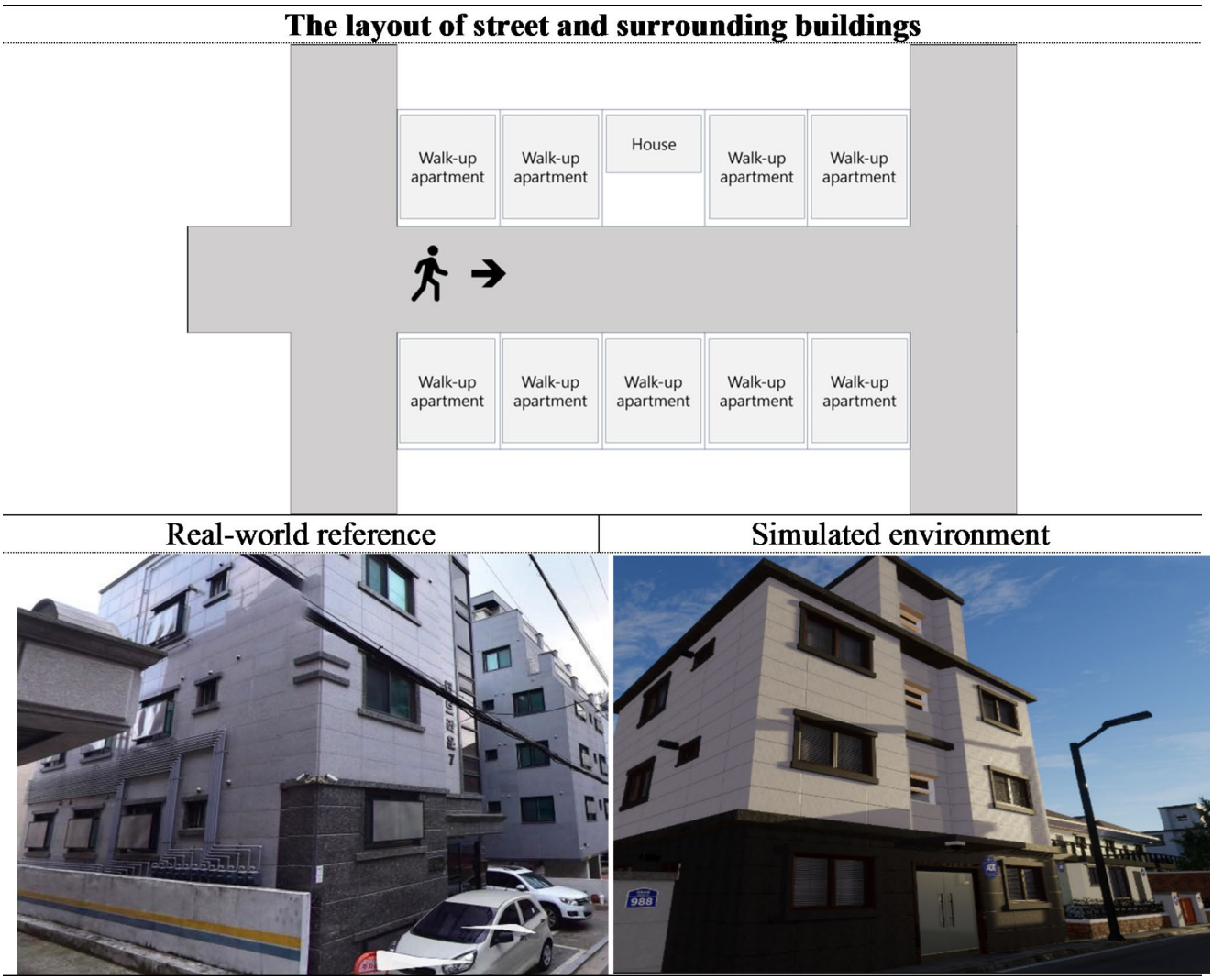

Fig. 2 Surrounding building layout and example of reference and virtual environment. *Reference location: Sang-do Ro 45 Gil, Seoul; Source: Naver Roadview

environment of the reference site as closely as possible. However, because of the impracticality of replicating the exact light levels, we selected specific times of the day rather than using precise illuminance values. Drawing from a previous study (Son et al. 2023), we chose the following times for virtual lighting conditions: 18:00, 19:00, 19:30, 20:00, 20:30, 21:00, 21:30, and 22:30. In the virtual environment, the Sun, Moon, streetlamps, and interior lighting of buildings were adjusted to simulate varying light levels corresponding to these times. To enhance the realism of the simulation, all objects except the Sun and Moon were baked using LightMap, a tool in Unity for realistic lighting environments. The Sun and Moon were rendered using Physically Based Sky, with each color defined by a unique Hex Color Code as part of the High-Definition Render Pipeline function. The surface color of the Sun was FFAB25 with a luminescent color of FFC996, while the Moon's surface color was white with a luminescent color of CEECFF. The altitudes of the Sun and Moon were determined based on the survey date (April 26, 2021) as referenced in a previous study (Son et al. 2023). The sunset time on the reference day was 19:17 (Korea Astronomy and Space Science Institute 2023). We assumed that the Sun and Moon emitted equal amounts of light on all visible sides.

For streetlamps, both the surface and luminescent colors were set to white. The vertical illuminance in front of the window needed to be less than 10 lx, considering the streetlamp installation regulations (Enforcement Rule of the Act on the Prevention of Light Pollution Due to Artificial Lighting, Korea Ministry of Government Legislation 2020) at the reference study site. However, from the perspective of a pedestrian at the center of the road, the illuminance of the streetlights was set to 30 lx owing to the distance from the window and reality of the street environment. The value was

based on prior real-world measurements (Son et al. 2023) and iterative adjustments to ensure realistic lighting conditions in the virtual environment.

The lighting inside the buildings was depicted using self-luminous (emission) textures. To replicate environments similar to actual residential areas, we varied the usage of interior lighting across different times of the day (indicated by the ratio of interior lighting on). As detailed in Table 1, we assumed that all lights were off until 8 p.m., gradually transitioning to all lights being on by 9:30 p.m., and subsequently all lights off by 10:30 p.m. Table 1 and Fig. 3 illustrate the lighting environments created by the Sun, Moon, streetlamps, and building interior lighting. These environments were meticulously developed in collaboration with a professional virtual environment production company, involving iterative cycles of design, review, and refinement to achieve a high level of realism and accuracy. Detailed protocols and setup methods for the simulation environment are provided in Appendix A.

3.2 Participants

The study focused on young adults in their 20 s and 30 s as participants, who are typically proficient in using VR equipment and experience minimal side effects such as VR sickness (Kim and Lee 2022; Lavoie et al. 2021). In particular, young females were chosen as suitable subjects due to their reported high levels of nighttime anxiety (20 s: 51.3%, 30 s: 46.9%, 40 s: 45.2%, 50 s: 43.2%, 60 s and above: 38.5%, Statistics Korea 2022). Recruitment began on June 22, 2022, using a combination of online and offline snowball sampling methods, resulting in a total of 100 participants (Table 2). Given the limitation that VR equipment can only be used by one person at a time, practical constraints restrict the number of participants in the experiment. Therefore, like many previous studies (Kim and Kim 2019; Schneider and Bengler 2020; Schwebel et al. 2016; Son et al. 2023), this study also focused on a specific homogeneous cohort with a small sample size.

