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Research Article

CPTED-based analysis of factors influencing perceived safety in the street environment of Nagoya

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ABSTRACT

Grounded in Crime Prevention Through Environmental Design (CPTED) and informed by social-psychological theory, this study examines how street-environment features shape pedestrians' perceived safety through normative cueing and perceived guardianship. We combined a field survey and spatial analysis to sample representative sites in the Shinsakae district (Nagoya), then conducted laboratory experiments comprising eye-tracking, Semantic Differential (SD) ratings, and a virtual-reality (VR) replication. Stimuli were 24 photographs (12 daytime, 12 nighttime). Fifty participants (architecture=20; non-architecture=30) first viewed photographs while gaze behavior was recorded, followed by SD ratings on 22 bipolar adjective pairs; a subset of scenes was presented in VR. Areas of Interest (AOIs) were defined by seven CPTED-related factors that also function as social signals: lighting and sightlines (normative clarity, reduced ambiguity), cleanliness vs. untidiness (injunctive norms), greenery (affect regulation), signage/graffiti and fly-posting (disorder cues), and pedestrian/vehicle activity (perceived capable guardianship and social density). Eye-tracking heat maps and scan paths showed consistent attention to lighting elements, moving vehicles, and salient signage; untidy cues captured attention in ways associated with lower safety ratings. SD results converged with the gaze patterns: lighting and cleanliness were the most influential positive contributors, whereas visible disorder reduced perceived safety; the VR condition approximated daytime judgments but not nighttime. Taken together, the findings suggest that physical design acts partly by shaping normative expectations and perceived guardianship—pointing to interventions that pair maintenance and lighting with place management to strengthen collective efficacy and the salience of prosocial norms.

Keywords: urban street design; safety perception; CPTED; eye-tracking, virtual reality; social psychology; social norms; collective efficacy; pedestrians

1. Introduction

1.1. Background and aim

With the rapid progression of urbanization, public concern for safety and environmental quality has grown. Against this backdrop, Crime Prevention Through Environmental Design (CPTED) has emerged as a planning theory that reduces opportunities for crime through environmental design, thereby enhancing residents' sense of safety and quality of life. CPTED is commonly organized into four principles—target

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hardening, access control, natural surveillance, and territorial reinforcement—and has been promoted by administrative bodies such as the Metropolitan Police Department[1,2] (**Table 1**).

Table 1. The four principles of CPTED (Source: Tokyo metropolitan police department).

Principle	Description
①Target hardening	Physically strengthen potential targets (e.g., robust locks, security glazing) to resist forced entry and deter intrusion.
②Access control	Create boundaries and control entry so people cannot easily approach premises or buildings.
③Natural surveillance	Secure sightlines from streets and windows and improve lighting so "eyes on the street" can monitor surroundings and prevent intrusion.
④Territorial reinforcement	Improve maintenance of homes and their surroundings and encourage resident activity/interaction to signal ownership and create an environment that discourages outsiders from entering.

Although CPTED theory and practice have spread worldwide, systematic evaluations of its concrete application and effectiveness in urban settings—particularly in major regional cities such as Nagoya—remain limited. One reason is that effective CPTED implementation requires customization to a city's characteristics and culture; even within a regional city like Nagoya, urban environments are diverse, and practice-oriented analyses that address district-specific issues and needs are labor-intensive. In recent years, as urban activities in Nagoya have diversified, crime prevention has become a key policy issue, prompting the need for measures that focus on improving the safety of the urban environment and enhancing pedestrians' perceived safety in public streets. Here, the safety of the urban environment concerns physical elements that deter crime—such as lighting, surveillance cameras, and improved access control—whereas pedestrians' perceived safety refers to the subjective feeling of being safe in a place—that is, experiencing security in day-to-day settings with minimal anxiety about victimization (Syropoulos et al., 2024[5]; Himschoot et al., 2024[6])." Accordingly, regional cities would benefit from the systematic application of CPTED and factor-by-factor analyses that clarify how its principles shape individuals' perceived safety—for example, better lighting and sightlines (natural surveillance) are associated with higher perceived safety, visible disorder/cleanliness cues (territorial reinforcement) influence safety appraisals, and greening or place-maintenance interventions reduce safety concerns—within standardized CPTED processes (van Rijswijk & Haans, 2018[7]; Keizer, Lindenberg, & Steg, 2008[8]; Branas et al., 2018[9]; Cozens & Love, 2015; Cozens, 2022)."Scope clarification. In this paper, 'perceived safety' specifically refers to pedestrians' subjective appraisal while using streets and sidewalks. This focus is consistent with our stimuli—24 photographs captured from typical pedestrian positions—and with our outcome measures of pedestrians' visual safety perception.

In this study, safety perception refers to an individual's subjective appraisal of the safety of their immediate environment. This perception is shaped not only by how one responds to potential threats thought to be present in a place but also by social, cultural, psychological, and environmental factors.

To ground our approach, the next subsection reviews prior work on environmental and social-psychological determinants of perceived safety and the measurement tools used in this field (Section 1.2).

