Virtual Reality (2025) 29:145
https://doi.org/10.1007/s10055-025-01211-3

ORIGINAL ARTICLE

# Fear of crime revisited: analyzing the effects of urban nighttime illuminance on neural and psychological responses using recorded virtual environments and electroencephalogram data

**Woojin Park[1] · Dongpil Son[2] · Boyeong Im[2] · Jaeseok Her[2] · Young-Jae Kim[1] · Seung-Nam Kim[1]**

Received: 21 March 2025 / Accepted: 4 August 2025
© The Author(s) 2025

**Abstract**

This study employed virtual reality (VR) and electroencephalogram (EEG) techniques to investigate the relationship between nighttime illuminance, neural responses, and fear of crime. Illuminance was measured at 13 discrete time points across four narrow streets in Seoul, followed by 360-degree video capture. A total of 95 participants viewed 10 randomly selected videos depicting 40 distinct lighting scenarios via head-mounted displays while their brain activity was continuously recorded as they reported their perceived fear of crime. A cross-classified multilevel analysis revealed that higher illuminance was associated with lower fear of crime and more positive emotional states. Furthermore, the findings indicated that the lower reported fear of crime among male participants may be influenced by both social desirability bias and inherent neurophysiological differences in emotional responses to fear-inducing environments. This study also demonstrated that participants' perceived immersion in the VR environment amplified both psychological and emotional reactions, demonstrating the effectiveness of VR in assessing environmental factors. By integrating subjective perceptions with objective neurophysiological data, this research highlights the potential of VR and EEG as effective tools for urban designers and landscape architects to evaluate the impact of lightning on public spaces. These findings contribute to the development of safer and more emotionally supportive public environments.

**Keywords** Urban safety · Fear of crime · Virtual reality · Illuminance · Electroencephalogram

## 1 Introduction

According to Maslow's hierarchy of needs (Maslow 1943), the need for safety represents a fundamental human requirement, ranking second only to physiological needs. The concept of safety encompasses the fundamental human desire to protect oneself and one's family from potential disasters, accidents, and crimes. Among these, ensuring safety from crime represents a critical public service that urban governments are obliged to provide. Consequently, those responsible for urban policy, planning and design are committed to creating public spaces that are not only physically secure but also psychologically and emotionally supportive. While ensuring actual safety through environmental design is of paramount importance, enhancing perceived safety, such as reducing fear of crime, is equally crucial for safeguarding individuals' psychological, emotional, and perceived well-being (Boomsma and Steg 2014a). This is because perceived safety and fear of crime levels exert a direct influence

✉ Seung-Nam Kim
snkim@cau.ac.kr

Woojin Park
wjpark7@cau.ac.kr

Dongpil Son
dpson@auri.re.kr

Boyeong Im
byim@auri.re.kr

Jaeseok Her
jsher@auri.re.kr

Young-Jae Kim
jya1205@cau.ac.kr

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

[2] Architecture and Urban Research Institute, Sejong, South Korea

Published online: 03 September 2025

on people's stress levels, social interactions, and nighttime activities (Evans and Fletcher 2000; Wu 2014).

As urban areas evolve and economic and industrial activities expand, the necessity for safe and vibrant nighttime environments has become increasingly critical. In response to this, urban lighting has emerged as a crucial tool for supporting nighttime activities and reducing fear of crime (Hu et al. 2020). According to Appleton's prospect-refuge theory (Appleton 1975), people perceive greater safety in environments where potential victims can easily identify threats, while potential offenders have fewer places to hide. This theory suggests that brighter environments can effectively reduce fear of crime, aligning with the longstanding recognition of lighting as a fundamental element in mitigating crime-related fears (Boyce et al. 2000).

The research examining the impact of illuminance—or lighting—on fear of crime—or perceived safety—can be broadly categorized into field-based and lab-based studies. However, each of these approaches has its own inherent constraints. Field experiments have generally demonstrated that improved lighting can enhance perceived safety; however, they have struggled to isolate the specific effects of lighting due to the influence of uncontrollable external factors (Atkins et al. 1991; Castro-Toledo et al. 2017; Haans and de Kort 2012; Kim and Noh 2018; Mattoni et al. 2017; Painter 1996). Conversely, lab-based studies utilizing photographs or visual simulation techniques have partially addressed these constraints, demonstrating that brighter lighting conditions enhance perceptions of visibility and safety (Boomsma and Steg 2014a, b; Nasar and Bokharaei 2017; van Rijswijk and Haans 2018). However, the virtual or static visual materials utilized in these studies often fail to fully replicate the dynamic sense of presence and immersive realism of real-world environments, thereby limiting the ecological validity and methodological robustness of their findings (Kim and Lee 2022; Mouratidis and Hassan 2020). Moreover, these studies have relied heavily on subjective responses, which may be susceptible to influence by individual experiences and gender differences (Quann and Hung 2002; Sutton and Farrall 2005).

To address these considerations, recent research has increasingly employed objective methods, such as electroencephalogram (EEG) assessments, to capture emotional states with greater accuracy (Martínez-Tejada et al. 2021). These methods provide a more reliable measure of fear of crime, reducing the biases associated with self-report surveys (Olszewska-Guizzoet al. 2020). EEG techniques enable the precise measurement of neurophysiological responses to built environments (Son et al. 2023), offering a way to mitigate the constraints of subjective data. Against this backdrop, this study employed recorded virtual reality (VR) technology and EEG equipment to examine the relationship between nighttime illuminance, objectively measured neurophysiological responses (valence), and self-reported psychological responses (fear of crime) on four narrow streets in Seoul, South Korea. By integrating EEG measurements, this study seeks to offer a deeper understanding of how lighting influences both psychological and neurophysiological reactions, ultimately contributing to advancements in urban design and public safety research.

## 2 Literature review

### 2.1 Definition and determinants of fear of crime

The concept of fear of crime is inherently ambiguous and therefore has been defined in various ways by scholars. For instance, Yin (1980, p. 496) described it as "the perception and fear of the possibility of victimization," whereas Conklin (1975, p. 7) defined it as "the fear of strangers who may harm ordinary citizens in everyday life." Baumer (1985, p.239) viewed fear of crime as "people's rational response to crime victimization." Expanding on this, Warr (2000) contended that fear of crime extends beyond mere environmental perception, emphasizing the emotional reactions elicited by such perceptions. Ferraro and Grange (1987) further refined the typologies of fear of crime proposed by various scholars, categorizing them into two types of subjects: personal fear—fear for oneself—and general fear—fear for others.

Building on these definitions, previous research has identified personal victimization experiences, social control, and environmental factors as key influences on fear of crime. These findings have contributed to the development of several theoretical frameworks, including vulnerability theory (Quann and Hung 2002; Skogan 1986), collective efficacy theory (Sampson et al. 1997; Shaw and McKay 1942), and theories highlighting the role of the physical environment in shaping such fear of crime (Jacobs 1961; Jeffery 1971; Newman 1972). A substantial body of literature underscores that both direct and indirect experiences of crime victimization are primary determinants of fear of crime and perceived safety (Quann and Hung 2002; Skogan 1986). This emphasis on victimization has contributed to the development of the vulnerability theory, which examines how personal experiences foster feelings of vulnerability and how these fears are disseminated through social networks. Beyond individual experiences, theoretical approaches to fear of crime have expanded to encompass the significance of social control within local communities. Shaw and McKay (1942) argued that diminished social control within neighborhoods can heighten fear of crime. Expanding on this notion, Sampson et al. (1997) introduced collective efficacy theory, positing

that a community's capacity to maintain social cohesion and informal social control can effectively mitigate fear of crime. Finally, research has increasingly recognized the influence of environmental factors, demonstrating that the physical environment plays a crucial role in shaping individuals' fear of crime alongside personal characteristics (Jacobs 1961; Jeffery 1971; Newman 1972). The following subsection examines how illuminance affects fear of crime as a key environmental factor.

## 2.2 Illuminance and fear of crime

The level of illuminance is a key environmental factor, particularly during nighttime hours (Loewen et al. 1993). Early field experiments generally indicated that brighter illuminance effectively enhances perceived safety. Boyce et al. (2000) proposed a foundational framework for understanding the impact of lighting on safety perceptions through experiments conducted in diverse urban and suburban environments. Haans and de Kort (2012) and Mattoni et al. (2017) focused on street level conditions and demonstrated that illuminance significantly influences perceived safety, which can in turn help reduce fear of crime in certain contexts. Advancing these insights, Kim and Noh (2018) explored the effects of lighting in exceptionally dark environments, such as areas under bridges, settings commonly perceived as more threatening. Their research demonstrated that extreme darkness exacerbates emotion, providing insights beyond typical urban contexts examined in previous studies. Incorporating innovative methodologies, Castro-Toledo et al. (2017) complemented a traditional survey approach (i.e., self-report questionnaires) with heart rate measurements, thereby offering a deeper understanding of the physiological responses to fear. A meta-analysis conducted by Ceccato (2020) also reinforced the critical role of bright illuminance in creating safer environments. Collectively, these findings contribute to a nuanced understanding of how illuminance influences fear of crime and perceived safety, illustrating a progression from broad perceptions of safety to specific environmental effects and methodological innovations. These findings underscore the importance of lighting in shaping safety perception and fear of crime in different contexts.

However, field-based studies frequently encounter limitations in the control of external factors other than illuminance. To address this issue, researchers have conducted lab-based experiments using image information, including photographs, simulated virtual environments, and video recordings. For instance, using 100 real-world photographs, van Rijswijk and Haans (2018) demonstrated that illuminance quality exerts both direct and indirect effects on perceived safety, mediated by factors such as opportunities for prospect, refuge, and escape. These results align with the findings from field research (Haans and de Kort 2012) and established theories (Appleton 1975; Fisher and Nasar 1992). Similarly, Boomsma and Steg (2014a, b) conducted experimental research using five simulated virtual environments with different levels of brightness and showed that brighter settings increase perceived safety. They argued that low illuminance levels reduce perceived safety by lowering entrapment (i.e., escapability). Additionally, using simulated virtual lighting environments, Nasar and Bokharaei (2017) demonstrated that both higher illuminance and uniformity levels reduce fear of crime in plazas after dark. Consequently, studies employing simulated virtual environments enable a reliable approximation of real-world fearful situations, allowing researchers to test how changes in lighting influence fear of crime (Lin 2017). However, because these experiments were conducted in a two-dimensional format, it remains challenging to ascertain whether participants accurately perceived spatial dimensions and presence akin to real-world environments when reporting fear of crime.

In response, recent research has utilized head-mounted (HMD)-based immersive VR experiments to examine emotional responses, including fear of crime (Son et al. 2023). For instance, Son et al. (2023) employed a quasi-controlled experiment utilizing recorded VR (RVR) video to analyze fear of crime under various illuminance conditions. They reported that higher illuminance and uniformity diminished fear of crime, and this effect was more pronounced in residential areas characterized by significant illuminance differences between daytime and nighttime.

Despite these approaches, both field- and lab-based experiments have heavily relied on subjective survey responses, raising concerns about biases associated with participant characteristics. For instance, studies commonly indicate that men report lower levels of fear of crime than women (Chataway and Hart 2019; Fetchenhauer and Buunk 2005; Son et al. 2023), potentially because men underreport their fears due to socially constructed gender norms. To investigate this hypothesis, Pierce and Kirkpatrick (1992) conducted two surveys and found that male participants tended to underreport fear when they were aware that their heart rates were being monitored. Similarly, Sutton and Farrall (2005) introduced the lie scale by employing the Eysenck Personality Questionnaire Revised (EPQ-R) and discovered that men underreported their fear of crime for presenting socially desirable responses. Boomsma and Steg (2014a) also found that women tend to experience greater fear and feel less safe under reduced street lighting, highlighting notable gender differences in perceived safety and fear of crime. This aligns with broader findings indicating that women often report higher levels of crime-related

fear than men (Chataway and Hart 2019; Fetchenhauer and Buunk 2005).

Consequently, while numerous studies have demonstrated that improving illuminance can reduce fear of crime, the heavy reliance on subjective survey responses remains a significant limitation. Therefore, incorporating objective measures that reduce the impact of respondents' sociodemographic characteristics is crucial. In this context, biosignal data emerges as a viable alternative for capturing more reliable emotional responses.