3.3 Experiment procedure and survey questionnaire

Each participant signed an informed consent form prior to participation (Fig. 4). Next, an experimental assistant explained the purpose and intent of the experiment and asked participants to complete a pre-questionnaire regarding their personal characteristics. Information was collected on several factors that may affect their level of fear of crime, such as age, sex, education level, residential type, household size, frequency of walking on narrow streets, average returning home time, and previous VR usage experience. Crime victimization experiences were also gathered to control for personal experiences that could directly affect fear of crime.

After completing the pre-questionnaire, participants were instructed to wear a Vive Pro head-mounted display (HMD) with 4 k resolution. They engaged in a warm-up task designed to familiarize themselves with the VR device and enhance immersion in the virtual environment. The layout of this virtual environment mirrored that of the main experiment, except the natural illuminance was set to simulate 2 p.m. This approach ensured participants` acclimatization to the virtual environment and equipment, under conditions where nighttime lighting effects were avoided to maintain consistency in experimental conditions.

Table 1 Lighting environment design by time of day

Time of day	Solar altitude and azimuth*				Lighting environment		
	Azimuth (Degree minute second)	Altitude (Degree minute second)	Right ascension (Hour minute second)	Declination (Degree minute second)	Natural illuminance (lx)**	Streetlamp illuminance (lx)***	Building interior lighting***
18:00	276 30 21.00	14 07 32.13	02 16 06.82	13 38 07.44	59,321		All off
19:00	285 21 09.29	02 27 31.98	02 16 16.28	13 38 55.20	19,549		All off
19:30	289 57 01.36	03 13 08.39	02 16 21.03	13 39 19.13	400		All off
20:00	294 45 05.79	08 42 19.00	02 16 25.76	13 39 42.95	20	30	All off
20:30	299 55 20.61	14 02 00.10	02 16 30.56	13 40 07.04	10	30	Randomized 1/10 on
21:00	305 24 03.68	18 59 37.82	02 16 35.28	13 40 30.71	1	30	Randomized 1/2 on
21:30	311 31 04.89	23 43 17.43	02 16 40.12	13 40 54.97	0.5	30	All on
22:30	325 24 44.92	31 38 07.74	02 16 49.70	13 41 42.90	0.2	30	Randomized 1/3 on

*Source: https://astro.kasi.re.kr/life/pageView/10

**Estimation from solar altitude and azimuth

***Assumptions in this study for real-world replication

The sunset time on the reference day (April 26, 2021) was 19:17



Fig. 3 Simulated lighting environment by time

Table 2 Participant characteristics

Category	Frequency	Mean	S.D
Age		23.59	2.96
Height		170.12	8.08
Self-reported average visual acuity of both eyes		0.75	0.53

	0	1
Sex (0 = Female, 1 = Male)	44	56
Wearing glasses (0 = No, 1 = Yes)	80	20
Educational attainment (0 = Less than a bachelor's degree, 1 = Postgraduate or higher)	80	20
Residential type (0 = Single family house, 1 = Apartment)	51	49
Household size (0 = More than 2 people, 1 = 1 person)	60	40
Past VR experience (0 = No, 1 = Yes)	72	28

	1	2	3	4	5
Walking in the street in the past 7 days[1] (1 = 0–2 days, 2 = 3–4 days, 3 = 5–6 days, 4 = 7 days)	13	21	30	36	
Average returning home time for the last 7 days[1] (1 = Before 20:00, 2 = 20:00–22:00, 3 = After 22:00)	15	36	49		
Self-perceived household income level (1 = Very low, 2 = Low, 3 = Medium, 4 = High, 5 = Very high)	3	8	59	27	3

		0 = No	1 = Yes
Experience of crime victimization	Self-experience of street crime	98	2
	Self-experience of other crimes	96	4
	Others' experience of street crime	92	8
	Others' experience of other crimes	92	8
	In/direct experience of crime victimization[2]	85	15

		1 = Very low	2 = Low	3 = High	4 = Very high
Perceived crime vulnerability	Possibility of crime victimization (self)	28	58	14	0
	Self-defense level[3]	4	34	55	7
	Severity and continuity of harm	8	55	33	4

[1]Recategorized existing questionnaire items to account for the frequency of responses to each item.

[2]1 = if any of the above four items applies; 0 = otherwise.

[3]Reverse coded for analysis, i.e. high defense = 1, low defense = 4

Number of participants = 100

Participants were given the opportunity to explore this virtual space through both teleportation and walking for as long as desired. While most participants moved using the controller, walking within the 3 m × 3 m space of the VR lab was also permitted. While this mixed locomotion mode raised concerns about disrupting the consistency of participants' experiences it was adopted to provide an experience as close as possible to real urban walking, particularly at points of interest.

To further enhance immersion, an experimental assistant provided contextual narration as follows:

> You have just stepped out of your home and are now walking down the street.

Next, the participants were asked to experience four out of eight environments with varying lighting conditions (technically, at different times of the day). Four environments were randomly chosen before the experiment to minimize the effect of the order of experience. During the experiment, the assistant repeatedly asked two questions for each environment to measure perceived fear of crime. The participants responded on a 7-point Likert scale while wearing the HMD. Two questions assessed fear of crime against oneself (fear of self-victimization, FSV) and fear of crime against others (fear of others' victimization, FOV). The experimental assistant provided the following narration for each experience:

> You are on your way back home alone and have paused momentarily, looking around your surroundings.
> In the situation you are in now, how high is your fear of victimization that crimes, such as theft, violence, sexual assault, robbery, and murder, could happen to you?
> In the situation you are in now, how high is your fear of victimization that crimes, such as theft, violence, sexual assault, robbery, and murder, could happen to others (family and acquaintances)?

The experimental assistant asked participants to fully experience each environment before answering the questions above. Although there was no time limit and formal duration check, most participants completed their evaluations of the four environments within 10 to 15 min.

Finally, the participants were asked to complete a post-questionnaire using the Sense of Presence Scale developed by Lessiter et al. (2001, p. 290). This scale, which is widely used in VR experimental studies to test the validity of experiments, comprises four subscales: sense of physical space, engagement, ecological validity, and negative effects (Pieri et al. 2022; Son et al. 2023; Yan et al. 2020). Each participant rated each item on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The presented experimental protocol was confirmed through a pilot experiment conducted on May 31, 2022, at the Chung-Ang University VR Lab. The main experiment was conducted at the same location, from June 22 to July 31, 2022. All the processes described