Methodological rationale—VR & eye-tracking. We combine VR with eye-tracking because these tools are well-suited to the study of perceived safety. VR offers high experimental control and ecological realism, allowing us to manipulate lighting, sightlines, and social density (day vs. night; cleaner vs. untidy scenes) while holding other features constant and safely recreating conditions that are impractical to test in situ;

immersion in VR is also associated with more naturalistic responses through increased presence (Pan & Hamilton, 2018[10]; Parsons, 2015[11]; Cummings & Bailenson, 2016[12]; Slater, 2009[13]). Eye-tracking provides moment-by-moment, objective indices of overt attention (e.g., fixation counts/durations, time-to-first-fixation, pupil diameter) that can be spatially mapped to CPTED-relevant areas of interest, thereby complementing SD ratings and reducing sole reliance on self-report (Holmqvist et al., 2011[14]; Duchowski, 2017[15]; Hessels et al., 2025[16]; see also recent urban-environment applications: Yuan et al., 2025[17]).

Overview of objectives. Building on the above background, this paper aims to (i) identify and estimate the relative importance of seven CPTED-based factors—cleanliness, lighting, retail/business type, greening, people, vehicles, and graffiti/fly-posting—on pedestrians' perceived safety in Nagoya's street environment; (ii) compare day–night differences and assess how well a VR replication approximates real-world judgments; (iii) integrate eye-tracking indices with SD ratings to link overt attention to safety appraisals; and (iv) derive actionable planning and place-management recommendations for the Shinsakae district. A fuller statement of objectives follows in Section 1.2.6.

1.2. Literature review, social-psychological mechanisms, research gaps, and aims

1.2.1. Foundations and domain evidence

Classic urbanism argues that design and patterns of use shape everyday safety. Jacobs (1961)[3] posited that eyes on the street—enabled by permeable frontages, mixed uses, and short blocks—support safer sidewalks, while Newman (1972)[4] translated similar ideas into CPTED mechanisms (natural surveillance, territorial reinforcement, etc.). Subsequent studies document robust links between lighting/sightlines and perceived safety[18], with cleanliness/order and place maintenance/greening also associated with higher reassurance[19]; effects of human activity/retail mix[20,21] tend to be context-dependent and strongest when uses are well managed and visibility is preserved[22-27].

1.2.2. VR applications in perceived-safety research (brief review)

In the last decade, virtual reality (VR) has been used to examine how lighting and time-of-day shape perceived safety and fear of crime in urban streets: simulated-VR studies show that higher nighttime illuminance and improved lighting configurations reduce fear and raise perceived safety in narrow residential environments[28,29]; related work combines VR with physiological indices (e.g., EEG) to link illuminance with neural and psychological responses. VR experiments also test environmental interventions (e.g., lighting and sound cues) that influence situational fear of crime, and street-crossing scenarios under varying illumination, demonstrating effects on users' safety judgements and behavior. Beyond streets, VR has been applied to park lighting quality and to validate VR-based streetscape evaluations, which report strong correspondence with (and in some cases stronger sensitivity than) conventional methods. A recent systematic review concludes that VR is a suitable tool to study environmental attributes affecting walking/cycling and related appraisals, supporting its use in perceived-safety research[30,31]. These precedents motivate our VR replication and help contextualize why our VR results approximate daytime judgments better than nighttime ones[32,33].

1.2.3. Environmental determinants relevant to CPTED

Building on prior work, we focus on seven recurring, CPTED-relevant factors: cleanliness, lighting, retail/business type, greening, people, vehicles, and graffiti/fly-posting. These factors appear consistently in street-safety appraisals and map onto CPTED principles such as natural surveillance, access control, and territorial reinforcement.

1.2.4. Social-psychological mechanisms

Beyond physical form, perceived safety is shaped by social–cognitive processes: (a) normative cues—cleanliness and the absence of graffiti communicate strong injunctive norms, while visible disorder can legitimize rule-breaking; (b) collective efficacy/guardianship—the visible presence of attentive others (shop staff, passersby, stewards) can raise perceived guardianship, whereas crowded yet anonymous settings may reduce confidence; (c) affect and appraisal—lighting, sightlines, and greening reduce ambiguity and lower threat appraisal, with greening offering restorative benefits; (d) territoriality and place identity—well-maintained, locally managed frontages and resident markers signal ownership and monitoring. Together, these pathways clarify how the seven factors convey social meaning that influences safety judgments.

1.2.5. Research gaps

Prior studies often examine single measures (e.g., lighting upgrades) or rely primarily on questionnaires/crime statistics, offering limited insight into how attention to specific street elements links to safety appraisals, especially across day vs. night and VR replications of real scenes. Comprehensive analyses that quantify the relative weight of multiple CPTED-relevant factors and align objective attention metrics (eye-tracking) with subjective evaluations remain scarce.

1.2.6. Present study: Objectives and contributions

In response, this study (i) identifies and estimates the relative importance of seven CPTED-based factors—cleanliness, lighting, retail/business type, greening, people, vehicles, and graffiti/fly-posting—on pedestrians' perceived safety in Nagoya's street environment; (ii) compares day–night differences and assesses how well a VR replication approximates real-world judgments; (iii) integrates eye-tracking indices with SD ratings to link overt attention to safety appraisals; and (iv) derives actionable planning and place-management recommendations for the Shinsakae district. Our contributions are twofold: combining eye-tracking with VR to articulate gaze–appraisal links, and quantifying factor weights to inform CPTED-based practice.