### 2.3 EEG analysis of emotional responses

Advancements in EEG analysis techniques have enabled the objective and reliable quantification of human emotions, including fear of crime (Cohen 2017). EEG measures electrical activity of neurons in the brain using electrodes placed on the scalp (Teplan 2002). These recorded electrical signals are transformed into frequency domains and classified into five distinct categories: alpha (α), beta (β), gamma (γ), delta (δ), and theta (θ) waves. Among these, alpha and beta waves are particularly important, as they are associated with different brain states and regions, playing a central role in the analysis of arousal and valence—two primary dimensions of emotional experience (Table 1, Teplan 2002).

Alpha waves (8–13 Hz) are linked to relaxation and reduced anxiety, typically observed in calm states with eyes closed (Martínez-Tejada et al. 2021; Siirtola et al. 2023). In contrast, beta waves (>13 Hz) correspond to active thinking, focus, and heightened alertness (Teplan 2002). Arousal is measured by the beta-to-alpha ratio, with higher ratios generally signifying greater emotional excitement (Jebelli et al. 2018). Meanwhile, valence, which reflects positive emotion, is determined by the difference in the beta-to-alpha ratio between the left and right hemispheres (Jebelli et al. 2018). The right hemisphere primarily governs emotions, particularly negative ones, while the left hemisphere is associated with rationality and positive emotions (Kliemann et al. 2016).

Since Martínez-Tejada et al. (2021) found a strong correlation between self-reported emotions and both valence and arousal, EEG has proven effective for measuring emotional responses to built environments. When combined with VR experiments, EEG enhances accuracy and simplifies the assessment of emotional states such as valence and arousal. VR provides controlled settings that reduce interferences from external factors like climate, weather, or noise, allowing researchers to fully measure neurophysiological responses with fewer disruptions (Choi et al. 2023). Additionally, the immersiveness of HMD-based VR minimizes errors in EEG measurements, allowing for more precise assessments of emotional dimensions (Marín-Morales et al. 2018). Thus, combining EEG with VR can be an optimal method for emotion research using biosignal data.

Moreover, researchers increasingly recognize the importance of incorporating other physiological indicators—such as heart rate or galvanic skin response—to capture a broader "fear response" that extends beyond self-reported data. This approach is particularly relevant in fear-of-crime studies, where underreporting or social desirability biases may obscure actual levels of anxiety or fear (Castro-Toledo et al. 2017).

Several studies have utilized EEG in VR settings to examine the impact of physical environments on emotional states, focusing primarily on valence and arousal (Table 2). Marín-Morales et al. (2018) demonstrated that changes in architectural design within VR environments significantly influenced participants' emotional responses, affecting both valence and arousal. Similarly, Kim and Kang (2018) found that natural landscapes were more effective in reducing anxiety and lowering arousal levels than urban settings. Additionally, Olszewska-Guizzo et al. (2020) showed that urban green spaces enhance emotional well-being by affecting frontal alpha asymmetry, a key indicator of valence. Kim et al. (2021) investigated how different architectural elements in VR influence emotional reactions, revealing that specific design features impact both valence and arousal. Cho et al. (2022) found that emotional responses to urban design varied by participants' gender and residential background, with significant differences observed in both valence and arousal.

However, these studies have certain limitations. First, they often involve relatively small sample sizes and a limited number of scenarios, weakening the generalizability of the findings (Table 2). Moreover, the absence of post-experimental evaluations in some studies restricted the ability to thoroughly assess participants' subjective experiences and validate the simulated environments. Given the synergy between EEG and VR technology, this study aimed to provide an objective analysis of the relationship between illuminance and fear of crime. By leveraging the strengths of both EEG and VR, we sought a more precise understanding of how lighting conditions influence emotional responses associated with fear of crime, with particular attention to

**Table 1** Types of EEG and their featuress.
*Source*: Teplan (2002)

| Characteristics | Alpha waves | Beta waves |
|---|---|---|
| Frequency range | 8–13 Hz | >13 Hz |
| Dominant brain state | Relaxation, eyes closed, and stress relief | Arousal, focus, mental activity, and eyes open |
| Role | Mental relaxation, meditation, and stress reduction | Cognitive activity, problem-solving, and information processing |

**Table 2** Summary of studies using EEG for human emotion analysis in VR environments

| Study | Environment/context | EEG analysis focus | Key findings | Observation (P X S)[a] |
|---|---|---|---|---|
| Choi et al. (2023) | Immersive VR in various contexts | Neural applications and emotion | Review of EEG studies reporting enhanced emotional analysis through VR integration | 45 (45 * 1) |
| Martínez-Tejada et al. (2021) | Video game play | Emotional response correlation | Strong correlation between EEG patterns and self-reported emotions survey | 48 (12 * 4) |
| Marín-Morales et al. (2018) | VR architecture | Valence, arousal | Architectural changes in VR significantly affect emotional states | 152 (38 * 4) |
| Kim and Kang (2018) | Urban and natural landscapes | Fear of crime (valence, arousal) | Natural environments reduce anxiety more effectively than urban settings | 162 (27 * 6) |
| Olszewska-Guizzo et al. (2020) | Urban green spaces | Frontal alpha asymmetry (FAA) | Green spaces enhance emotional well-being by positively affecting FAA | 198 (22 * 9) |
| Kim et al. (2021) | VR environments (architectural elements) | Emotional impact of design | Changes in architectural elements in VR influence emotional responses measured by EEG | 33 (33 * 1) |
| Cho et al. (2022) | Urban design (gender and residence) | Valence, emotional response | Emotional responses vary by individual characteristics, with significant EEG changes observed | 540 (45 * 12) |

[a]P: number of participants, S: number of scenarios

valence. The following sections outline the detailed methodology employed in this study.

## 3 Experiment design and analysis method

### 3.1 Overview

This study employed data from an experiment previously described in our companion paper (Son et al. 2023), following a similar experimental procedure. Illuminance levels were initially measured on four narrow streets in Sangdo 1-dong, Seoul, and 360° camera footage was recorded at the same locations and times of day. Postprocessing was performed to adjust the recorded videos' illuminance to match the real-world environment, and these videos were then converted into VR format for HMD use. A total of 101 adults in their twenties, were recruited to experience the VR videos and rate their perceived fear of crime. The relationship between measured illuminance and perceived fear of crime was analyzed using a cross-classified multilevel analysis.

A key difference from the companion paper is that this study incorporates EEG data to objectively examine reactions to varying illuminance levels. As a result, the number of observations was reduced from 1010 (101 subjects × 10 environments) to 622 (95 subjects × 6.55 environments) due to the exclusion of EEG data with recording errors. To ensure that this data exclusion did not introduce systematic bias, we conducted additional analyses comparing included and excluded samples. The results indicated that EEG data loss occurred largely at random and did not lead to meaningful differences across participants or conditions. Full results are provided in the last sheet of the Supplementary Material.

Although the EEG data were collected simultaneously as part of the original experiment, we decided to present the findings in two separate papers for several reasons. First, EEG data measured in 0.1-s increments require complex preprocessing, which differs significantly from the simpler Likert-scale fear of crime responses. Second, the instability of the EEG device resulted in accurate data being unavailable for about one-third of the observations. We considered that both a traditional analysis and an objective analysis using EEG would provide valuable insights. Lastly, the scope and quantity of data made it challenging to cover everything in a single paper. While the companion paper focuses on the relationship between illuminance and fear of crime, this study emphasizes objective EEG measurements, particularly for explaining gender differences in reported fear of crime. The following subsections outline the experimental design, highlighting the distinct aspects of both studies.

### 3.2 Study areas

The study area comprised four narrow streets in Sangdo 1-dong, Seoul, South Korea. These streets correspond to the four site types defined by the Korean Standard for Road Lighting (Korean Agency for Technology and Standards 2019): (a) residential areas with high pedestrian traffic, (b) residential areas with low pedestrian traffic, (c) commercial areas with high pedestrian traffic, and (d) commercial areas with low pedestrian traffic. The four alleyways, with an average width of 3.7–7.6 m, are shared by vehicles and pedestrians, which makes pedestrians more vulnerable to crime (Perkins et al. 1993).

### 3.3 Measuring nighttime illuminance and 360° video recording

In April 2021, we measured the illuminance levels of the four selected streets over four consecutive days, one day per

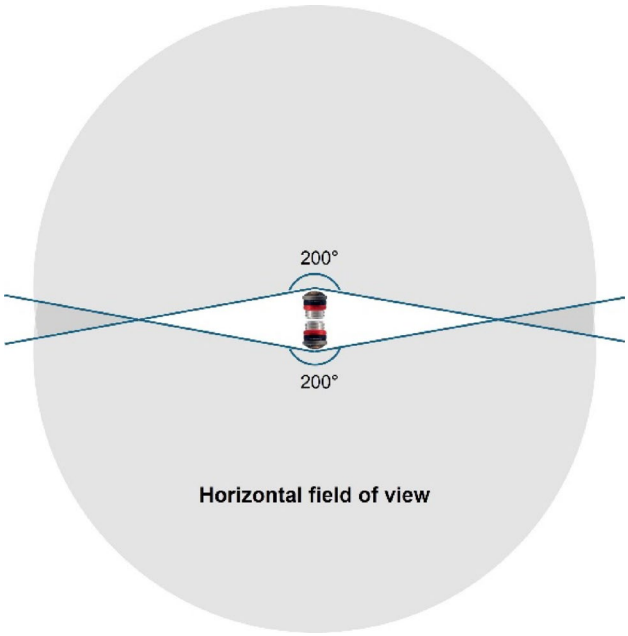



**Fig. 1** Horizontal field of view of an omnidirectional camera setup

street (Appendix 1). Measurements were taken 13 times at each site from 6 to 11 pm, with slight adjustments to the starting time each day to account for the changing sunset. For each time slot on each street, horizontal and vertical illuminance were measured using a Konica Minolta T-10A illuminometer at 18 and 9 points, respectively, based on the Korean Standard for Road Lighting (Korean Agency for Technology and Standards 2019). From these measurements, we calculated the mean, minimum, maximum illuminance, and uniformity for each site and time slot.

Two different sets of 360° video recordings were produced: one for the main experiment and the other for the warm-up task. Both recordings employed omnidirectional camera setups, but they differed in terms of purpose, recording conditions, equipment used, and production methods.

For the main experiment, recordings were taken immediately after the illuminance measurements using an omnidirectional setup consisting of two Panasonic GH5S cameras equipped with Enataniya HAL200 3.6 MFT wide-angle lenses (Fig. 1). A total of 40 videos were produced (Fig. 2 and Table 3), excluding three time slots with no significant illuminance changes compared to adjacent ones. Each video was edited to a 30-s length for the VR experiment. To ensure visuals that are realistic to the human eye, log shooting mode was activated during complete darkness, followed by extensive post-production adjustments, including sharpening, color grading, and noise reduction. All filming and editing were conducted by a professional VR production