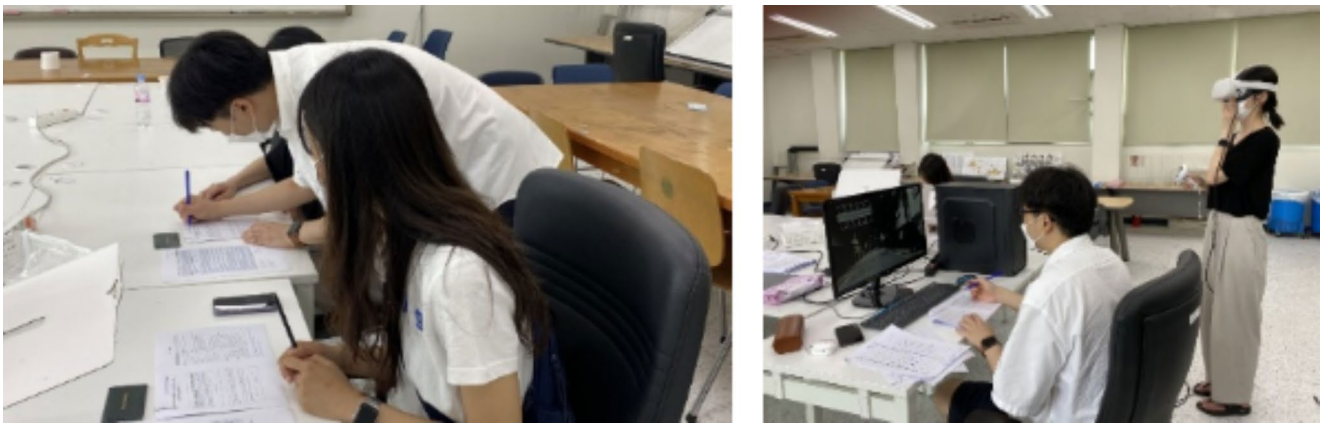

Fig. 4 Photos of experiment participation

so far were approved by the Institutional Review Board of Chung-Ang University (1041078-202203-HR-092).

3.4 Analysis methods and variables

The dependent variables used to test the impact of the lighting environment on fear of crime were FSV and FOV, measured on a 7-point Likert scale (1 = not fearful at all, 7 = very fearful). Therefore, ordinal logistic regression models were employed in the analysis. The key test variables for lighting environments included three factors: natural illuminance (lx), streetlamps on or off (dummy), and the ratio of building interior lighting on. Owing to the large variation in the natural illuminance, a log-transformed value was applied.

Table 3 presents the other dependent variables. Participant characteristics were primarily sourced from the pre-questionnaire survey, with some variables redefined or consolidated to streamline them. Regarding crime victimization experience, any affirmative response to the four questions (see Table 2) was coded 1 for 'yes,' reflecting the infrequent occurrence of positive responses. Variables related to vulnerability to crime were consolidated into a single factor through a factor analysis of three items: possibility of crime victimization, self-defense level, and severity and continuity of harm, yielding a Cronbach's alpha of 0.577. Additionally, the 13 items from the 'sense of presence' questionnaire were reduced to three factors via factor analysis: sense of presence/immersion, adverse physiological reactions, and ecological validity (see Table 4). Each factor demonstrated strong internal consistency, with Cronbach's alpha values of 0.851, 0.867, and 0.837, respectively. Other variables used to control for external factors that may influence the virtual environment experience encompassed height, wearing glasses, visual acuity, previous VR experience, and the survey assistant.

4 Results

4.1 Fear of crime by lighting environment (time of day)

Table 5 presents the fear of crime levels in different lighting environments, specifically at different times of the day. A total of 400 observations were collected, with each participant rating their fear of crime in four different environments. The mean FSV and FOV values were 2.058 and 2.425, respectively, with a score of less than 4, indicating that the participants generally had a low level of fear of crime.

However, there were noticeable variations in fear of crime based on changes in lighting conditions at different times of the day. The fear of crime increased gradually until 7:30 p.m., and then decreased around 8:00 p.m. This variation seemed related to the timing of streetlamp activation, which was assumed to be at 8 p.m. when designing the virtual lighting environments. Additionally, participants' fear of crime appeared to be influenced by the lighting in buildings. Fear of crime decreased after 8:30 p.m., when the lights were turned on inside buildings, but increased again at 10:30 p.m., when the lights were turned off. In the following subsection, we analyze the impact of these variables while controlling for other factors using an ordinal logistic regression.

4.2 Results of ordinal logistic regression analysis

Table 6 demonstrates the results of the ordinal logistic regression analysis, investigating the relationship between lighting environment and fear of crime. The model fit was statistically significant for both FSV ($\chi^2 = 113.155$, $p < 0.001$) and FOV ($\chi^2 = 124.660$, $p < 0.001$), suggesting that the models effectively differentiate levels of fear of crime based on the independent variables. The results of the Goodness-of-Fit tests (both Pearson and Deviance) for

Table 3 Definition of the variables

Variable	Definition	Note
Dependent variable		
Fear of self-victimization (FSV)	7-point Likert scale	
Fear of other's victimization (FOV)	7-point Likert scale	
Test variable		
ln (natural illuminance)	log-transformed natural illuminance	
Streetlamp on/off	On = 1	
Building interior lights-on ratio		
Control variable		
Age		Personal characteristic control
Gender	Male = 1	Personal characteristic control
Educational attainment	Postgraduate or higher = 1	Personal characteristic control
Occupation	Have = 1	Personal characteristic control
Residential type	Apartment = 1	Household characteristic control
Self-perceived household income level	1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high	Household characteristic control
Household size	1 person = 1	Household characteristic control
1-week narrow street walking frequency	Frequency of walking on the narrow street for the last week (5–7 days = 1)	Individual behavior, experience, perception control
Average returning home time	After 22:00 = 1	Individual behavior, experience, perception control
In/direct experience of crime victimization	Yes = 1 (see main text and Table 2)	Individual behavior, experience, perception control
Crime vulnerability	Result of factor analysis using three crime vulnerability measurements (see main text)	Individual behavior, experience, perception control
Height	cm	Control of other factors that may influence virtual environment experience
Wearing glasses	Yes = 1	Control of other factors that may influence virtual environment experience
Self-reported average visual acuity of both eyes	Without contact lens and glasses	Control of other factors that may influence virtual environment experience
Previous VR experience	Yes = 1	Control of other factors that may influence virtual environment experience
Survey assistant	Assistant A = 1, B = 0	Control of other factors that may influence virtual environment experience
Factor 1 (sense of presence/immersion)	Result of factor analysis using the 13-item sense of presence questionnaire (see main text and Table 4)	Perceived sense of presence level control
Factor 2 (adverse physiological reactions)	Result of factor analysis using the 13-item sense of presence questionnaire (see main text and Table 4)	Perceived sense of presence level control
Factor 3 (ecological validity)	Result of factor analysis using the 13-item sense of presence questionnaire (see main text and Table 4)	Perceived sense of presence level control
Order of presentation	Order of presentation of virtual environments (one value from 1 to 4)	Order effect control

Table 4 Factor analysis of responses to 13 sense of presence survey items

Item	Factor		
	Sense of presence/immersion	Adverse physiological reactions	Ecological validity
I felt that the characters and/or objects could almost touch me	.796	.064	.126
I felt I was visiting the places in the displayed environment	.786	-.033	.342
My experience was intense	.768	.007	.166
I enjoyed myself	.721	-.138	-.011
I felt involved in the displayed environment	.676	-.035	.233
I had a sense of being in the scenes displayed	.644	-.087	.423
I felt dizzy	-.051	.918	.003
I felt nauseous	-.095	.874	-.063
I had eyestrain	.039	.802	.143
I felt I had a headache	-.048	.802	-.122
The displayed environment seemed natural	.183	-.014	.896
The content seemed believable to me	.173	.039	.854
I had a strong sense that the characters and objects were solid	.391	-.055	.724
Category total	6	4	3
Cronbach's alpha	.851	.867	.837