1.2.7. Conceptual model and hypotheses

We propose a CPTED-informed, social-psychological framework in which seven street-environment factors shape pedestrians' perceived safety through four pathways: (a) normative cues (injunctive norms signaled by cleanliness/disorder), (b) perceived guardianship/collective efficacy (visibility of attentive others and place management), (c) affective appraisal and ambiguity reduction (lighting, sightlines, greening lower threat appraisal), and (d) territoriality/place identity (maintenance and locally managed frontages signal ownership).(**Table 2**.)

Table 2. Mapping of factors to CPTED principles and pathways.

Factor (AOI)	**Primary CPTED principle(s)**	**Dominant social-psychological pathway(s)**	**Expected direction**
Lighting / sightlines	Natural surveillance	Ambiguity reduction; normative clarity	**Positive**
Cleanliness (absence of litter, tidy frontages)	Territorial reinforcement	Injunctive **normative cues**; place identity	**Positive**
Greening (well-kept trees/planters)	Territorial reinforcement; (contextually) access control	Affective restoration; ambiguity reduction	**Positive**

Factor (AOI)	Primary CPTED principle(s)	Dominant social-psychological pathway(s)	Expected direction
Retail/business type (frontage activity & management)	Natural surveillance; territorial reinforcement	Guardianship; normative clarity via place management	**Positive when day-serving/managed; neutral/negative when late-night, poorly managed**
People (pedestrian presence)	Natural surveillance	Guardianship; social density	**Positive at typical densities** (may attenuate at high density/night)
Vehicles (moving/stopped)	— (can obstruct natural surveillance)	Occlusion/noise; hazard appraisal	**Negative**
Graffiti/fly-posting	Territorial reinforcement (low)	Disorder → weakened norms & guardianship	**Negative**

Table 2. (*Continued*)

Hypotheses

- H1 (Lighting): Higher lighting/sightline quality is associated with higher perceived safety, mediated by lower ambiguity and clearer normative expectations[7,18,19].
- H2 (Cleanliness): Cleaner environments predict higher perceived safety via stronger injunctive norms[20,21].
- H3 (Greening): Well-maintained greening is positively associated with perceived safety through affective restoration and ambiguity reduction[8,21].
- H4 (People): Greater presence of pedestrians (within typical street densities) predicts higher perceived safety via perceived guardianship[9,22].
- H5 (Vehicles): Higher salience of vehicles (movement/occlusion) predicts lower perceived safety through hazard appraisal and reduced natural surveillance[23,24,27].
- H6 (Graffiti/fly-posting): Visible disorder predicts lower perceived safety by weakening normative cues and guardianship[27].
- H7 (Retail/business type): Frontages with day-serving, well-managed uses predict higher perceived safety than nightlife-oriented or poorly managed frontages[25,26].
- H8 (Time-of-day moderation): Daytime strengthens positive effects of lighting/people and attenuates the negative effects of vehicles/disorder; nighttime does the reverse.
- H9 (Attention–appraisal link): Eye-tracking attention to positive cues (lighting, tidy frontages, managed retail) is associated with higher safety ratings; attention to disorder/vehicles is associated with lower ratings.

1.3. Structure of the study

This study integrates field surveys with eye-tracking and VR experiments to comprehensively analyze how CPTED affects safety perception across different environments. Chapter 2 describes the study area, field data collection, and experiment-area selection. Chapter 3 details the eye-tracking and VR experimental designs used to elicit safety-perception responses. Chapter 4 presents and analyzes the experimental results. Chapter 5 (Discussion) compares findings against the four CPTED principles. Chapter 6 proposes concrete measures to improve safety in the Shinsakae district based on the foregoing analysis.

2. Study area and field survey

2.1. Study area

(1) Overview of the Shinsakae district, Nagoya

We selected Shinsakae (Chū-ku, Nagoya) as the study area (**Figure 1**). The district mixes business, commercial, and residential functions. Large and small office buildings line Hirokōji-dōri, and the area along the Airport Line and Hirokōji-dōri has also developed as an entertainment quarter (Higashi-Shinmachi) (**Figure 2**). According to Chū Ward Office statistics (September 2022)[36], the total population is 11,714, including 2,146 foreign residents (18.3%), the highest foreign-resident ratio in Nagoya; accordingly, there is a high concentration of foreign-run shops.