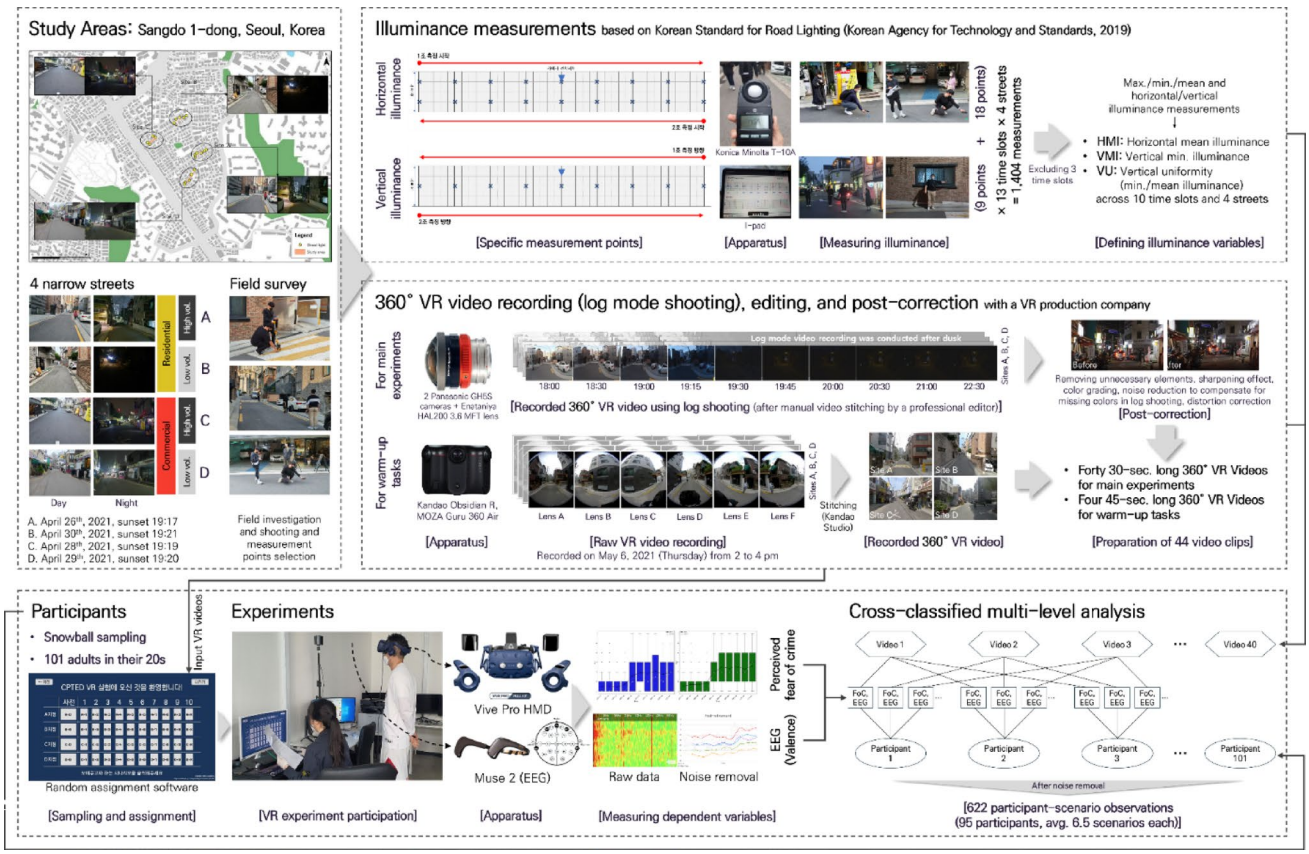
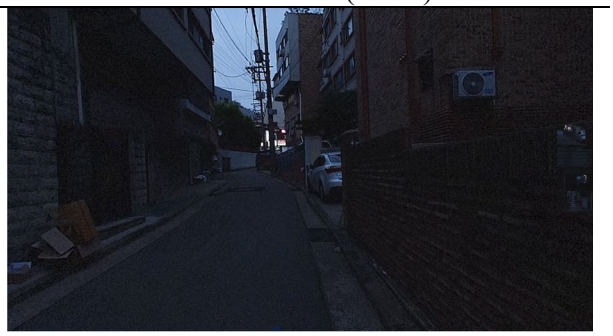
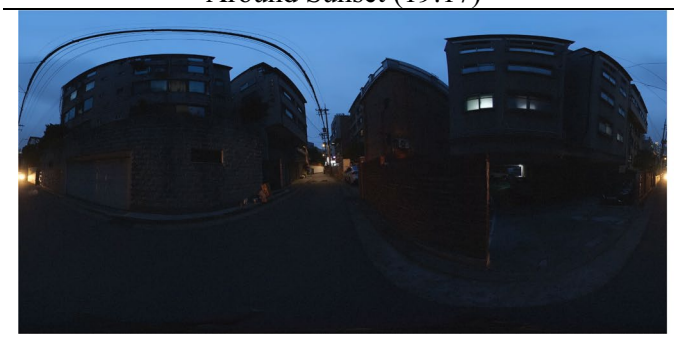
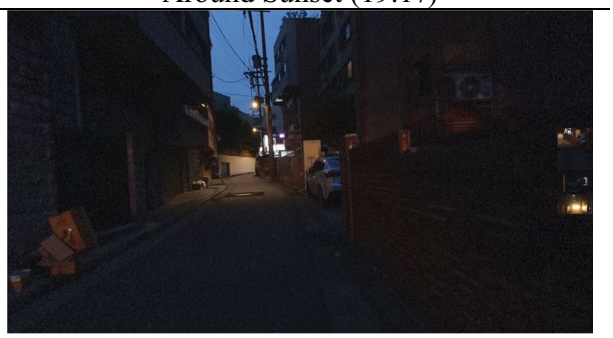



**Fig. 2** Research framework: Study area, data collection, VR experiment, and analysis

**Table 3** Sample screenshots of 360° videos by viewing mode and time of day

| 360° video screenshot (equirectangular view) | 360° video screenshot (VR playback mode) |
|---|---|
|  |  |
| Before Sunset (18:34) | Before Sunset (18:34) |
|  |  |
| Around Sunset (19:17) | Around Sunset (19:17) |
|  |  |
| After sunset (19:34) | After sunset (19:34) |

Recorded at Site B, a low-traffic residential area in Sangdo 1-dong, Seoul, on April 30, 2021. The VR playback mode refers to the VR mode function of a desktop video viewer, which may differ in resolution and visual quality from that of a head-mounted display (HMD). In the VR playback screenshots, a directional keymap interface appears near the center-right area, indicating an option to change the viewing direction.

company, as nighttime recording required specialized techniques and equipment.

In contrast, the videos for the warm-up task were simply to help participants familiarize themselves to the recorded VR environment. These were recorded by the research team during the daytime, when ample natural lighting made post-processing unnecessary. For this purpose, we used a Kandao Obsidian R, a high-end omnidirectional camera with six lenses and auto-stitching capability, which allowed for efficient recording without the need for professional support or manual stitching.

Due to practical constraints related to equipment availability, production complexity, and post-processing costs, all videos described were produced in a monoscopic format. While monoscopic videos inherently lack binocular depth cues—potentially limiting emotional immersion and perceived realism—they offer certain advantages in VR settings. Studies have shown that stereoscopic presentations may induce higher visual discomfort than monoscopic ones, particularly when viewed through HMDs, due to the vergence-accommodation conflicts (Lambooij et al. 2009; Hartle and Wilcox 2022). Thus, monoscopic video may offer a viable alternative under certain constraints, especially when

supported by high production quality and careful post-processing, as in our study.

### 3.4 Participants

This study targeted adults in their twenties due to their relatively higher reported fear of crime (Statistics Korea 2022) and greater familiarity with VR equipment (Schneider and Bengler 2020). A total of 101 participants were recruited in May 2021 through snowball sampling. However, due to faulty EEG data as discussed below, the final analysis included data from 95 participants. The sample consisted of 52 males (54.7%—) and 43 females (45.3%), with a mean age of 25.0 years (SD = 2.2). Approximately half of the participants (45.3%—) had prior VR experience, and 27.4% reported that they or someone they knew had been a victim of crime. All participants provided informed consent and received compensation for their participation at the end of the experiment.

### 3.5 Experiment procedures, VR apparatus, and survey questionnaire

The experiment employing the recorded VR videos and corresponding questionnaire survey (hereafter, "VR survey") was conducted from May 28 to June 26, 2021, in the VR Lab of Chung-Ang University. First, the facilitator explained the purpose and procedure of the experiment and asked participants to complete a pre-questionnaire that collected sociodemographic information (age, gender, education level, residential type, and household size) and other personal details (frequency of walking alleyways, average time of returning home, experience with VR, past victimization, and crime vulnerability).

Participants then wore a Vive Pro HMD device, commonly used in VR studies (Rockcastle et al. 2021; Scorpio et al. 2020, 2021), along with the Muse 2 EEG measurement device (Fig. 2). The facilitator checked electrode contacts using the Mind Monitor app on an iPad Pro, allowing for real-time monitoring of EEG data, including absolute band power via power spectral density (PSD) logs and spectrograms. Participants could adjust sensor positions if significant inaccuracies were detected in the EEG measurements.

Following a simple warm-up task to enhance familiarity with the VR environment, each participant viewed 10 randomly selected VR videos from a pool of 40 (four streets × 10 time slots). To ensure a seamless experience and maintain participants' immersion, we developed a Unity-based playback tool that automatically loads and plays a predetermined sequence of videos randomly assigned to each participant and records the timestamp for each viewing session. This tool operated in the background and was visible only to the facilitator—not to the participant. To reinforce the immersive context, the facilitator repeated a scripted narration at the start of each video: "You are on your way back home from an appointment. You have now paused for a moment and are looking around." After viewing each video, participants rated their perceived "fear of self-victimization" (FSV) and "fear of others' victimization" (FOV) on a 7-point Likert scale using two specific questions:

1. In the situation you are now in, how high is your fear of victimization that crimes such as theft, violence, sexual assault, robbery, and murder can happen to you? (FSV)
2. In the situation you are now in, how high is your fear of victimization that crimes such as theft, violence, sexual assault, robbery, and murder can happen to others? (FOV)

After the VR survey, participants completed the "sense of presence" questionnaire developed by Lessiter et al., (2001), using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) to assess the validity of the VR experiment (Appendix 2) The results showed high scores in the "ecological validity" and "engagement" categories (above 4), but relatively low scores in the "sense of physical space" category, likely due to the limitations of recorded VR videos that do not allow real-time interaction. Most participants did not report any physiological discomfort, with only a few experiencing dizziness (n = 12) or eyestrain (n = 15). Overall, these results support the reliability of the experiment.

### 3.6 EEG data collection, preprocessing, and emotional variable definition

EEG signals were recorded using a Muse 2 headband, whose reliability has been confirmed in prior verification studies (Kappenman and Luck 2010; Krigolson et al. 2017; Youssef et al. 2018). Compared to medical-grade EEG devices, the Muse 2 provides advantages in cost, ease of use, and comfort, especially for VR applications (Martínez-Tejada et al. 2021; Ratti et al. 2017). The Muse 2 incorporates five electrodes: a reference electrode (FPZ) on the forehead, two input electrodes (AF7 and AF8) positioned on each side of the forehead, and two posterior electrodes (TP9 and TP10) on the ears (Fig. 2).

Data were sampled at 256 Hz and transmitted via Bluetooth using the Mind Monitor app on an iPad (Garcia-Moren et al. 2020). Signals were recorded at 0.1-s intervals, with each interval representing an epoch—a 0.1-s window of continuous EEG activity, allowing detailed analysis of the brain's electrical responses. After recording, the relative power spectral density (PSD) for four frequency bands was

calculated using a fast Fourier transform (FFT), categorizing the EEG data into five wave types (δ, θ, α, β, and γ). Noise reduction steps included outlier removal, filtering, abnormal channel and segment exclusion, and removal of data with eye-movement noise or excessive power values (Fig. 3). A notch filter removed 60 Hz noise, while a 0.1 Hz high-pass filter and a 45 Hz low-pass filter eliminated DC offsets, low-frequency skin potentials, and high-frequency noise (Kannathal et al. 2005; Suhaimi et al. 2020). Artifacts caused by eye movements were removed using electrooculography (EOG), and signals with power values exceeding ± 100 μV were also eliminated, yielding 662 observations from 95 participants, each experiencing an average of 6.5 scenarios. The nature of the cross-classified multilevel analysis, as explained in Sect. 3.7, does not allow for a traditional power analysis to directly estimate the statistical power of the sample size. However, the number of observations in our study is not only considerably larger compared to similar prior research (Table 2) but also notably exceeds those commonly found in typical VR experimental studies (Schneider and Bengler 2020; Schwebel et al. 2016).