Extraction method: Principal Component Analysis

Rotation method: Varimax with Kaiser Normalization, with rotation converging in five iterations

Table 5 Perceived fear of crime by lighting environment (time of day)

Time of day	Lighting environment			FSV***				FOV***				N
	Set natural illuminance (lx)*	Set streetlamp illuminance (lx)**	Building interior lighting**	Mean	S.D	Max	Min	Mean	S.D	Max	Min	
18:00	59,321		All off	1.328	0.740	5	1	1.541	0.916	5	1	61
19:00	19,549		All off	1.706	0.935	5	1	1.961	1.171	5	1	51
19:30	400		All off	2.256	1.235	5	1	2.667	1.365	5	1	39
20:00	20	30	All off	1.800	0.959	5	1	2.140	1.020	5	1	50
20:30	10	30	Randomly 1/10 on	2.720	1.372	6	1	3.180	1.728	7	1	50
21:00	1	30	Randomly 1/2 on	2.128	1.282	5	1	2.638	1.245	7	1	47
21:30	0.5	30	All on	2.083	1.152	7	1	2.500	1.291	7	1	48
22:30	0.2	30	Randomly 1/3 on	2.611	1.353	6	1	3.000	1.401	7	1	54
Total				2.058	1.224	7	1	2.45	1.385	7	1	400

Note: FSV = fear of self-victimization; FOV = fear of others' victimization; S.D. = standard deviation

*Estimation from solar altitude and azimuth

**Assumptions in this study for real-world replication

***7-point Likert scale (1 = not fearful at all, 7 = very fearful)

both models (FSV and FOV) were not significant ($p > 0.05$), indicating a good fit. The Pseudo R-Square values (approximately, 0.1–0.3) also suggest that both models had a moderate level of explanatory power. Lastly, the non-significant result of the Test of Parallel Lines for the FOV model ($p > 0.05$) indicates that the proportional odds assumption holds. In contrast, the significant result of the Test of Parallel Lines for the FSV model ($p < 0.05$) means that the slope coefficients are not the same across response categories. However, this does not imply that the analysis results are not statistically significant since it is possible to have slope coefficients that do not intersect, even if the slopes for each category are not parallel (Lee et al. 2005).

The results showed that the natural illuminance level was negatively associated with both FSV and FOV, as was the streetlamp on/off variable. This result supports the need for nighttime streetlamps and reinforces the descriptive statistics showing that FSV and FOV were lower at 8 p.m., when streetlamps were on, than at 7:30 p.m. Additionally, the higher the building interior light-on ratio, the lower the

Table 6 Ordinal logistic regression analysis results

Variable	FSV		FOV	
	Estimate	Sig	Estimate	Sig
Test variable (lighting environment)				
ln (natural illuminance)	-0.299	0.000**	-0.316	0.000**
Streetlamp on/off (on = 1)	-1.065	0.031*	-1.172	0.016*
Building interior lights-on ratio	-1.181	0.004**	-1.192	0.002**
Control variable				
Age	-0.075	0.087	-0.066	0.111
Gender (male = 1)	-0.172	0.596	-0.126	0.692
Educational attainment (postgraduate or higher = 1)	-0.868	0.008**	-0.079	0.793
Occupation (have = 1)	-0.367	0.349	-0.554	0.139
Residential type (apartment = 1)	0.073	0.759	-0.346	0.137
Self-perceived household income level (5 pt. scale)	-0.214	0.128	-0.005	0.968
Household size (1 person = 1)	-0.063	0.788	-0.532	0.018*
1-week narrow street walk (5–7 days = 1)	-0.455	0.048*	-0.218	0.325
Average returning home time (after 22:00 = 1)	0.165	0.459	-0.066	0.755
In/direct experience of crime victimization (yes = 1)	0.909	0.001**	0.666	0.016*
Crime vulnerability	-0.185	0.167	-0.518	0.000**
Height	-0.022	0.290	0.009	0.671
Wearing glasses	-0.147	0.580	0.782	0.002**
Self-reported average visual acuity of both eyes	0.248	0.250	0.360	0.084
Previous VR experience (yes = 1)	0.332	0.189	-0.342	0.150
Survey assistant (A = 1)	-0.350	0.098	0.188	0.358
Factor 1 (sense of presence/immersion)	-0.126	0.225	-0.003	0.973
Factor 2 (adverse physiological reactions)	0.401	0.000**	0.501	0.000**
Factor 3 (ecological validity)	-0.092	0.392	-0.179	0.085
Order of presentation	-0.111	0.196	-0.100	0.225
Intercept 1	-9.174	0.010	-3.801	0.269
Intercept 2	-7.696	0.030	-2.260	0.510
Intercept 3	-6.487	0.068	-1.023	0.766
Intercept 4	-5.601	0.115	-0.105	0.976
Intercept 5	-3.901	0.275	1.325	0.700
Intercept 6	-2.269	0.538	1.813	0.599
Model Fit Information				
-2Log L (0), -2Log L (β)	1,119.773	1,005.818	1,257.967	1,133.307
χ^2	113.155		124.660	
Sig	0.000		0.000	
Goodness-of-Fit Tests				
Sig. (Pearson)	1.000		0.296	
Sig. (Deviance)	1.000		1.000	
Test of parallel lines				
Sig	0.000		1.000	
Pseudo R-square				
Cox and Snell	0.246		0.268	
Nagelkerke	0.262		0.280	
McFadden	0.101		0.099	

Note: FSV = fear of self-victimization; FOV = fear of others' victimization

*$p < 0.05$, **$p < 0.01$, N = 400

FSV and FOV. This finding suggests that fear of crime can be reduced not just by natural light but also by different types of urban lighting. The following subsection further discusses the complex effects of these various light sources.

Other control variables also showed meaningful relationships with the fear of crime. People with more than a graduate degree had a lower FSV. The FOV was lower for those who lived alone. Unlike previous studies (Boyce 2019; Son et al. 2023), gender did not affect fear of crime. People who had been on a narrow street in the past week (5–7 days) had a lower FSV, indicating that participants familiar with the simulated environment—low-rise residential neighborhoods—may experience decreased fear of crime. Participants who were victims or knew victims had a higher fear of crime, consistent with previous studies (Farrall et al. 2007; Kanan and Pruitt 2002; Mesch 2000; Son et al. 2023).

Finally, in all models, participants who felt a strong adverse physiological reaction had a higher fear of crime. This may stem from existing concerns about underlying conditions or their physical or mental states; however, further research on this matter is required.

5 Discussion

This study makes a significant contribution to the existing body of literature. Using SVR experiments, this study demonstrated that higher light levels are associated with lower fear of crime, supporting evidence from previous on-site studies (Ceccato and Nalla 2020; Cho et al. 2019; Fisher and Nasar 1992; Painter 1996). In addition, the SVR experiments allowed us to successfully isolate and examine the effects of various light sources encountered in urban environments, which had been rarely verified in previous studies. Previous studies have mainly focused on lighting characteristics and outcomes (color, temperature, illuminance value, and uniformity ratio of illuminance) and lacked consideration of contextual factors, such as the lighting from streetlamps and surrounding buildings over time (Abd-Alhamid et al. 2019; Chen et al. 2019; Heydarian et al. 2015; Nasar and Bokharaei 2017; Son et al. 2023).