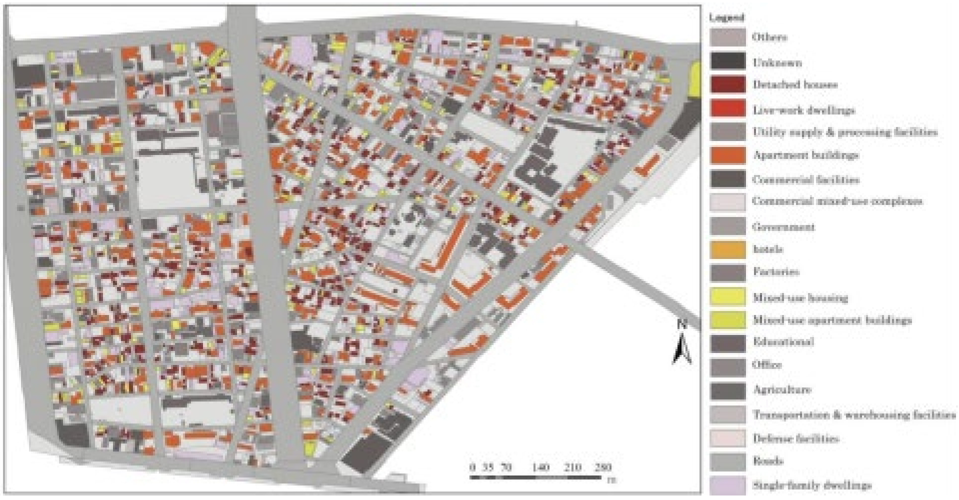


Figure 1. Distribution of building uses in the study area (Shinsakae, Nagoya, Japan).

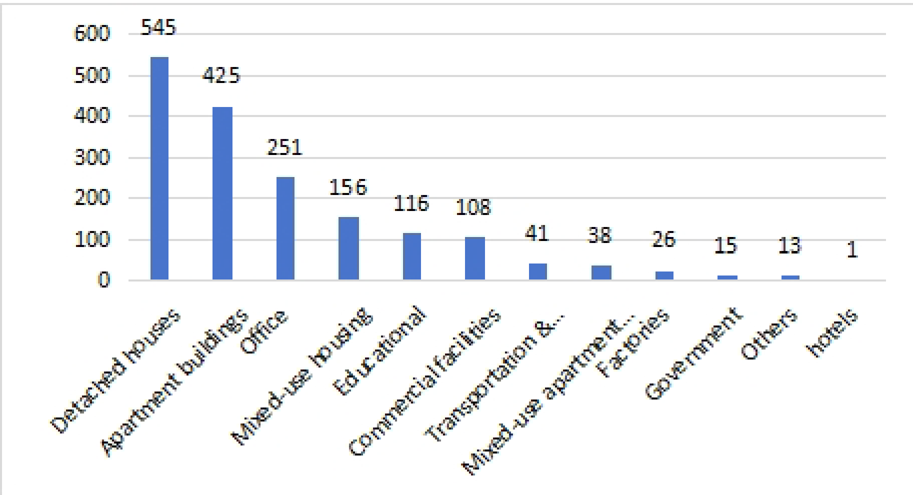


Figure 2. Building-type counts in the study area(Shinsakae, Nagoya, Japan).

(2) Rationale for Selection

Because Shinsakae can be expected to have relatively high crime incidence and presents specific safety challenges, a CPTED-based analysis offers critical input for countermeasures. Moreover, CPTED-based evaluation is useful at the design stage of new buildings and public spaces. Enhancing safety can increase the area’s attractiveness, support residential retention, and help attract visitors.

2.2. Field survey

(1) Purpose and outline

To select the experimental sites for the safety-perception study, we surveyed four items within Shinsakae: lighting, waste collection sites, cleanliness problems, and security cameras. For lighting, we recorded fixture types, illuminance, and spatial distribution. For waste collection sites, we recorded facility types, counts, and locations. For cleanliness, we assessed overall street-level cleanliness (including frontages) and recorded litter counts and distribution. For cameras, we recorded counts and locations (**Table 3**). We then created heat maps of these items in ArcGIS.

Table 3. Outline of the field survey (Shinsakae, Nagoya, Japan).

Purpose	**To select sites for the safety-perception evaluation experiments.**
Survey items	(1) Lighting—illuminance, count, location; (2) Security cameras—count, location; (3) Waste collection sites—type, location; (4) Untidy locations (litter, graffiti/fly-posting)—count, location.
Study area	Shinsakae, Naka Ward, Nagoya, Aichi Prefecture, Japan.
Method	On-site measurements; features recorded and mapped (ArcGIS).
Survey period	November–December 2023.

(2) Survey items and relation to CPTED

To ensure conceptual consistency, we consolidated the mapping between our field-survey items and the seven experimental AOI factors and the four CPTED principles (**Table 4**). Following the definitional anchors in **Table 1**, we treat CCTV as organized/mechanical surveillance under Natural surveillance, and we subsume maintenance/image (including waste-collection facilities, cleanliness, and graffiti/fly-posting) under Territorial reinforcement. Target hardening was not directly measured in this study.

Table 4. CPTED mapping of field-survey items and experimental AOI factors (consolidated).