Next, the valence and arousal indices were calculated using α and β waves from the AF8 and AF7 sensors on the prefrontal cortex (Jebelli et al. 2018), as defined in Sect. 2.2. However, only the valence was ultimately retained for the analysis, consistent with Cho et al. (2022), due to the inherent instability of EEG-based arousal measurement.[1]

$$Valence = \frac{\alpha(AF8)}{\beta(AF8)} - \frac{\alpha(AF7)}{\beta(AF7)} \quad (1)$$

$$Arousal = \frac{\beta(AF8)}{\alpha(AF8)} \quad (2)$$

In addition, instead of using raw valence values, which can vary due to genetics, health, and mood on the experiment day, we focused on "valence difference" (Ve – Vs). This was calculated as the change in EEG valence from immediately before (Ve) to just after experiencing the virtual environment (Vs). This measure captures the emotional shift during the experiment and serves as a key variable in our analysis. Similar to Bromm et al. (1989), who emphasized pre- and

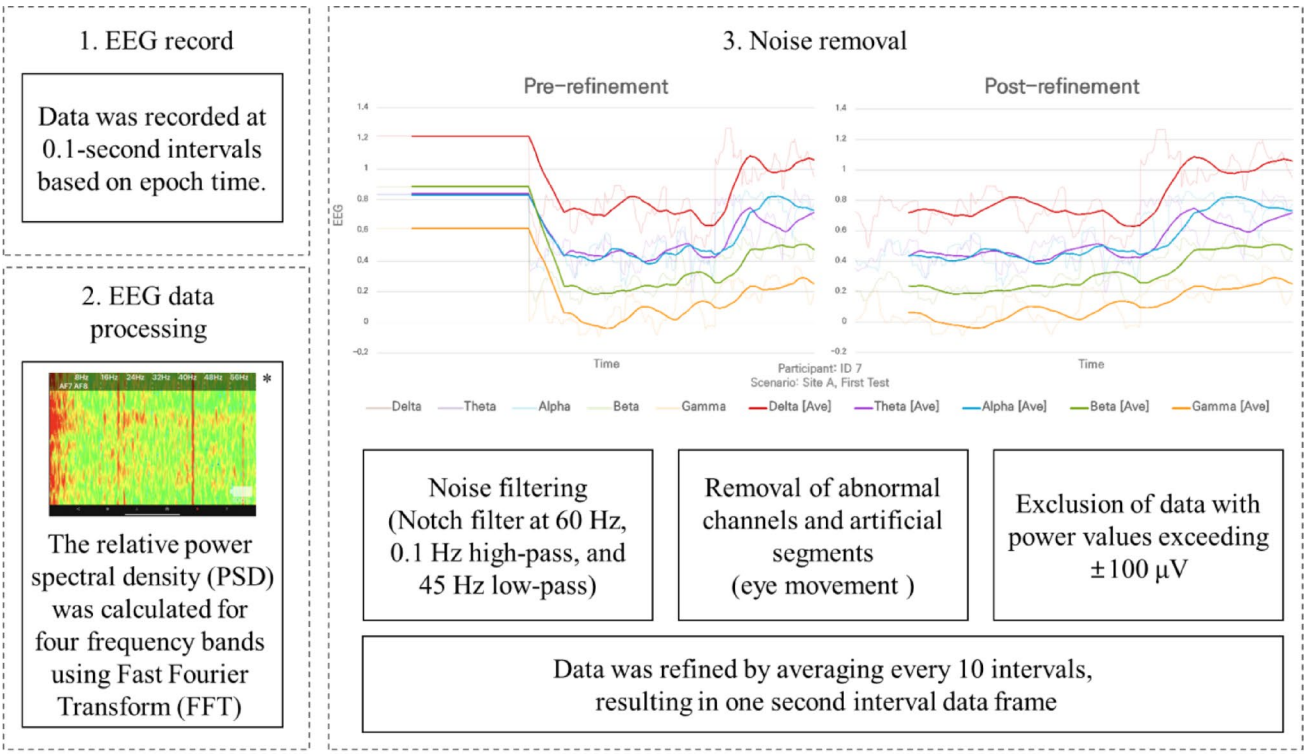



**Fig. 3** EEG data preprocessing and noise removal process

[1] In a set of parallel analysis, we replaced valence with arousal. The results presented in the Supplementary Material, revealed no statistically significant associations with illuminance or fear of crime variables across all submodels. Including these null findings in the main text would have lengthened the manuscript without substantive insights. We attribute the absence of significant effects to the comparative difficulty of deriving reliable arousal markers from EEG—unlike valence, which benefits from the well-validated frontal-alpha asymmetry (FAA) indicator (Galvão et al. 2021; Gkintoni et al. 2025).

post-stimulus EEG changes to evaluate the effects of drugs on spontaneous and evoked EEG activities, our approach underscores the importance of analyzing changes (rather than static values) to more accurately capture dynamic emotional responses during experiments.

### 3.7 Analysis method, variables, and model specification

The VR experiment dataset (95 participants, 40 scenarios, and 622 participant-scenario observations) featured a hierarchical structure grouped by both participants and scenarios. Therefore, this study employed cross-classified multilevel analysis. Unlike our companion paper, this study used a pooled sample model, integrating data from all four sites.

The model type varied based on the applied variables (Fig. 4). Model A-1 assessed the effects of illuminance levels on the valence difference. Three illuminance variables—log-transformed horizontal mean illuminance (HMI), log-transformed vertical minimum illuminance (VMI), and vertical uniformity (VU: minimum illuminance/average illuminance)—were tested in separate models (three sub-models) to avoid multicollinearity. Model A-2 examined the effects of illuminance on fear of crime, defined by FSV and FOV. The three illuminance variables were tested separately, as in Model A-1, resulting in a total of six sub-models. Model B explored the combined effects of illuminance levels and valence difference on fear of crime, resulting in nine sub-models. In total, the analysis comprised 15 models (3 from A-1, 6 from A-2, and 6 from B). As in the companion study, all 15 models controlled for individual characteristics collected through pre- and post-experiment surveys.

Table 4 presents the definitions and levels of variables employed in the analysis. As control variables, a gender dummy variable (male = 1) was included, along with interaction terms between gender and the three illuminance variables to investigate gender differences in the influence of illuminance on fear of crime. For the 13-item sense of presence questionnaire, factor analysis yielded three factors: perceived sense of presence/immersion, adverse physiological reactions, and ecological validity, which were used as independent variables (Appendix 3; Cronbach's alpha for each factor was 0.833, 0.755, and 0.703). Order effects and inter-site differences were controlled for using the "order of presentation of current video" and site dummy variables. All research methods and procedures explained so far were conducted with the approval of Chung-Ang University's Institutional Review Board (Approval number: 1041078-202203-HR-092).

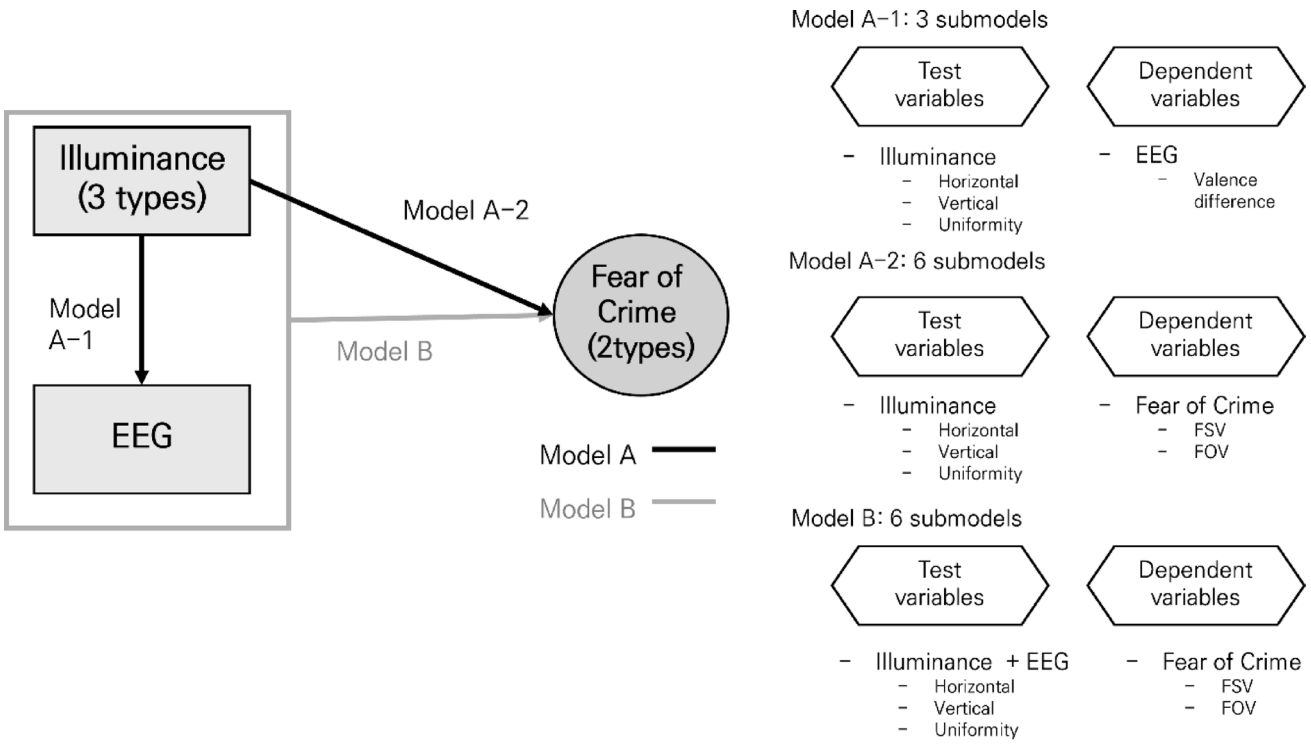



**Fig. 4** Analysis framework consisting of three model types depending on the applied variables

**Table 4** Definition and level of the variables employed in the analysis

| Variable | Note | Level |
|---|---|---|
| **Dependent variables** | | |
| *Fear of crime* | | |
| Fear of self-victimization (FSV) | 7-point Likert scale | Within (participant*video) |
| Fear of others' victimization (FOV) | 7-point Likert scale | Within (participant*video) |
| *EEG* | | |
| Valence difference (VD)* | Direct measurement | Within (participant*video) |
| **Test variables** | | |
| Ln (horizontal mean illuminance) (HMI)** | Direct measurement | Between (video) |
| Ln (vertical minimum illuminance) (VMI)** | Direct measurement | Between (video) |
| Vertical uniformity (VU)** | Vertical minimum/avg. illuminance | Between (video) |
| **Control variables** | | |
| Age | | Between (participant) |
| Gender | Male = 1 | Between (participant) |
| Gender × illuminance** | Interaction term | Within (participant*video) |
| Education | Postgraduate or higher = 1 | Between (participant) |
| Residential type | | |
| Single-family house/walk-up apartment *** | | Between (participant) |
| Apartment complex/studio apartment *** | | Between (participant) |
| Household size | | |
| One-person household | Ref.: 3 + | Between (participant) |
| Two-person household | Ref.: 3 + | Between (participant) |
| Familiarity with the area | Familiar = 1 | Between (participant) |
| Narrow street walk | | |
| 3–4 days | Ref.: less than 3 days | Between (participant) |
| 5–7 days | Ref.: less than 3 days | Between (participant) |
| Avg. returning home time | | |
| 8–10 pm | Ref.: before 8 pm | Between (participant) |
| 10 pm or later | Ref.: before 8 pm | Between (participant) |
| Experience of crimes | Yes = 1 | Between (participant) |
| Risk of FSV | 4-point scale (1 = very low, 2 = low, 3 = high, 4 = very high) | Between (participant) |
| Self-defence level | | Between (participant) |
| Severity and continuity of harm (self) | | Between (participant) |
| Past experience of VR | Yes = 1 | Between (participant) |
| Sense of presence/immersion | Factor analysis result (Appendix 3) | Between (participant) |
| Adverse physiological reactions | | Between (participant) |
| Ecological validity | | Between (participant) |
| Order of presentation of the current video | One value out of 1–10 | Within (participant *video) |
| Pedestrian/two-wheeled vehicle traffic**** | Those appearing in the video | Between (video) |
| Site A | Ref.: Site D | Between (video) |
| Site B | | Between (video) |
| Site C | | Between (video) |

*This variable was also utilized as an independent variable, depending on the model

**Illuminance was measured over time as shown in Appendix 4

***In this interaction term, the "illuminance" variable, which is multiplied by the gender variable, refers to the specific illuminance variable that is applied in the current model among the three

****Reference group is other residential types (dormitories, tiny studios, etc.)

*****Number of pedestrians, motorbikes, and electric kickboards that appeared in the video

**Table 5** Illuminance measurement by time (average of the four streets)

| | Time | Horizontal mean illuminance (lux) | Vertical minimum illuminance (lux) | Vertical uniformity |
|---|---|---|---|---|
| 1st | 18:00 | 3432.181 | 2003.611 | 0.702 |
| 2nd | 18:30 | 1335.333 | 774.292 | 0.728 |
| 3rd | 19:00 | 482.524 | 272.560 | 0.675 |
| 4th | 19:15 | 130.707 | 82.443 | 0.732 |
| 5th | 19:30 | 33.377 | 20.308 | 0.621 |
| 6th | 19:45 | 11.726 | 9.852 | 0.371 |
| 7th | 20:00 | 12.463 | 13.253 | 0.332 |
| 9th | 20:30 | 11.874 | 12.509 | 0.341 |
| 9th | 21:00 | 9.916 | 10.740 | 0.305 |
| 10th | 22:30 | 5.278 | 5.274 | 0.296 |

Vertical uniformity = Vertical minimum illuminance/vertical average illuminance, Sunset time was around 19:17–19:20 on the survey days in Seoul (GMT + 9)

# 4 Results and discussion

## 4.1 Preliminary analysis

### 4.1.1 Illuminance by time

Table 5 summarizes the average measured illuminance values in the four selected streets at each time of the day. This indicates that the illuminance level significantly dropped immediately after sunset.