According to our analysis, the effects of various lighting sources on the fear of crime are multifaceted (Table 7 and Fig. 5). The type of lighting that primarily contributes to reducing the fear of crime varies depending on the time of day. In general, as natural illuminance decreases, the fear of crime increases, particularly becoming more pronounced after sunset when darkness falls rapidly. However, the contribution of natural illuminance to the fear of crime diminishes as the night progresses, gradually being replaced by artificial lighting. Despite the continuous decline in natural illuminance, the fear of crime did not correspondingly increase throughout the night.

Notably, there are two periods where the fear of crime decreases after sunset (8:00 p.m. and between 9:00 p.m. and 9:30 p.m.). The first decrease occurs immediately after the streetlamps are turned on at 8:00 p.m. During this period, even though natural illuminance drops significantly from 400 to 20 lx, the fear of crime decreases, indicating the dominant influence of streetlamp over natural illuminance. Subsequently, as natural illuminance falls below the maximum nighttime illuminance standard for residential areas (10 lx), there is a sharp increase in the fear of crime around 8:30 p.m.

The second decrease in the fear of crime is observed when interior building lights are turned on. From 8:30 p.m. to 10:30 p.m., the fear of crime inversely correlates with the proportion of interior building lights that are on. During this timeframe, with limited natural illuminance and lighted streetlamps, the influence of interior building lighting becomes predominant. The interior lighting not only enhances overall street brightness but also signals human presence, suggesting potential assistance nearby. This concept aligns with the 'eyes on the street' theory, bolstering psychological security (Jacobs 1961; Park and Garcia 2020; Zhu et al. 2023). This psychological effect may have played a larger role because the VR settings did not authentically simulate the presence of passersby on the street.

In Son et al.'s (2023) RVR study, the fear of criminal victimization exhibited a similar pattern, with increases and decreases in illuminance corresponding to specific times of the day, corroborating the findings of this study (Table 7 and Fig. 5). After sunset, the fear of crime increased sharply due to the rapid decline in illuminance, but after 8:00 p.m., with the stabilization of illuminance levels due to streetlights, interior lights, and neon signs maintaining a certain level of illuminance (5 lx), the fear of crime did not significantly

Table 7 Comparison of two virtual reality studies: changes in fear of crime victimization by lighting environments over time

Time of day	Lighting environment					Fear of crime			
	SVR (current study)			RVR (Son et al. 2023)		SVR (current study)		RVR (Son et al. 2023)	
	Set natural illuminance (lx)	Set streetlamp illuminance (lx)	Building interior lighting	Measured vertical mean illuminance (lx)	Measured horizontal mean illuminance (lx)	FSV	FOV	FSV	FOV
18:00	59,321		All off	1905.22	3107.11	1.33	1.54	1.23	1.35
19:00	19,549		All off	285.02	584.44	1.71	1.96	1.38	1.42
19:30	400		All off	9.70	17.55	2.26	2.67	3.24	3.88
20:00	20	30	All off	4.57	4.75	1.80	2.14	3.32	3.76
20:30	10	30	Randomly 1/10 on	4.54	4.63	2.72	3.18	3.80	4.52
21:00	1	30	Randomly 1/2 on	4.57	4.60	2.13	2.64	4.04	4.69
21:30	0.5	30	All on			2.08	2.50		
22:30	0.2	30	Randomly 1/3 on	4.47	4.75	2.61	3.00	3.00	3.64

Note: FSV = fear of self-victimization; FOV = fear of others' victimization

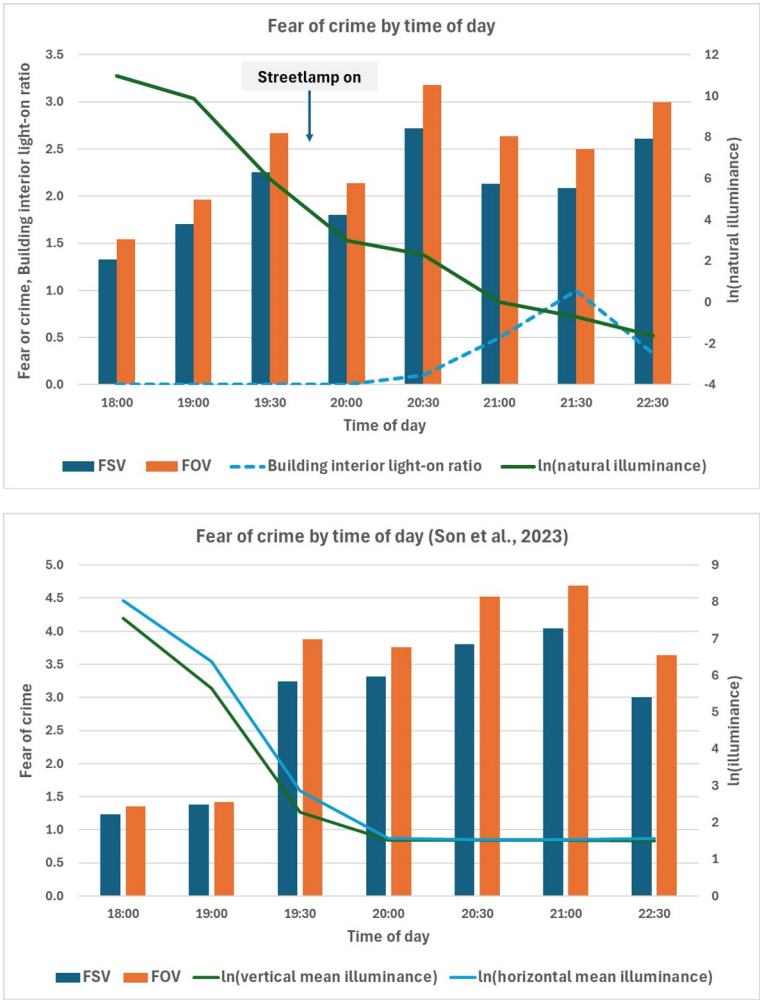

Fig. 5 Comparison of Fear of crime by time (top: current study, bottom: Son et al. 2023)

increase and even slightly decreased. Son et al. (2023) presumed that the temporary decrease in fear of crime after 9 p.m. was due to the surrounding buildings' interior lights and neon signs. This study validated that presumption by examining specific factors in the simulated environment, such as different levels of lights on/off at various times.