Item (source)	Operationalization (brief)	Primary CPTED principle	Rationale (mechanism)
Lighting (field & AOI)	Illuminance counts/locations (field); AOI: luminous elements in images/VR	Natural surveillance	Increases nighttime visibility and "eyes on the street," raising detection risk and reassurance.
Security cameras (field)	Visible cameras/signage mapped	Natural surveillance (organized/mechanical)	Formal surveillance elevates perceived detection and complements natural sightlines. (Corrected from Access control).
Waste collection sites (field)	Facility type: boxed / netted / uncovered	Territorial reinforcement	Facility quality signals place management and ownership; better facilities reduce disorder and communicate care.
Untidy locations (field)	Litter counts; graffiti / fly-posting locations	Territorial reinforcement	Disorder cues imply weak informal control; maintenance signals ownership and norms.
Cleanliness (AOI)	AOI for clean/untidy foregrounds & frontages	Territorial reinforcement	Clean, maintained frontages communicate injunctive norms and capable guardianship.
Graffiti / fly-posting (AOI)	AOI for disorder signage/graffiti	Territorial reinforcement	Visible incivilities undermine norms and reassurance.
Greening (AOI)	AOI for trees/planters/vegetation	Territorial reinforcement	When maintained, greenery conveys care and positive image; may also modulate affect. (Sightlines managed to avoid refuge)
People (AOI)	AOI for pedestrians/staff	Natural surveillance	Presence of attentive others → perceived

Item (source)	Operationalization (brief)	Primary CPTED principle	Rationale (mechanism)
			capable guardianship/eyes on street.
Vehicles (AOI)	AOI for moving/parked vehicles	Access control	Traffic management and curb use regulate through-movement and permeability; vehicles can either support presence or obstruct sightlines depending on configuration.
Retail/business type (AOI)	Ground-floor use categories & frontage openness	Natural surveillance	Active, transparent frontages and staffed premises increase visibility and organized guardianship (land-use as social signal).

Table 4. (*Continued*)

Notes. *(i) We follow the* ***Table 1*** *four-principle formulation for definitional anchors; CCTV is treated as organized/mechanical surveillance within Natural surveillance. (ii) Maintenance/image elements (waste facilities, cleanliness, graffiti/fly-posting, and maintained greenery) are grouped under Territorial reinforcement. (iii) Target hardening was not directly measured in the current field/experimental setup.*

(3) Methods

The methods for each item were as follows (**Table 5**; **Figure 3**).

①Lighting: For streetlights, we placed a light meter on the ground directly beneath the source (20:00–24:00) and plotted measured values and locations on a map. For building-mounted lights (entrance lights and exterior garden lighting), we placed the meter on the nearest surface to the source and plotted the readings. We used the same approach for parking-lot lighting and illuminated signage.

②Security cameras: We plotted locations that had camera signage or cameras visible from the street.

③Waste collection sites: We mapped site types (e.g., netted, boxed, uncovered) and locations.

④Untidy locations: We mapped streets and public areas with scattered litter, fly-posting, or graffiti.

Table 5. Categories, counts, and proportions of survey items.

Survey item	Type	Description	Count	Proportion(%)
Lighting	Streetlight source	Lighting from streetlights	483	46
	Building-mounted source	Entrance/exterior lighting on buildings	272	26
	Parking-lot source	Lighting in parking areas	139	13
	Signboard source	Lighting from vending machines and shop signs	152	15
	Total lighting sources		1046	
Waste collection sites	Boxed type	Best; resistant to disturbance by crows	238	48
	Netted type	Ordinary; may be disturbed by crows	208	42
	Uncovered type	Poor; easily disturbed by crows	47	10
	Total waste-site count		493	
Security cameras	Security cameras	Cameras at houses, shops, and parking lots	574	100
	Total camera count		574	
Untidy locations	Scattered litter	Places with cigarette butts, paper, etc.	80	86
	Graffiti	Places with graffiti	12	13
	Fly-posting	Places with posted handbills	1	1
	Total untidy-location		93	

Survey item	Type	Description	Count	Proportion(%)
	count			

Table 5. (*Continued*)

Illuminance measurement (lighting)	Boxed waste-collection site	Netted waste-collection site	Uncovered waste-collection site
			

Figure 3. Example photographs from the field survey.

2.3. Organizing results and selecting experimental sites

Using ArcGIS and **Figure 4**, we generated heat maps (kernel density) for each item (**Figure 5**). To choose experimental sites, we focused on locations with the lowest composite safety-perception scores. First, we input the field-survey data (lighting, cameras, waste sites, dirty areas) into ArcGIS and produced kernel density maps for each. Next, we divided Shinsakae into a 30×30 m grid and conducted raster analysis. For each grid cell, we computed scores based on the survey items according to the ranges and criteria in **Table 6** From the software output, we identified the five lowest-scoring cells (**Figure 6**).

Waste-collection sites (quality-weighted).

Each waste-collection site was assigned a categorical quality score $q \in \{-5,0,+5\}$ for uncovered, netted, and boxed facilities, respectively. We produced separate KDEs by type and combined them linearly:

$$W^*(x) = (-5) \cdot \mathrm{KDE}_{\mathrm{uncovered}}(x) + 0 \cdot \mathrm{KDE}_{\mathrm{netted}}(x) + (+5) \cdot \mathrm{KDE}_{\mathrm{boxed}}(x).$$

The composite perceived-safety score at location x is:

$$S(x) = 10 \cdot \overline{L}(x) + 10 \cdot \overline{CCTV}(x) - 10 \cdot \overline{U}(x) + \overline{W}(x)$$

This operationalization matches our field scoring rule: lighting × 10 + cameras × 10 – untidy × 10 + waste-site count × (−5,0,+5), with the latter implemented via the quality-weighted KDE combination above.