In Korea, the Korean Standard for Road Lighting (KSA 3701:2019 2019) stipulates that vertical illuminance on residential streets must be kept at < 10 lx from 60 min after sunset until 60 min before sunrise. Given that Table 5 reports the mean values for two residential streets and two mixed residential–commercial streets, the nighttime illuminance levels we measured adhere precisely to this national road-lighting requirement.

### 4.1.2 Valence difference by illuminance level and time

Figure 5 shows that the valence difference increased with the HMI, implying that a brighter environment induces positive human emotions. In contrast, since illuminance and time of day were inversely related, the valence difference tended to decrease as time progressed.

### 4.1.3 Fear of crime by time

Figure 6demonstrates that perceived fear of crime (both FSV and FOV) increased as time progressed. On a seven-point Likert scale, the mean fear of crime was generally below three before sunset. However, immediately after sunset, the deviation increased, accompanied by an elevated mean and median. Although the mean values remained relatively low at four points (moderate level) across all time slots, the number of ratings at five points or higher increased after sunset.

### 4.1.4 Valence difference and fear of crime

Together, Figs. 6 and 7 suggest a relationship between fear of crime and emotional responses during the experiment. Although the trends in Fig. 7 are subtle, they align with the notion that fear of crime, whether focused on oneself (FSV) or others (FOV), contributes to a more negative emotional trajectory (lower valence difference). These findings support the broader hypothesis that fear of crime is associated with negative emotional states, as demonstrated by its relationship with both fear levels observed at different times of the day (Fig. 6) and physiological responses measured through valence difference (Fig. 7).

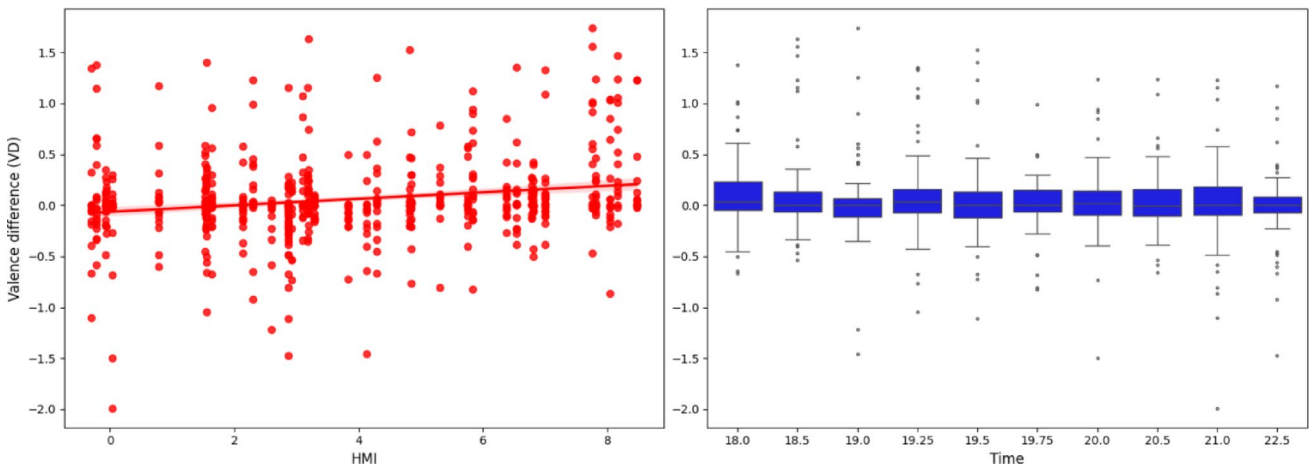



**Fig. 5** Valence difference by illuminance level (left) and time (right). Note: HMI = ln (Horizontal mean illuminance)

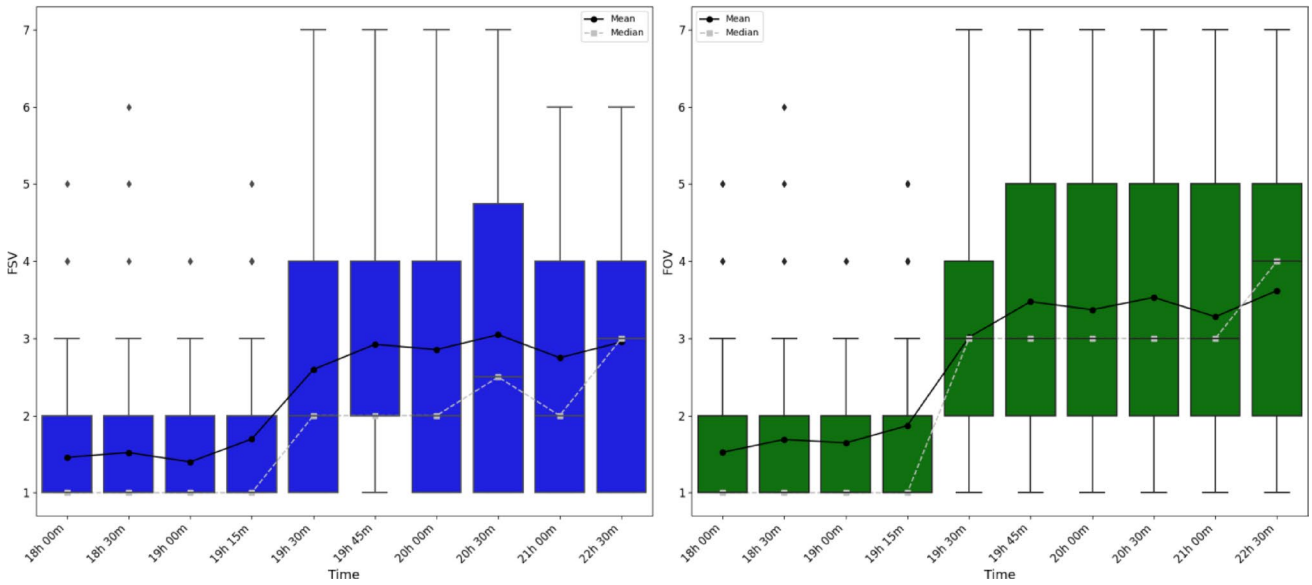



**Fig. 6** Perceived fear of crime, FSV (left) and FOV (right) by time. Note: FSV = fear of self-victimization; FOV = fear of others' victimization

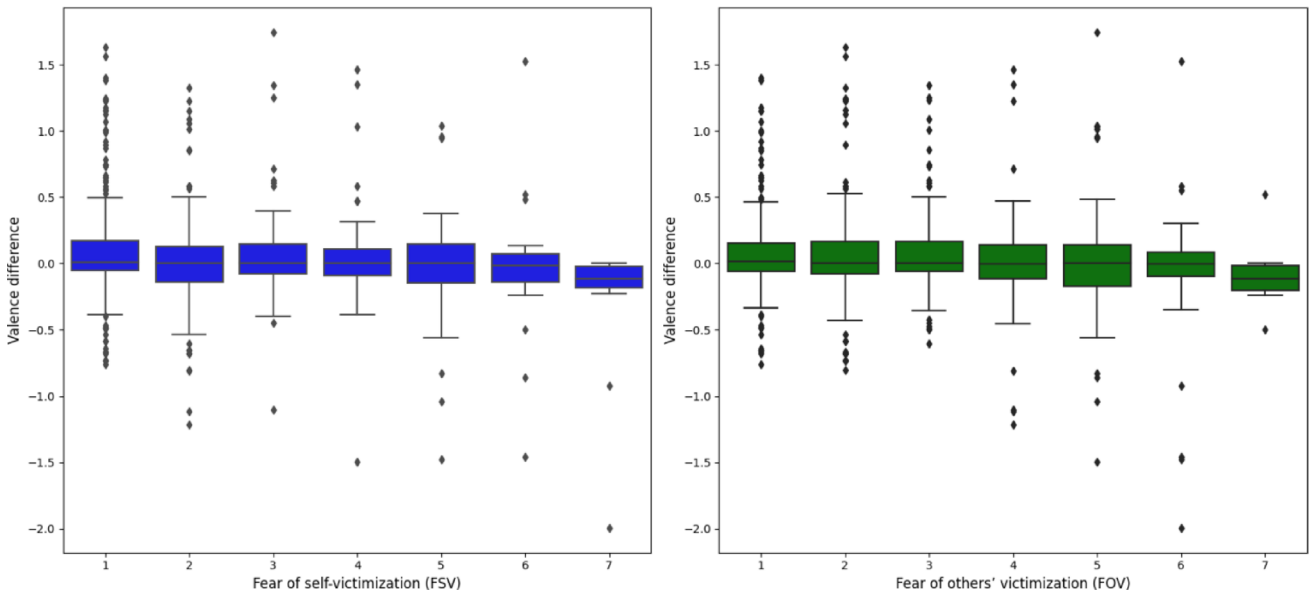



**Fig. 7** Relationship between valence difference and fear of crime

#### 4.1.5 Illuminance level, valence difference, and fear of crime by time

Figure 8 illustrates the relationships among the key variables, showing that illuminance gradually decreases over time, accompanied by a corresponding decrease in positive emotions (i.e., valence difference) and a consequent increase in fear of crime. This suggests that a decrease in illuminance would influence both fear of crime, assessed through participants' subjective psychological responses, and emotional state, as measured via objective neurophysiological measures from EEG data, thereby establishing a negative association between fear of crime and valence difference. Nonetheless, this result was obtained without controlling for other factors; therefore, we performed a cross-classified multilevel analysis to ascertain the relationship among the variables.

### 4.2 Cross-classified multilevel analysis

All results of the 15 cross-classified multilevel models with fear of crime and valence differences as dependent variables, are presented in the Supplementary Materials. The results show that all models had posterior predictive p-values (PPP

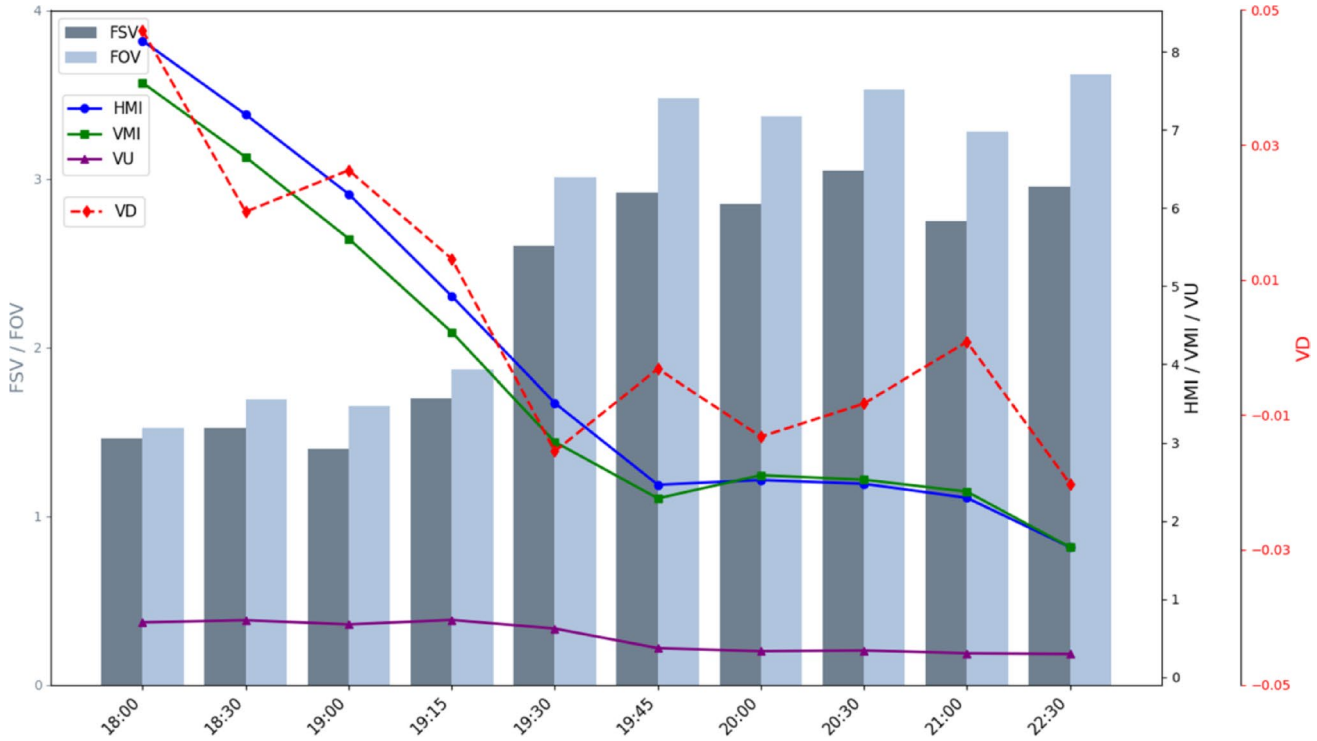



**Fig. 8** Illuminance level, valence difference, and fear of crime by time. Note: HMI = ln (horizontal mean illuminance); VMI = ln (vertical minimum illuminance); VU = Vertical uniformity; VD = Valence Difference; FSV = fear of self-victimization; FOV = fear of others' victimization