This study has some limitations. First, all simulated virtual environments, including our own, cannot perfectly replicate the exact conditions of their real-world counterparts. In particular, the natural illuminance values we set using Unity`s LightMap tool in the virtual environment differ in measurement principle from those measured in the actual reference street, making it challenging to completely reproduce an identical lighting environment. However, technological advancements will reduce the disparities between VR environments and real settings (Son et al. 2023). For instance, future research could address this issue by utilizing DIALux lighting design software to directly measure illuminance in SVR and test various lighting scenarios with different types of illuminances (Sun et al. 2020). Other platforms, such as Unreal Engine or Radiance, could also be considered for creating virtual environments with more realistic lighting simulations. In addition, it is worth noting that despite the limitation, the sense of presence survey results (higher sense of physical space, engagement, and ecological validity scores and lower negative effect score) for virtual environments in this study were quite higher than those of previous RVR studies, which are generally known to show higher realism (Appendixes B and C).

Second, this study employed a mixed locomotion approach (both room-scale walking and teleportation) due to the physical constraints of the VR lab. This may have disrupted participants' consistent experiences of the environment. Future research could explore the use of larger indoor spaces or an infinite walking simulator to achieve more realistic walking experiences within virtual environments.

Another limitation of this study is its limited generalizability. This study exclusively recruited healthy participants in their 20 s and 30 s. VR experiments can induce symptoms like dizziness and headaches, known as VR sickness, thereby restricting recruitment to younger, healthy individuals. Consequently, the findings may not generalize to broader

populations. Moreover, as the study focused on a representative residential street in Seoul, Korea, results could vary in areas with different spatial characteristics. Future studies should consider diverse spatial contexts and population groups to enhance the applicability of their findings.

6 Conclusions

Whereas previous studies have predominantly focused on the impact of combined illuminance from all light sources on fear of crime, this study employed SVR experiments to explore the nuanced effects of diverse lighting sources. The findings revealed that fear of crime is influenced not only by natural light but also by artificial lights, encompassing streetlamps and interior building lighting. Specifically, while a decrease in natural illuminance contributes to an increase in fear of crime in general (especially shortly after sunset), the role of natural illuminance was minimized immediately after streetlamp activation. After p.m. 8:30, when natural light diminishes and streetlamps remain lit, fear of crime was significantly influenced by the proportion of interior building lights turned on, validating the hypothesis proposed by Son et al. (2023). Certainly, public regulation of interior building lighting is not feasible, and we acknowledge that the effects of such lighting extend beyond mere brightness to encompass psychological comfort and security. Nonetheless, understanding how each lighting source affects pedestrian perceptions of fear of crime is crucial for enhancing safety in public spaces. The insights from this study can inform the design of optimal lighting environments aimed at reducing fear of crime in narrow residential streets. It is essential to comprehensively consider the lighting environment of the surrounding space rather than solely focusing on improving illuminance levels to mitigate fear of crime.

This study highlights the potential of SVR experiments in evaluating specific factors under controlled conditions, suggesting their broader application in future crime prevention studies. Rapid advancements in VR technology can address various technical issues discussed above through follow-up studies. Subsequent research endeavors will be able to conduct experiments within more authentic VR environments, incorporating various lighting sources and the presence of people on the streets and inside buildings. VR technologies can also be effectively leveraged for assessing physiological factors such as electroencephalography, eye movements, and heart-rate data, particularly in relation to variations in lighting environments. Given that both mental and physical states significantly influence individuals' fear of crime, future research must holistically consider individual characteristics. Furthermore, recruiting a more diverse cohort of participants will enhance the generalizability of findings.

Appendix

Appendix A

Virtual environment simulation protocols

Basic information

- Simulation engine: Unity 2020.3.x
- Rendering pipeline: Unity HDRP (High Definition Render Pipeline)
- All simulated environments were designed and developed by Rising Craft Studio.

Street and surrounding building setting

- Reference street: 43 Sangdoro 45-gil – a typical narrow street in a densely populated, low-rise residential area in Seoul, South Korea.
- Street: 50 m long and 6 m wide, without a sidewalk.
- Building type: Walk-up apartments or single-family houses, which are typical residential types in low-rise residential areas in Seoul.
- Front façade width of each building: 10 m

Lighting environment setting

- Natural illuminance by time: See Table 1

Reference illuminance level from natural sources in different conditions (Source: https://docs.unity3d.com/Packages/com.unity.render-pipelines.high-definition@14.0/manual/Physical-Light-Units.html):

Illuminance (lx)	Natural light level
120,000	Very bright sunlight
110,000	Bright sunlight
20,000	Blue sky at midday
1,000 – 2,000	Overcast sky at midday
< 1	Moonlight with a clear night sky
0.002	Starry night without moonlight

- Sun and Moon
  - Rendering pipeline: Physically Based Sky
  - Sun: Surface color – FFAB25, luminescent color – FFC996
  - Moon: Surface color – FFFFFF (white), luminescent color – CEECFF

- Azimuth, altitude, and right ascension: Refer to Korea Astronomy and Space Science Institute (see Table 1).
- Assumed that the Sun and Moon emitted equal amounts of light on all visible sides.

- Streetlamp
  - Set illuminance: 30 lx
  - Emitter Vertical Angle: 78 degrees or less
  - Surface and luminescent color: White
- Building interior lighting
  - Employed self-luminous (emission) textures (unable to set specific illuminance level)
- For optimization, all objects except the Sun and Moon were baked with LightMap, and real-time illuminance changes were not considered.

Appendix B

Results of the sense of presence questionnaire

Item	Frequency of response					Mean	S.D
	1	2	3	4	5		
Sense of physical space						3.95	
I had a sense of being in the scenes displayed	1	1	14	52	32	4.13	0.76
I felt I was visiting the places in the displayed environment	0	3	15	48	34	4.13	0.77
I felt that the characters and/or objects could almost touch me	3	12	32	29	24	3.59	1.07
Engagement						4.20	
I felt involved in the displayed environment	0	0	5	53	42	4.37	0.58
I enjoyed myself	0	2	4	36	58	4.50	0.67
My experience was intense	1	5	30	49	15	3.72	0.82
Ecological validity						4.29	
The content seemed believable to me	0	0	9	39	52	4.43	0.66
The displayed environment seemed natural	0	3	12	39	46	4.28	0.79
I had a strong sense that the characters and objects were solid	0	6	13	40	41	4.16	0.87
Negative effects						1.46	
I felt dizzy	68	19	4	7	2	1.56	1.00
I felt nauseous	84	7	5	3	1	1.30	0.78
I felt I had a headache	81	11	4	4	0	1.31	0.73
I had eyestrain	63	17	14	4	2	1.65	1.00

Source: Lessiter et al. (2001, p. 290)

S.D. = standard deviation

Number of observations = 100

Appendix C

Comparison of 'sense of presence' scores between the current study and other virtual reality studies.

	Simulated VR		Recorded VR	
	Current study	Yan et al. (2020)	Pieri et al. (2022)	Son et al. (2023)
Sense of physical space	4.0	3.8	3.1	3.8
Engagement	4.2	4.0	3.4	4.1
Ecological validity	4.3	3.4	4.0	4.5
Negative effect	1.5	2.3	1.4	1.6

Acknowledgements This work was supported by the Architecture and Urban Research Institute, and was developed based on a research project titled "A Study on Crime Prevention Through Environmental Design (CPTED) Factors Utilizing Virtual Environments.". This research was also supported by the Chung-Ang University Research Scholarship Grants in 2023 and the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology [NRF-2021R1C1C1013336].