1)Lighting	2)Waste collection sites
	

3)Security cameras

4)Untidy locations

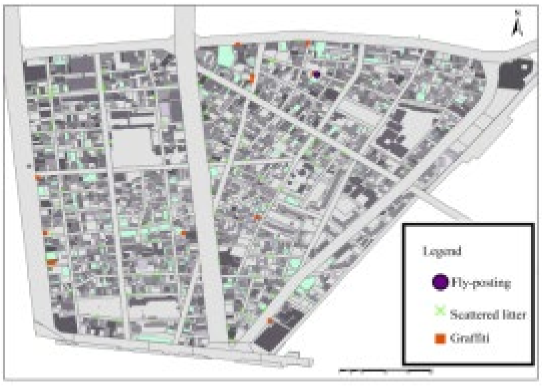
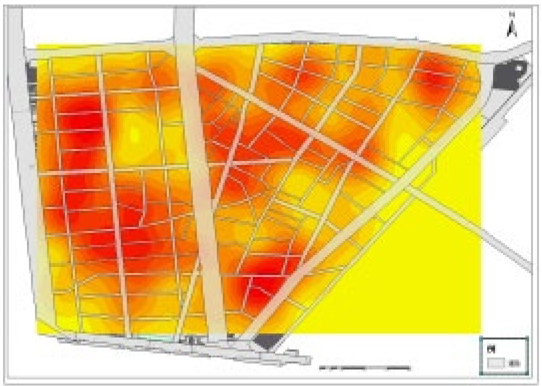


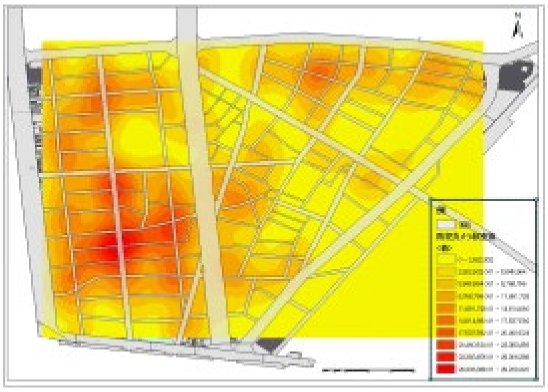
Figure 4. Spatial distribution of survey items.

1)Lighting

2)Waste collection sites



3)Security cameras



4)Untidy locations

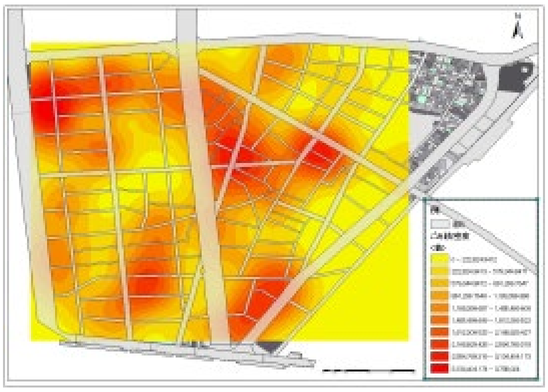


Figure 5. Kernel density analysis map of the study area.

Table 6. Initial ArcGIS scoring criteria.

Survey item	Rule	Score calculation
Lighting	Higher illuminance → higher score.	10
Waste collection sites	Uncovered sites → negative(-5); netted → medium(0); boxed → high(5).	−5~5
Security cameras	More installed cameras → higher score.	10

Survey item	Rule	Score calculation
Untidy locations (litter, graffiti/fly-posting)	More litter/graffiti → lower score; cleaner state → higher score.	−10

Table 6. (*Continued*)

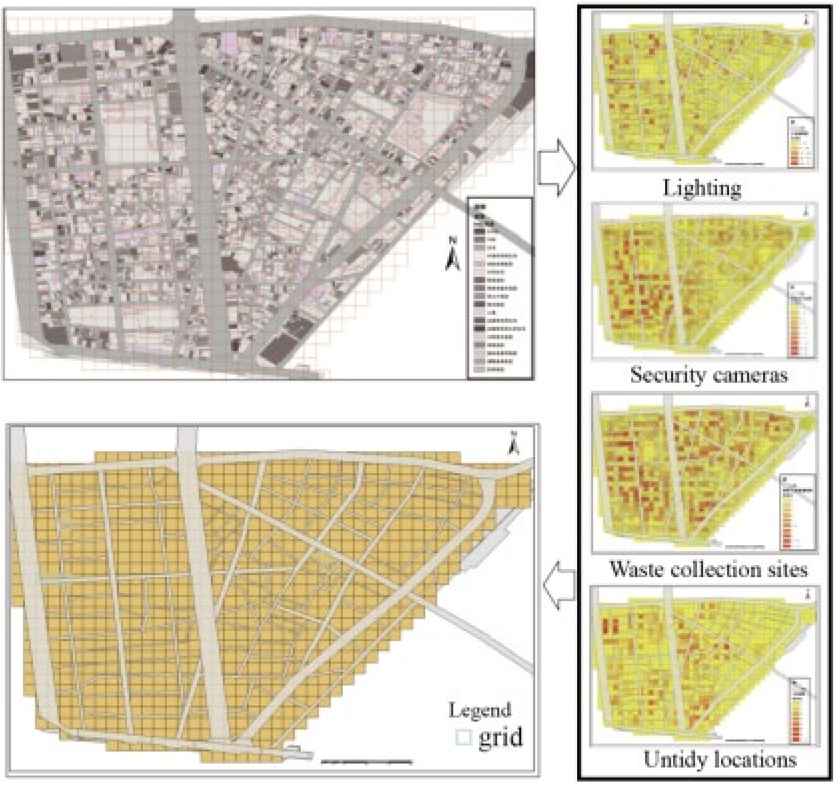


Figure 6. Grid-based selection of experimental sites in Shinsakae (30×30m grid).