**Table 6** Effects of illuminance variables on valence difference and fear of crime (Models A-1 and A-2)

| | Model A-1 | | | Model A-2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | VD | | | FOV | | | FSV | | |
| | Est | *P* value | Sig | Est | *P* value | Sig | Est | *P* value | Sig |
| HMI | 0.067 | 0.000 | * | −0.419 | 0.000 | * | −0.432 | 0.000 | * |
| VMI | 0.070 | 0.000 | * | −0.399 | 0.000 | * | −0.410 | 0.000 | * |
| VU | 0.610 | 0.002 | * | −4.015 | 0.000 | * | −4.242 | 0.000 | * |

VD: valence difference; FSV: fear of self-victimization; FOV: fear of others' victimization, HMI: ln (horizontal mean illuminance); VMI: ln (vertical minimum illuminance); VU: vertical uniformity, All variables presented in Table 4 are controlled, with the entire results presented in the Supplementary Materials, Number of observations = 622

*is the case where the 95% confidence interval does not contain the value "0," which means that the coefficient is significant

values) greater than 0.05, supporting the appropriateness of the cross-classified analysis. The relatively high PPP values, ranging from approximately 0.4–0.5, also indicate an overall strong model fit. Tables 6, 7, and 8 summarize the coefficients and significance levels of the key variables. In the three sub models of Model A-1, all illuminance variables were positively associated with valence difference, which represents a positive emotional state (Table 6). This suggests that EEG is influenced by the surrounding environment, verifying that valence can be a feasible proxy measure to assess positive human perceptions (Cho et al. 2022; Marín-Morales et al. 2018). This also complements the results of Kim and Kang (2018), who identified that fear of crime is associated with EEG. In the six sub models of Model A-2, all illuminance variables were negatively associated with fear of crime, supporting previous empirical evidence (Boyce et al. 2000; Kim and Noh 2018; Mattoni et al. 2017; Son et al. 2023). As shown, the three illuminance variables—HMI, VMI, and VU—influenced both positive emotions measured by objective EEG data and perceived fear of crime assessed through the subjective questionnaire survey. This suggests that not only survey data (psychological responses) but also measured EEG data (neurophysiological responses) may significantly contribute to assessing fear of crime levels in relation to illuminance.

Table 7 presents the key results of the six sub-models (three illuminance variables × two fear of crime variables) of Model B. The results show that the valence difference is negatively associated with both fear of crime variables, implying that EEG data representing positive emotions correspond to a lower perceived fear of crime. The three illuminance variables still demonstrated a significant negative

**Table 7** Effects of illuminance and valence difference on fear of crime (Model B)

| | FSV | | | FOV | | |
|---|---|---|---|---|---|---|
| | Est | *P* value | Sig | Est | *P* value | Sig |
| HMI | −0.398 | 0.000 | * | −0.408 | 0.000 | * |
| VD | −0.298 | 0.000 | * | −0.344 | 0.000 | * |
| VMI | −0.379 | 0.000 | * | −0.388 | 0.000 | * |
| VD | −0.296 | 0.000 | * | −0.342 | 0.000 | * |
| VU | −3.855 | 0.000 | * | −4.066 | 0.000 | * |
| VD | −0.320 | 0.000 | * | −0.365 | 0.000 | * |

VD: valence difference; FSV: fear of self-victimization; FOV: fear of others' victimization, HMI: ln (horizontal mean illuminance); VMI: ln (vertical minimum illuminance); VU: vertical uniformity, All variables presented in Table 4 are controlled, with the entire results presented in the Supplementary Materials, Number of observations = 622

*is the case where the 95% confidence interval does not contain the value "0," which means that the coefficient is significant

**Table 8** Effects of other control variables on valence difference and fear of crime (Models A-1 and A-2)

| Variable | Model A-1 | | | Model A-2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | VD | | | FSV | | | FOV | | |
| | HMI | VMI | VU | HMI | VMI | VU | HMI | VMI | VU |
| Gender (male = 1) | −0.017 | 0.114 | 0.114 | −2.107* | −1.784* | −2.155* | −0.992* | −0.799* | −1.046* |
| Gender × illuminance | 0.020 | 0.001 | 0.000 | 0.253* | 0.241* | 1.982* | 0.146* | 0.137* | 1.178* |
| Narrow street walk (5–7 days) | 0.121 | −0.184 | −0.187 | −0.432* | −0.429 | −0.417 | −0.504 | −0.503 | −0.489 |
| Experience of crimes | −0.074 | −0.270* | −0.261* | 0.501* | 0.499* | 0.515* | 0.398 | 0.395 | 0.405 |
| Sense of presence/ immersion | −0.108* | −0.092 | −0.090 | 0.190* | 0.185* | 0.204* | 0.278* | 0.273* | 0.286* |
| Adverse physiological reaction | −0.040 | −0.039 | −0.041 | 0.215* | 0.213* | 0.208* | 0.174 | 0.172 | 0.172 |

VD: valence difference; FSV: fear of self-victimization; FOV: fear of others' victimization, HMI: ln (horizontal mean illuminance); VMI: ln (vertical minimum illuminance); VU: vertical uniformity, In the interaction term (gender × illuminance), the "illuminance" variable, which is multiplied by the gender variable, refers to the specific illuminance variable that is applied in the current model among the three. All variables presented in Table 4 are controlled, with the entire results presented in the Supplementary Materials. Only significant coefficients are suggested in this table (number of observations = 622)

*is the case where the 95% confidence interval does not contain the value "0," which means that the coefficient is significant

association with fear of crime, as shown in Model A-2, even after controlling for the valence difference. Another noteworthy point is that Model B, which includes both the valence difference and illuminance variables, demonstrates a higher model fit compared to Models A-1 and A-2, which included these variables separately (see the Supplementary Materials).

Table 8 provides an overview of the coefficients and significance levels of the control variables, highlighting statistically significant effect (at the 5% probability level) on the valence difference or fear of crime variables in Models A-1 and A-2. Several control variables were noteworthy, including gender (male = 1), gender × illuminance (interaction term), frequency of walking on a narrow street, experience of crimes, sense of presence/immersion, and adverse physiological reactions.

The main focus of this study was the effect of the gender (male = 1) and the interaction term between previously examined gender and illuminance. It is noteworthy that, in earlier models, all illuminance variables exhibited a positive relationship with valence difference and a negative relationship with fear of crime. As posited earlier the results showed that gender (male = 1) demonstrated a negative relationship with fear of crime across all models. This suggests that (1) men may inherently experience less fear than women because of innate biological differences or (2) men may underreport their fear of crime due to a social desirability bias (Sutton and Farrall 2005).

Nevertheless, results indicate that gender did not have a significant effect on valence in any of the models. This suggests that no innate biological differences exist between men and women in terms of positive emotions, as measured by valence (which is expected to be related to fear of crime) (Pierce and Kirkpatrick 1992). Moreover, the interaction term did not demonstrate a significant relationship with valence difference across all models. This implies that changes in emotional states due to variations in illuminance are not influenced by gender. Unlike subjective self-reported fear of crime, no gender-based differences were observed in the objectively measured valence difference. This finding tentatively supports the possibility that men might underreport their level of fear of crime to some extent (Sutton and Farrall 2005).

Meanwhile, the interaction term showed a positive and significant relationship with fear of crime, with the corresponding coefficient size being smaller than that of the illuminance variables in all models (see both Tables 6 and 8). This implies that the reduction in fear of crime due to

increased illuminance was partially offset by the positive coefficient of the interaction term. In other words, the decrease in fear of crime with increasing illuminance was not as pronounced for men as it was for women. Conversely, it can be interpreted that the increase in fear of crime with decreasing illuminance is more significant for women than for men. This suggests that men may be inherently less fearful of crime in darker environments compared to women. Thus, the impact of gender on fear of crime appears to be mixed with innate biological differences and social norms related to gender roles.

Regarding other control variables, the results demonstrated that the higher the perceived sense of presence and immersion in the recorded lighting environment, the lower the positive emotions and the higher the FSV. This outcome was expected, given that the videos were mostly shot at night; hence, the more realistic they appear, the more negative and fear-inducing they become. This finding suggests that the quality of VR experiences may influence the participants' environmental perceptions, potentially affecting the reliability of VR surveys. The crime experience variable also generally showed a negative relationship with valence difference and a positive relationship with FSV, supporting the theories and empirical evidence discussed in Sect. 2 (Quann and Hung 2002; Skogan 1986). Finally, participants who experienced stronger adverse physiological reactions exhibited higher levels of FSV. Further research is necessary to explore the underlying causes of this finding.

## 5 Conclusions

Using a VR experiment with 360° camera footage and EEG devices, this study explored the relationship between nighttime illuminance in Seoul's alleyways, participants' perceived fear of crime, and valence differences, a measure of emotional states. A cross-classified multilevel analysis demonstrated that higher illuminance levels were associated with reduced fear of crime and increased positive emotional states. Unlike previous studies that primarily relied on subjective psychological responses (Son et al. 2023), this study integrated EEG-derived valence differences as objective neurophysiological measures, demonstrating that brighter environment contributes to both a diminished fear of crime and enhanced emotional well-being. By bridging the VR experiment and EEG measurement, this research highlighted the broader role of lighting environments in shaping both psychological and neurophysiological responses.

Furthermore, this study sheds light on gender differences in fear of crime. We utilized EEG data collected through VR experiments to examine the potential underreporting of fear of crime due to social desirability biases, as suggested by Sutton and Farrall (2005). The results indicate that the lower fear of crime reported by men reflects a combination of both social norms leading to underreporting and innate biological differences in emotional responses to fear-inducing environments. This study underscores the importance of mixed methods to capture the complex interactions among gender, lighting, and fear of crime.

Finally, participants' perceived level of immersion in the VR environment also emerged as a significant factor, influencing both EEG-measured neurophysiological responses and their perceived fear of crime. As participants found the VR environments more realistic, they reported stronger psychological and emotional reactions, highlighting VR's effectiveness as a tool for investigating the influence of environmental factors on fear of crime.

These findings underscore the potential of integrating EEG and VR as innovative tools for urban illuminance and fear of crime studies. This approach particularly enables urban designers and landscape architects to objectively assess the emotional and psychological impacts of lighting, ensuring safe public spaces. Hence, this study provides valuable perspectives by offering a methodological approach that evaluates the effects of urban environmental changes, including lighting, before real-world implementation. It also contributes to a more inclusive urban planning strategy by demonstrating that lighting environment design should accommodate gender-specific emotional and psychological responses.

Despite these significant contributions, several limitations must be addressed in future studies. First, there are inherent limitations related to the 360° videos used in the experiment. Due to practical constraints, a monoscopic format was used. While this format has the advantage of causing less visual discomfort from vergence-accommodation conflicts when viewed through HMDs (Lambooij et al. 2009; Hartle and Wilcox 2022), it fundamentally lacks binocular depth cues, which may limit emotional immersion and perceived realism. Additionally, rather than using videos recorded while navigating through the streets, we employed stationary 360° recordings captured from fixed locations. This was a deliberate choice, as RVR experiments generally offer less experimental control than simulated VR (SVR), and maintaining consistent environmental conditions across videos becomes more challenging as the

spatial coverage expands. For this reason, we focused on fixed viewpoints to minimize variation in non-target variables. Nevertheless, such constraints in video format may limit emotional engagement, which is critical in perception research. Future studies should consider comparing different approaches, including stereoscopic and dynamic recordings, as well as SVR environments based on digital twins of actual sites.