Author contributions Dongpil Son: Conceptualization; Funding acquisition; Project administration; Writing—original draft; Writing—review & editing. Boyeong Im: Conceptualization; Writing—original draft; Writing—review & editing. Jaeseok Her: Formal analysis; Writing—original draft; Writing—review & editing. Woojin Park: Data curation; Formal analysis; Investigation; Writing—review & editing. Seok-Jin Kang: Conceptualization; Supervision; Validation; Writing—review & editing; Seung-Nam Kim: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Software; Supervision; Validation; Writing—original draft; Writing—review & editing.

Data availability The datasets generated during and/or analyzed during the current study are available in the OPENICPSR repository, https://www.openicpsr.org/openicpsr/192485/Research-2-1-Upload.sav.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval All the research procedures were approved by the Chung-Ang University Institutional Review Board (approval number: 1041078-202203-HR-092).

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License,

which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

References

Abd-Alhamid F, Kent M, Bennett C, Calautit J, Wu Y (2019) Developing an innovative method for visual perception evaluation in a physical-based virtual environment. Build Environ 162:106278. https://doi.org/10.1016/j.buildenv.2019.106278

Appleton J (1975) The experience of landscape. Wiley, London

Boomsma C, Steg L (2014) The effect of information and values on acceptability of reduced street lighting. J Environ Psychol 39:22–31. https://doi.org/10.1016/j.jenvp.2013.11.004

Boyce PR (2019) The benefits of light at night. Build Environ 151:356–367. https://doi.org/10.1016/j.buildenv.2019.01.020

Boyce PR, Eklund NH, Hamilton BJ, Bruno LD (2000) Perceptions of safety at night in different lighting conditions. Light Res Technol 32:79–91. https://doi.org/10.1177/096032710003200205

Ceccato V, Nalla MK (2020) Crime and fear in public places: towards safe, inclusive and sustainable cities. CrimRxiv. https://doi.org/10.21428/cb6ab371.4aca704d

Chalfin A, Hansen B, Lerner J, Parker L (2022) Reducing crime through environmental design: evidence from a randomized experiment of street lighting in New York City. J Quant Criminol 38:127–157. https://doi.org/10.1007/s10940-020-09490-6

Chen Y, Cui Z, Hao L (2019) Virtual reality in lighting research: Comparing physical and virtual lighting environments. Light Res Technol 51:820–837. https://doi.org/10.1177/1477153518825387

Cheon S, Kim JA (2020) Quantifying the influence of urban sources on night light emissions. Landsc Urban Plan 204:103936. https://doi.org/10.1016/j.landurbplan.2020.103936

Cho Y, Jeong H, Choi A, Sung M (2019) Design of a connected security lighting system for pedestrian safety in smart cities. Sustainability 11:1308. https://doi.org/10.3390/su11051308

Falchi F, Cinzano P, Elvidge CD, Keith DM, Haim A (2011) Limiting the impact of light pollution on human health, environment and stellar visibility. J Environ Manage 92:2714–2722. https://doi.org/10.1016/j.jenvman.2011.06.029

Farrall S, Gray E, Jackson J (2007) Theorising the fear of crime: The cultural and social significance of insecurities about crime. Experience and expression in the fear of crime working paper No.5. Available at https://ssrn.com/abstract=1012393

Ferraro KF (1996) Women's fear of victimization: Shadow of sexual assault? Soc Forces 75:667–690. https://doi.org/10.2307/2580418

Ferraro KF, Grange RL (1987) The measurement of fear of crime. Sociol Inq 57:70–97. https://doi.org/10.1111/j.1475-682X.1987.tb01181.x

Fisher BS, Nasar JL (1992) Fear of crime in relation to three exterior site features: prospect, refuge, and escape. Environ Behav 24:35–65. https://doi.org/10.1177/0013916592241002

Fotios S, Monteiro AL, Uttley J (2019) Evaluation of pedestrian reassurance gained by higher illuminances in residential streets using the day–dark approach. Light Res Technol 51:557–575. https://doi.org/10.1177/1477153518775464

Fox KA, Nobles MR, Piquero AR (2009) Gender, crime victimization and fear of crime. Secur J 22:24–39. https://doi.org/10.1057/sj.2008.13

Gibson CL, Zhao J, Lovrich NP, Gaffney MJ (2002) Social integration, individual perceptions of collective efficacy, and fear of crime in three cities. Justice Q 19:537–564. https://doi.org/10.1080/07418820200095341

Hanyu K (1997) Visual properties and affective appraisals in residential areas after dark. J Environ Psychol 17:301–315. https://doi.org/10.1006/jevp.1997.0067

Hanyu K (2000) Visual properties and affective appraisals in residential areas in daylight. J Environ Psychol 20:273–284. https://doi.org/10.1006/jevp.1999.0163

Heydarian A, Carneiro JP, Gerber D, Becerik-Gerber B, Hayes T, Wood W (2014) Immersive virtual environments: experiments on impacting design and human building interaction. In. CAADRIA Proceedings. In: Proceedings of the 19th international conference on computer-aided architectural design research in Asia (CAADRIA), (729–738). https://doi.org/10.52842/conf.caadria.2014.729

Heydarian A, Carneiro JP, Gerber D, Becerik-Gerber B, Hayes T, Wood W (2015) Immersive virtual environments versus physical built environments: a benchmarking study for building design and user-built environment explorations. Autom Constr 54:116–126. https://doi.org/10.1016/j.autcon.2015.03.020

Hong T, Lee M, Yeom S, Jeong K (2019) Occupant responses on satisfaction with window size in physical and virtual built environments. Build Environ 166:106409. https://doi.org/10.1016/j.buildenv.2019.106409

Jacobs J (1961) The death and life of great American cities. Random House, New York

Jeffery C (1971) Crime prevention through environmental design. Am Behav Sci 14(4):598–598. https://doi.org/10.1177/000276427101400409

Kanan JW, Pruitt MV (2002) Modeling fear of crime and perceived victimization risk: the (in) significance of neighborhood integration. Sociol Inq 72:527–548. https://doi.org/10.1111/1475-682X.00033

Kim D, Park S (2017) Improving community street lighting using CPTED: a case study of three communities in Korea. Sustain Cities Soc 28:233–241. https://doi.org/10.1016/j.scs.2016.09.016

Kim J, Kim S (2019) Finding the optimal D/H ratio for an enclosed urban square: testing an urban design principle using immersive virtual reality simulation techniques. Int J Environ Res Public Health 16:865. https://doi.org/10.3390/ijerph16050865

Kim SN, Lee H (2022) Capturing reality: validation of omnidirectional video-based immersive virtual reality as a streetscape quality auditing method. Landsc Urban Plan 218:104290. https://doi.org/10.1016/j.landurbplan.2021.104290

Korea Astronomy and Space Science Institute (2023) Calculate solar altitude and azimuth. https://astro.kasi.re.kr/life/pageView/10. Accessed 12 November 2023

Korea Ministry of Government Legislation (2020) Enforcement rule of the act on the prevention of light pollution due to artificial lighting. https://law.go.kr/lsInfoP.do?lsiSeq=218439&lsId=011759&chrClsCd=010202&urlMode=lsInfoP&viewCls=lsInfoP&efYd=20200527&vSct=%EB%B9%9B%EA%B3%B5%ED%95%B4%EB%B0%A9%EC%A7%80&ancYnChk=0#0000. Accessed 11 November 2023