The survey recorded 574 security cameras in the area, of which 540 were privately installed and located mostly on private property; only 34 cameras were installed in public areas. Given their small proportion in public space, we judged that cameras had a limited effect on street-level safety perception for this study and therefore did not use camera placement as a criterion in selecting the experimental sites.

Raster analysis of Shinsakae indicated that three of the five lowest-scoring cells clustered around 1-27 Shinsakae, Naka-ku, Nagoya (Kawaradōri). We selected as the experimental area the rectangle shown in **Figure 6** covering the three lowest-scoring cells and at least one intersection—for subsequent eye-tracking and VR experiments.

3. Safety-Perception experiments

3.1. Objective

The experiment quantifies how environmental-design elements of urban streets affect pedestrians' visual safety perception. We measure gaze with eye-tracking and collect ratings via Semantic Differential (SD) questionnaires to identify the main influencing factors. The findings are intended to inform the future construction of a semantic-segmentation (SS)–based safety-perception system. Semantic segmentation classifies each image pixel into classes (e.g., street, building, vehicle, person), enabling automatic identification and quantification of elements that influence safety perception.

3.2. Experimental methods

(1) Eye-tracking

a) Overview

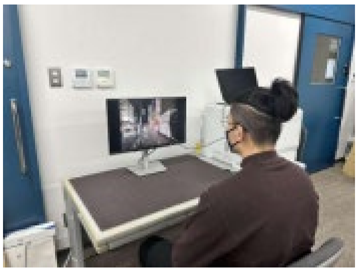
Field observations suggested marked day–night differences in how street environments might affect safety perception. We therefore quantify day–night differences and examine how specific factors operate. We evaluate brightness, visibility, cleanliness, the counts of pedestrians and vehicles, and their respective effects by time of day.

We selected 12 daytime and 12 nighttime photographs(Note 1) captured from typical pedestrian positions on sidewalks (excluding shots from building interiors or private property) and presented them to participants. Using a Tobii Pro Spark eye tracker (Note 2), we recorded fixation count, fixation duration, and pupil diameter, and then generated heat maps and scan-path diagrams to analyze how visual elements influence perceived safety. To minimize lighting confounds, all sessions were conducted in a light-controlled, windowless room (**Table 8**.); equipment specifications are summarized in **Table 7**.

Table 7. Experimental equipment.

Equipment	Description
Eye tracker	Tobii Pro Spark; sampling rate: 120 Hz
Display	Resolution 1920 × 1080; refresh rate: 60 Hz
Laptop (Windows)	CPU: Ryzen 9; GPU: RTX 3080 Ti
Laptop (macOS)	CPU: Apple M3 Pro
VR headset	Meta Quest 3; per-eye resolution 2064 × 2208; PPD 25; refresh rate 90 Hz

Table 8. Experimental photographs.

Eye-tracking experiment	Photograph-viewing experiment	VR experiment
		

b) Procedure

Before starting, we explained the protocol and adjusted seating distance from the monitor. After calibration and confirming participant comfort, we presented 24 photographs (day and night mixed) in random order, 10 seconds each, auto-advancing to the next image. The eye-tracking session took approximately 5–6 minutes.

(2) SD-based safety-perception ratings for photographs

a) Procedure

We projected the 12 daytime and 12 nighttime photos collected in Shinsakae and asked participants to rate them. Each photo was displayed for 10 seconds before automatic advance. The experiment had two parts: daytime first, then nighttime.

After each photo, participants completed an SD questionnaire rating “brightness,” “visibility,” “cleanliness,” “safety,” and “comfort” on seven-point scales. On seven-point scales (brightness: 1 = very dark … 7 = very bright; visibility: 1 = very poor … 7 = very good; cleanliness: 1 = very dirty … 7 = very clean; safety: 1 = very unsafe … 7 = very safe; comfort: 1 = very uncomfortable … 7 = very comfortable).

Order note. The SD-rating task used a fixed block order—daytime photographs were rated before nighttime photographs. This sequencing can introduce order effects (e.g., priming, fatigue, or contrast), potentially biasing nighttime ratings downward relative to daytime. We therefore interpret day–night differences conservatively and list this as a study limitation; future work will counterbalance block order or interleave scenes.