Second, although we measured two representative emotional states—valence and arousal—using neural response data (EEG), only valence was included in the final analysis. As previously mentioned, this was because the arousal showed no statistically significant associations with either illuminance or fear of crime in any of the models. This may stem from the complexity of our experimental setup. While we employed EEG devices suitable for academic research, arousal is known to be more challenging to measure accurately than valence (Galvão et al. 2021; Gkintoni et al. 2025). Therefore, future research may benefit from using higher-grade EEG systems or implementing more stable experimental conditions.

Third, our study exclusively involved young adults in their twenties, which limits the generalizability of the findings. Although early VR studies commonly recruited young and healthy participants due to concerns about VR sickness and low familiarity with the technology, recent research has expanded to include children and older adults—demographics that are often more vulnerable to traffic accidents and crime (Lee et al. 2025; Schaumburg et al. 2025; Yang et al. 2025). Future studies should include such vulnerable groups, as they may have significantly different perceptual and cognitive responses compared to younger adults.

Finally, this study did not differentiate among types of fear of crime—such as fear of theft, physical violence, or sexual assault—due to time constraints that limited the length of the VR experiment in order to reduce potential side effects like simulator sickness. In sum, future studies should build upon these findings by enhancing the sensory realism of virtual stimuli, improving the accuracy and stability of physiological measurements, including more diverse and vulnerable populations, and exploring specific dimensions of crime-related fear.

## Appendix 1: Date and time of illuminance measurement for each site

| | [Site A] Residential, high pedestrian volume | [Site B] Residential, low pedestrian volume | [Site C] Commercial, high pedestrian volume | [Site D] Commercial, low pedestrian volume |
|---|---|---|---|---|
| Day | April 26th, 2021 (Mon) | April 30th, 2021 (Fri) | April 28th, 2021 (Wed) | April 29th, 2021 (Thu) |
| Weather | Cloudy | Cloudy | Generally cloudy | Cloudy |
| Min. temperature | 10 °C | 11 °C | 13 °C | 12 °C |
| Max. temperature | 21 °C | 16 °C | 20 °C | 21 °C |
| Sunset* | 19:17 | 19:21 | 19:19 | 19:20 |
| 1st | 18:00 | 18:04 | 18:02 | 18:03 |
| 2nd | 18:30 | 18:34 | 18:32 | 18:33 |
| 3rd | 19:00 | 19:04 | 19:02 | 19:03 |
| 4th | 19:15 | 19:19 | 19:17 | 19:18 |
| 5th | 19:30 | 19:34 | 19:32 | 19:33 |
| 6th | 19:45 | 19:49 | 19:47 | 19:48 |
| 7th | 20:00 | 20:04 | 20:02 | 20:03 |
| 8th | 20:15 | 20:19 | 20:17 | 20:18 |
| 9th | 20:30 | 20:34 | 20:32 | 20:33 |
| 10th | 20:45 | 20:49 | 20:47 | 20:48 |
| 11th | 21:00 | 21:04 | 21:02 | 21:03 |
| 12th | 22:00 | 22:04 | 22:02 | 22:03 |
| 13th | 22:30 | 22:34 | 22:32 | 22:33 |

The three time slots (8th, 10th, and 12th measurements) that showed no significant changes in illuminance compared to adjacent slots were excluded in the experiment

* Sunset time is based on Seoul (GMT+9)

## Appendix 2: Results of the "sense of presence" survey

| Item | Frequency of response | | | | | Mean | S.D |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Sense of physical space | | | | | | 3.768 | |
| I had a sense of being in the scenes displayed | 1 | 5 | 14 | 37 | 38 | 4.116 | 0.921 |
| I felt I was visiting the places in the displayed environment | 1 | 6 | 11 | 44 | 33 | 4.074 | 0.902 |
| I felt that the characters and/or objects could almost touch me | 7 | 20 | 31 | 29 | 8 | 3.116 | 1.071 |
| Engagement | | | | | | 4.046 | |
| I felt involved in the displayed environment | 0 | 1 | 8 | 44 | 42 | 4.337 | 0.678 |
| I enjoyed myself | 1 | 1 | 7 | 45 | 41 | 4.305 | 0.745 |
| My experience was intense | 1 | 13 | 32 | 36 | 13 | 3.495 | 0.933 |
| Ecological validity | | | | | | 4.470 | |
| The content seemed believable to me | | | 1 | 18 | 76 | 4.789 | 0.435 |
| The displayed environment seemed natural | | | 3 | 24 | 68 | 4.684 | 0.531 |
| I had a strong sense that the character and objects were solid | 2 | 7 | 21 | 30 | 35 | 3.937 | 1.040 |
| Negative effects | | | | | | 1.582 | |
| I felt dizzy | 60 | 12 | 11 | 11 | 1 | 1.747 | 1.120 |
| I felt nauseous | 72 | 17 | 6 | | | 1.305 | 0.585 |
| I felt I had a headache | 79 | 15 | 1 | | | 1.179 | 0.412 |
| I had eyestrain | 42 | 19 | 19 | 13 | 2 | 2.095 | 1.177 |

The "sense of presence" indicators are adapted from Lessiter et al. (2001, p.290)

Number of observations: 95

## Appendix 3: Factor analysis results

| Item | Factor | | |
|---|---|---|---|
| | Sense of presence and engagement | Adverse physiological reactions | Ecological validity |
| I felt I was visiting the places in the displayed environment | **0.770** | −0.005 | −0.084 |
| My experience was intense | **0.768** | 0.059 | 0.248 |
| I had a sense of being in the scenes displayed | **0.725** | 0.132 | 0.264 |
| I felt involved in the displayed environment | **0.710** | −0.086 | 0.261 |
| I enjoyed myself | **0.709** | −0.070 | −0.026 |
| I felt that the characters and/or objects could almost touch me | **0.550** | 0.301 | 0.333 |
| I had a strong sense that the character and objects were solid | **0.538** | −0.023 | 0.433 |
| I felt dizzy | 0.054 | **0.881** | −0.085 |
| I felt nauseous | −0.068 | **0.833** | 0.158 |
| I felt I had a headache | 0.021 | **0.778** | −0.248 |
| I had eyestrain | 0.055 | **0.690** | −0.150 |
| The displayed environment seemed natural | 0.182 | −0.082 | **0.798** |
| The content seemed believable to me | 0.177 | −0.237 | **0.793** |
| Number of items | 7 | 4 | **2** |
| Cronbach`s alpha | 0.833 | 0.755 | 0.703 |

Bold values represent variables that load together on the same factor in the factor analysis results

Extraction method: principal component analysis

Rotation method: Varimax with Kaiser normalization (rotation converged in 4 iterations)

## Appendix 4: Measured illuminance by site and time

| Time | Site A | | Site B | | Site C | | Site D | |
|---|---|---|---|---|---|---|---|---|
| | Vertical minimum illuminance | Horizontal mean illuminance | Vertical minimum illuminance | Horizontal mean illuminance | Vertical minimum illuminance | Horizontal mean illuminance | Vertical minimum illuminance | Horizontal mean illuminance |
| 18:00 | 1234.00 | 3107.11 | 934.00 | 2336.06 | 1827.00 | 4787.22 | 1313.00 | 3498.33 |
| 18:30 | 458.00 | 1090.61 | 351.00 | 877.22 | 1065.00 | 2466.44 | 337.00 | 907.06 |
| 19:00 | 192.70 | 584.44 | 114.50 | 341.22 | 276.00 | 691.00 | 135.80 | 313.43 |
| 19:15 | 50.30 | 123.37 | 25.23 | 73.11 | 93.70 | 200.20 | 47.90 | 126.15 |
| 19:30 | 5.32 | 17.55 | 3.06 | 8.51 | 15.62 | 45.87 | 21.50 | 61.58 |
| 19:45 | 0.58 | 5.16 | 0.46 | 1.03 | 6.21 | 18.44 | 7.40 | 22.27 |
| 20:00 | 0.52 | 4.75 | 0.32 | 0.81 | 6.84 | 17.54 | 8.90 | 26.75 |
| 20:30 | 0.35 | 4.63 | 0.42 | 0.94 | 7.18 | 17.57 | 7.76 | 24.35 |
| 21:00 | 0.37 | 4.60 | 0.42 | 0.93 | 3.54 | 10.00 | 6.84 | 24.13 |
| 22:30 | 0.42 | 4.75 | 0.27 | 0.74 | 1.18 | 2.18 | 3.65 | 13.43 |

* Illuminance unit: lux

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10055-025-01211-3.

**Acknowledgements** We thank Editage (www.editage.com) for their professional English language editing services.

**Author contributions** Woojin Park: Data curation, formal analysis, investigation, methodology, software, visualization, writing—original draft, and writing—review & editing. Dongpil Son: Conceptualization, funding acquisition, methodology, project administration, resources, and writing—review & editing. Boyeong Im: Conceptualization, investigation, methodology, resources, and writing—review & editing. Jaeseok Her: Data curation, investigation, methodology, project administration, software, visualization, and writing—review & editing. Young-Jae Kim: Writing—original draft, and writing—review & editing. Seung-Nam Kim: Conceptualization, formal analysis, funding acquisition, methodology, project administration, resources, supervision, validation, writing—original draft, and writing—review & editing.

**Funding** This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2021R1C1C101333613; RS-2024-00457853). This work was also 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."

**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** This study was approved by the Chung-Ang University's 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

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

Atkins S, Husain S, Storey A (1991) The influence of street lighting on crime and fear of crime. Home Office, London

Baumer TL (1985) Testing a general model of fear of crime: data from a national sample. J Res Crime Delinq 22:239–255. https://doi.org/10.1177/0022427885022003004

Boomsma C, Steg L (2014a) Feeling safe in the dark: examining the effect of entrapment, lighting levels, and gender on feelings of safety and lighting policy acceptability. Environ Behav 46:193–212. https://doi.org/10.1177/0013916512453838

Boomsma C, Steg L (2014b) 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, 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

Bromm B, Meier W, Scharein E (1989) Pre-stimulus/post-stimulus relations in EEG spectra and their modulations by an opioid and an antidepressant. Electroencephalogr Clin Neurophysiol 73(3):188–197. https://doi.org/10.1016/0013-4694(89)90119-3

Castro-Toledo FJ, Perea-García JO, Bautista-Ortuño R, Mitkidis P (2017) Influence of environmental variables on fear of crime: comparing self-report data with physiological measures in an experimental design. J Exp Criminol 13:537–545. https://doi.org/10.1007/s11292-017-9295-1

Ceccato V (2020) The architecture of crime and fear of crime: Research evidence on lighting, CCTV and CPTED features 1. In: Crime and fear in public places. London, Routledge, pp 38–72

Chataway ML, Hart TC (2019) A social-psychological process of "fear of crime" for men and women: revisiting gender differences from a new perspective. Vict Offenders 14(2):143–164. https://doi.org/10.1080/15564886.2018.1552221

Cho HR, Kim S, Lee JS (2022) Spaces eliciting negative and positive emotions in shrinking neighbourhoods: a study in Seoul, South Korea, using EEG (electroencephalography). J Urban Health 99(2):245–259. https://doi.org/10.1007/s11524-022-00608-8

Choi JW, Kwon H, Choi J, Kaongoen N, Hwang C, Kim M, Kim BH, Jo S (2023) Neural applications using immersive virtual reality: a review on EEG studies. IEEE Trans Neural Syst Rehabil Eng 31:1645–1658. https://doi.org/10.1109/TNSRE.2023.3254551

Cohen MX (2017) Where does EEG come from and what does it mean? Trends Neurosci 40(4):208–218. https://doi.org/10.1016/j.tins.2017.02.004

Conklin JE (1975) The impact of crime. Macmillan, New York

Evans DJ, Fletcher M (2000) Fear of crime: testing alternative hypotheses. Appl Geogr 20(4):395–411. https://doi.org/10.1016/S0143-6228(00)00011-4