Lavoie R, Main K, King C, King D (2021) Virtual experience, real consequences: the potential negative emotional consequences of virtual reality gameplay. Virtual Real 25:69–81. https://doi.org/10.1007/s10055-020-00440-y

Lee H, Kim SN (2021) Perceived safety and pedestrian performance in pedestrian priority streets (PPSs) in Seoul, Korea: a virtual reality experiment and trace mapping. Int J Environ Res Public Health 18:2501. https://doi.org/10.3390/ijerph18052501

Lee JH, Lee Y (2021) The effectiveness of virtual reality simulation on the qualitative analysis of lighting design. J Digit Landsc Archit 6:195–202

Lee S, Min S, Park J, Yoon S (2005) The Practice on Logit and Probit Model. Pakyoungsa, Seoul

Lessiter J, Freeman J, Keogh E, Davidoff J (2001) A cross-media presence questionnaire: the ITC-Sense of Presence Inventory. Presence 10:282–297. https://doi.org/10.1162/105474601300343612

Liu M, Liu X, Zhang B, Li Y, Luo T, Liu Q (2022) Analysis of the evolution of urban nighttime light environment based on time series. Sustain Cities Soc 78:103660. https://doi.org/10.1016/j.scs.2021.103660

Loewen LJ, Steel GD, Suedfeld P (1993) Perceived safety from crime in the urban environment. J Environ Psychol 13:323–331. https://doi.org/10.1016/S0272-4944(05)80254-3

Mander S, Alam F, Lovreglio R, Ooi M (2023) How to measure light pollution-a systematic review of methods and applications. Sustain Cities Soc. https://doi.org/10.1016/j.scs.2023.104465

Mesch GS (2000) Perceptions of risk, lifestyle activities, and fear of crime. Deviant Behav 21:47–62. https://doi.org/10.1080/016396200266379

Mouratidis K, Hassan R (2020) Contemporary versus traditional styles in architecture and public space A virtual reality study with 360-degree videos. Cities 97:102499. https://doi.org/10.1016/j.cities.2019.102499

Nasar JL, Bokharaei S (2017) Impressions of lighting in public squares after dark. Environ Behavior 49:227–254. https://doi.org/10.1177/0013916515626546

Newman O (1972) Defensible space: people and design in the violent city. Macmillan, New York

Painter K (1996) The influence of street lighting improvements on crime, fear and pedestrian street use, after dark. Landsc Urban Plan 35:193–201. https://doi.org/10.1016/0169-2046(96)00311-8

Painter K, Farrington DP (1997) The crime reducing effect of improved street lighting: the Dudley project. Situat Crime Prev Success Case Stud 2:209–226

Peña-García A, Hurtado A, Aguilar-Luzón MC (2015) Impact of public lighting on pedestrians' perception of safety and well-being. Safety Sci 78:142–148. https://doi.org/10.1016/j.ssci.2015.04.009

Pieri L, Serino S, Cipresso P, Mancuso V, Riva G, Pedroli E (2022) The ObReco-360°: a new ecological tool to memory assessment using 360° immersive technology. Virtual Real 26:639–648. https://doi.org/10.1007/s10055-021-00526-1

Schneider S, Bengler K (2020) Virtually the same? Analysing pedestrian behaviour by means of virtual reality. Transp Res Part F 68:231–256. https://doi.org/10.1016/j.trf.2019.11.005

Schwebel DC, Combs T, Rodriguez D, Severson J, Sisiopiku V (2016) Community-based pedestrian safety training in virtual reality: a pragmatic trial. Accid Anal Prev 86:9–15. https://doi.org/10.1016/j.aap.2015.10.002

Son D, Hyeon T, Park Y, Kim SN (2023) Analysis of the relationship between nighttime illuminance and fear of crime using a quasi-controlled experiment with recorded virtual reality. Cities 134:104184. https://doi.org/10.1016/j.cities.2022.104184

Statistics Korea (2022) Safety levels of walking at night and reasons to fear walking at night. https://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1SSSA132R&vw_cd=MT_OTITLE&list_id=101_MT_CTITLE_gK&scrId=&seqNo=&lang_mode=ko&obj_var_id=&itm_id=&conn_path=MT_OTITLE&path=%252FstatisticsList%252FstatisticsListIndex.do. Accessed 10 November 2023

Sun Y, Liu X, Qu W, Cao G, Zou N (2020) Analysis of daylight glare and optimal lighting design for comfortable office lighting. Optik 206:164291. https://doi.org/10.1016/j.ijleo.2020.164291

Svechkina A, Trop T, Portnov BA (2020) How much lighting is required to feel safe when walking through the streets at night? Sustainability 12(8):3133. https://doi.org/10.3390/su12083133

van Gelder JL, De Vries RE, Demetriou A, Van Sintemaartensdijk I, Donker T (2019) The virtual reality scenario method: Moving from imagination to immersion in criminal decision-making research. J Res Crime Delinq 56:451–480. https://doi.org/10.1177/0022427818819696

van Rijswijk L, Haans A (2018) Illuminating for safety: investigating the role of lighting appraisals on the perception of safety in the urban environment. Environ Behav 50:889–912. https://doi.org/10.1177/0013916517718888

Warr M (1984) Fear of victimization: Why are women and the elderly more afraid? Soc Sci Q 65:681

Warr M, Ellison CG (2000) Rethinking social reactions to crime: personal and altruistic fear in family households. Am J Soc 106:551–578. https://doi.org/10.1086/318964

Wu P, Xu W, Yao Q, Yuan Q, Chen S, Shen Y, Cheng W, Zhang Y (2023) Spectral-level assessment of light pollution from urban façade lighting. Sustain Cities Soc 98:104827. https://doi.org/10.1016/j.scs.2023.104827

Xu Y, Fu C, Kennedy E, Jiang S, Owusu-Agyemang S (2018) The impact of street lights on spatial-temporal patterns of crime in Detroit, Michigan. Cities 79:45–52. https://doi.org/10.1016/j.cities.2018.02.021

Yan B, Ni S, Wang X, Liu J, Zhang Q, Peng K (2020) Using virtual reality to validate the (Chinese version) of the independent television commission-sense of presence inventory. SAGE Open 10:2158244020922878

Yin PP (1980) Fear of crime among the elderly: Some issues and suggestions. Soc Prob 27:492–504. https://doi.org/10.1525/sp.1980.27.4.03a00130

Park Y, Garcia M (2020) Pedestrian safety perception and urban street settings. Int J Sustain Transp 14(11):860–871. https://doi.org/10.1080/15568318.2019.1641577

Zhang J, Dai W (2021) Research on night light comfort of pedestrian space in urban park. Comput Math Methods Med 2021:3130747. https://doi.org/10.1155/2021/3130747

Zhu M, Teng R, Wang C, Wang Y, He J, Yu F (2023) Key environmental factors affecting perceptions of security of night-time walking in neighbourhood streets: a discussion based on fear heat maps. J Transp Health 32:101636. https://doi.org/10.1016/j.jth.2023.101636

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.