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

Fetchenhauer D, Buunk BP (2005) How to explain gender differences in fear of crime: towards an evolutionary approach. Sexualities Evol Gender 7(2):95–113. https://doi.org/10.1080/00207170500111044

Fisher B, Nasar J (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

Galvão F, Alarcao SM, Fonseca MJ (2021) Predicting exact valence and arousal values from EEG. Sensors. https://doi.org/10.3390/s21103414

Garcia-Moreno FM, Bermudez-Edo M, Rodríguez-Fórtiz MJ, Garrido JL (2020) A CNN-LSTM deep learning classifier for motor imagery EEG detection using a low-invasive and low-cost BCI headband. In: 2020 16th International Conference on Intelligent Environments (IE), IEEE, pp 84–91. https://doi.org/10.1109/IE49459.2020.9155016

Gkintoni E, Aroutzidis A, Antonopoulou H, Halkiopoulos C (2025) From neural networks to emotional networks: a systematic review of EEG-based emotion recognition in cognitive neuroscience and real-world applications. Brain Sci. https://doi.org/10.3390/brainsci15030220

Haans A, de Kort YA (2012) Light distribution in dynamic street lighting: two experimental studies on its effects on perceived safety, prospect, concealment, and escape. J Environ Psychol 32(4):342–352. https://doi.org/10.1016/j.jenvp.2012.05.006

Hartle B, Wilcox LM (2022) Stereoscopic depth constancy for physical objects and their virtual counterparts. J vis 22(4):9. https://doi.org/10.1167/jov.22.4.9

Hu X, Qian Y, Pickett ST, Zhou W (2020) Urban mapping needs up-to-date approaches to provide diverse perspectives of current urbanization: a novel attempt to map urban areas with nighttime light data. Landsc Urban Plann 195:103709. https://doi.org/10.1016/j.landurbplan.2019.103709

Jacobs J (1961) Death and life of great american cities. Random House, New York

Jebelli H, Hwang S, Lee S (2018) EEG-based workers' stress recognition at construction sites. Autom Constr 93:315–324. https://doi.org/10.1016/j.autcon.2018.05.027

Jeffery CR (1971) Crime prevention through environmental design. Sage, California

Kannathal N, Acharya UR, Lim CM, Sadasivan PK (2005) Characterization of EEG—a comparative study. Comput Methods Programs Biomed 80(1):17–23. https://doi.org/10.1016/j.cmpb.2005.06.005

Kappenman ES, Luck SJ (2010) The effects of electrode impedance on data quality and statistical significance in ERP recordings. Psychophysiology 47(5):888–904. https://doi.org/10.1111/j.1469-8986.2010.01009.x

Kim SK, Kang HB (2018) An analysis of fear of crime using multimodal measurement. Biomed Signal Process Control 41:186–197. https://doi.org/10.1016/j.bspc.2017.12.003

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

Kim DH, Noh KB (2018) Perceived adequacy of illumination and pedestrians' night-time experiences in urban obscured spaces: a case of London. Indoor Built Environ 27(8):1134–1148. https://doi.org/10.1177/1420326X18790630

Kim S, Park H, Choo S (2021) Effects of changes to architectural elements on human relaxation-arousal responses: based on VR and EEG. Int J Environ Res Public Health 18(8):4305. https://doi.org/10.3390/ijerph18084305

Kliemann D, Jacoby N, Anzellotti S, Saxe RR (2016) Decoding task and stimulus representations in face-responsive cortex. Cogn Neuropsychol 33(7–8):362–377. https://doi.org/10.1080/02643294.2016.1256873

Korean Agency for Technology and Standards (2019) Road traffic signs (KS A 3701:2019)

Krigolson OE, Williams CC, Norton A, Hassall CD, Colino FL (2017) Choosing MUSE: validation of a low-cost, portable EEG system for ERP research. Front Neurosci 11:109. https://doi.org/10.3389/fnins.2017.00109

KSA3701:2019 (2019) Lighting for roads. Seoul: Korean Standards Association (KSA)

Lambooij M, Fortuin M, Heynderickx I, IJsselsteijn W (2009) Visual discomfort and visual fatigue of stereoscopic displays: a review. J Imaging Sci Technol. https://doi.org/10.2352/J.ImagingSci.Technol.2009.53.3.030201

Lee C, Yun H, Lee J, Kim SN (2025) Safety on the line: examining the impacts of crosswalk design on child's perceived safety, cautious behavior, and visual attention with VR technology. Accid Anal Prev 213:107959. https://doi.org/10.1016/j.aap.2025.107959

Lessiter J, Freeman J, Keogh E, Davidoff J (2001) A cross-media presence questionnaire: the ITC-sense of presence inventory. Presence Teleoperators Virtual Environ 10(3):282–297. https://doi.org/10.1162/105474601300343612

Lin JHT (2017) Fear in virtual reality (VR): fear elements, coping reactions, immediate and next-day fright responses toward a survival horror zombie virtual reality game. Comput Hum Behav 72:350–361. https://doi.org/10.1016/j.chb.2017.02.057

Loewen LJ, Steel GD, Suedfeld P (1993) Perceived safety from crime in the urban environment. J Environ Psychol 13(4):323–331. https://doi.org/10.1016/S0272-4944(05)80254-3

Marín-Morales J, Higuera-Trujillo JL, Greco A, Guixeres J, Llinares C, Scilingo EP, Alcañiz M, Valenza G (2018) Affective computing

in virtual reality: emotion recognition from brain and heartbeat dynamics using wearable sensors. Sci Rep 8(1):13657. https://doi.org/10.1038/s41598-018-32063-4

Martínez-Tejada LA, Puertas-González A, Yoshimura N, Koike Y (2021) Exploring EEG characteristics to identify emotional reactions under videogame scenarios. Brain Sci 11(3):378. https://doi.org/10.3390/brainsci11030378

Maslow AH (1943) A theory of human motivation. Psychol Rev 50(4):370–396. https://doi.org/10.1037/h0054346

Mattoni B, Burattini C, Bisegna F, Fotios S (2017) The pedestrian's perspective: How do illuminance variations affect reassurance? In: 2017 IEEE international conference on environment and electrical engineering and 2017 IEEE industrial and commercial power systems Europe (EEEIC/I&CPS Europe), IEEE, pp 1–5. https://doi.org/10.1109/EEEIC.2017.7977648

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 Behav 49(3):227–254. https://doi.org/10.1177/0013916515626546

Newman O (1972) Defensible space: crime prevention through urban design. Macmillan, New York

Olszewska-Guizzo A, Sia A, Fogel A, Ho R (2020) Can exposure to certain urban green spaces trigger frontal alpha asymmetry in the brain?—preliminary findings from a passive task EEG study. Int J Environ Res Public Health 17(2):394. https://doi.org/10.3390/Ijerph17020394

Painter K (1996) The influence of street lighting improvements on crime, fear and pedestrian street use, after dark. Landsc Urban Plann 35(2–3):193–201. https://doi.org/10.1016/0169-2046(96)00311-8

Perkins DD, Wandersman A, Rich RC, Taylor R (1993) The physical environment of street crime: defensible space, territoriality and incivilities. J Environ Psychol 13(1):29–49. https://doi.org/10.1016/S0272-4944(05)80213-0

Pierce KA, Kirkpatrick DR (1992) Do men lie on fear surveys? Behav Res Ther 30(4):415–418. https://doi.org/10.1016/0005-7967(92)90055-1

Quann N, Hung K (2002) Victimization experience and the fear of crime. In: Nieuwbeerta P (ed.) Crime victimization in comparative perspective. Results from the International Crime Victims Survey, 1989–2000, The Hague: Netherlands Institute for the Study of Crime and Law Enforcement, pp 301–316

Ratti E, Waninger S, Berka C, Ruffini G, Verma A (2017) Comparison of medical and consumer wireless EEG systems for use in clinical trials. Front Hum Neurosci 11:398. https://doi.org/10.3389/fnhum.2017.00398

Rockcastle S, Danell M, Calabrese E, Sollom-Brotherton G, Mahic A, Van Den Wymelenberg K, Davis RJLR (2021) Comparing perceptions of a dimmable LED lighting system between a real space and a virtual reality display. Light Res Technol 53(8):701–725. https://doi.org/10.1177/1477153521990039

Sampson RJ, Raudenbush SW, Earls F (1997) Neighborhoods and violent crime: a multilevel study of collective efficacy. Science 277(5328):918–924. https://doi.org/10.1126/science.277.5328.918

Schaumburg M, Imtiaz A, Zhou R, Bernard M, Wolbers T, Segen V (2025) Immersive virtual reality for older adults: challenges and solutions in basic research and clinical applications. Ageing Res Rev 109:102771. https://doi.org/10.1016/j.arr.2025.102771

Schneider S, Bengler K (2020) Virtually the same? Analysing pedestrian behaviour by means of virtual reality. Transp Res Part F Traffic Psychol Behav 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

Scorpio M, Laffi R, Masullo M, Ciampi G, Rosato A, Maffei L, Sibilio S (2020) Virtual reality for smart urban lighting design: review, applications and opportunities. Energies 13(15):3809. https://doi.org/10.3390/en13153809

Scorpio M, Laffi R, Teimoorzadeh A, Sibilio S (2021) Immersive virtual reality as a tool for lighting design: applications and opportunities. J Phys Conf Ser 2042(1):012125. https://doi.org/10.1088/1742-6596/2042/1/012125

Shaw CR, Mckay MD (1942) Juvenile delinquency and urban areas. Chicago University Press, Chicago

Siirtola P, Tamminen S, Chandra G, Ihalapathirana A, Röning J (2023) Predicting emotion with biosignals: a comparison of classification and regression models for estimating valence and arousal level using wearable sensors. Sensors 23(3):1598. https://doi.org/10.3390/s23031598

Skogan W (1986) Fear of crime and neighborhood change. Crime Justice 8:203–229

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. https://doi.org/10.1016/j.cities.2022.104184

Son D, Im B, Her J, Park W, Kang SJ, Kim SN (2024) Street lighting environment and fear of crime: a simulated virtual reality experiment. Virtual Reality 29:8. https://doi.org/10.1007/s10055-024-01080-2

Statistics Korea (2022) Safety level for nighttime walking. Available at: https://kosis.kr/statHtml/statHtml.do?sso=ok&returnurl=https%3A%2F%2Fkosis.kr%3A443%2FstatHtml%2FstatHtml.do%3Flist_id%3D101_D21C%26obj_var_id%3D%26seqNo%3D%26query%3D%EC%95%BC%EA%B0%84+%EC%95%88%EC%A0%84%26tblId%3DDT_1SSSA132R%26vw_cd%3DMT_ZTITLE%26language%3Dkor%26orgId%3D101%26conn_path%3DMT_ZTITLE%26itm_id%3D%26lang_mode%3Dko%26. Accessed 11 Jan 2022

Suhaimi NS, Mountstephens J, Teo J (2020) EEG-based emotion recognition: a state-of-the-art review of current trends and opportunities. Comput Intell Neurosci 2020:8875426. https://doi.org/10.1155/2020/8875426

Sutton RM, Farrall S (2005) Gender, socially desirable responding and the fear of crime: are women really more anxious about crime? Br J Criminol 45(2):212–224. https://doi.org/10.1093/bjc/azh084

Teplan M (2002) Fundamentals of EEG measurement. Meas Sci Rev 2(2):1–11

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(8):889–912. https://doi.org/10.1177/0013916517718888

Warr M (2000) Fear of crime in the United States: avenues for research and policy. Crim Justice 4(4):451–489

Wu S (2014) Investigating lighting quality: examining the relationship between perceived safety and pedestrian lighting environment. PhD Thesis, Virginia Tech, Blacksburg, VA, United States

Yang Q, Zhang L, Chang F, Yang H, Chen B, Liu Z (2025) Virtual reality interventions for older adults with mild cognitive impairment: systematic review and meta-analysis of randomized

controlled trials. J Med Internet Res 27:e59195. https://doi.org/10.2196/59195

Yin PP (1980) Fear of crime among the elderly: some issues and suggestions. Soc Probl 27(4):492–504. https://doi.org/10.2307/800177

Youssef AE, Ouda HT, Azab M (2018) MUSE: A portable cost-efficient lie detector. In: 2018 IEEE 9th annual information technology, electronics and mobile communication conference (IEMCON), IEEE, pp 242–246. https://doi.org/10.1109/IEMCON.2018.8614795

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