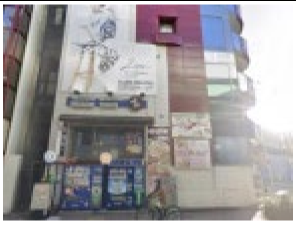
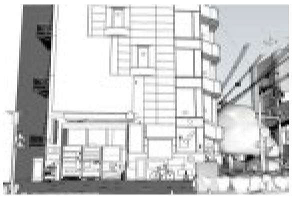
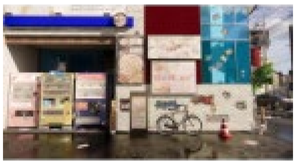
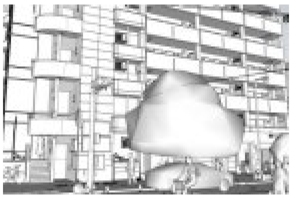
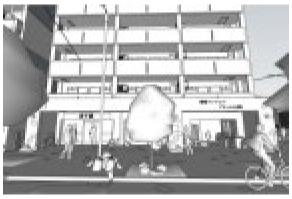
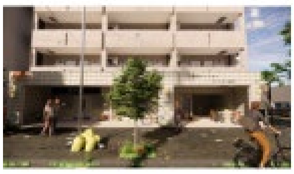
(3) VR experiment and SD ratings

a) Overview

Preparation comprised specification design, 3D modeling, and VR rendering. We used a controlled-variable design to compare the effects of time of day (day vs. night) and also controlled the numbers of pedestrians and vehicles, enabling quantitative comparisons of environmental effects on safety perception. To accentuate the influence of key factors, we modeled scenes based on reality and then increased litter, graffiti/fly-posting, and counts of people and vehicles.

We modeled in SketchUp 2023 and used Enscape with ray-tracing rendering to improve realism. Map data were obtained from MLIT’s PLATEAU[37]. Based on map position/extent, we combined on-site observations, our photographs, and Google Street View to construct the VR model (Table 9).

Table 9. Location ID, field photograph, 3D model, and VR scene.

Location ID	Field photograph	3D model	VR scene
①			
②			
③			

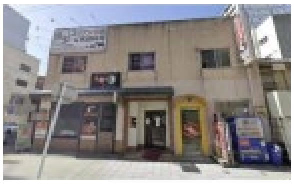
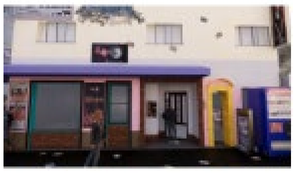
Location ID	Field photograph	3D model	VR scene
④			
⑤			

Table 9. (*Continued*)

b) VR scene modeling and rendering (SketchUp + Enscape)

We modeled the Shinsakae streetscape in SketchUp and rendered interactive scenes with Enscape. This pipeline was chosen because it affords fast, geometry-accurate scene construction from field photos and maps, while Enscape provides a physically-based daylight model, real-time global illumination, calibrated materials, and support for photometric light profiles—features that allow us to control and document lighting and visibility with a level of fidelity appropriate for perceived-safety experiments. This rationale complements the earlier justification for combining VR with eye-tracking to study safety perception[34][35].

Rendering fidelity goals. Our VR goal prioritized perceptual equivalence at pedestrian eye level over cinematic photorealism: (i) geometry fidelity sufficient to preserve sightlines, occlusions and frontage transparency; (ii) lighting fidelity sufficient to reproduce relative brightness/contrast of Areas of Interest (AOIs) across day vs. night; and (iii) stable camera exposure and field-of-view to avoid unintended visual confounds.

Lighting setup and calibration. Day scenes used Enscape's sun–sky model at Nagoya's latitude with clock time matched to the source photographs; night scenes implemented emissive/area lights for streetlights, façade/entrance luminaires and illuminated signage. To anchor VR brightness to the real environment, we used the field-measured illuminance collected in our survey (Section 2.2) as calibration references. Specifically, lights were tuned so that ground-level illuminance at sampling points in VR fell within the same categorical ranges (low/medium/high) and relative ordering observed on site; exposure was locked within day and within night sets to maintain comparability across scenes.

Camera and viewpoint control. VR camera height was set to 1.60 m (pedestrian eye level) unless the photographed vantage point required a small adjustment to match horizon line and parallax. The horizontal field-of-view was fixed to maintain constant scale and motion parallax cues across scenes. Photo vantage points and VR spawn points were co-registered to the same sidewalk locations used for the 24 stimuli.

Materials and tone mapping. We assigned typical reflectance ranges to dominant surfaces (e.g., asphalt, concrete, glazing) to avoid over-bright or overly absorptive artifacts and disabled post-processing effects that could add non-ecological highlights; tone mapping/exposure remained constant within the day and night sets.

Face-validity check. Prior to data collection, we ran an internal face-validity check by visually comparing VR frames against the paired field photographs and confirming that the relative brightness of lit

AOIs, legibility of sightlines, and occlusions by vehicles/frontages were preserved. Example photo–VR pairs and the lighting control sheet are provided in Appendix A: Stimulus Development and Calibration (Table S1).

c) Procedure

We set five observation points in VR (Fig. 7). Seated participants wore a VR headset and, using the VR controller, could freely rotate their viewpoint and translate within a predefined local zone around each observation point (with 6-DoF head tracking) for 30 seconds per point—points ①–③ at 12:00 (day) and ④–⑤ at 20:00 (night). During VR viewing we asked which items drew attention. After viewing, participants completed the VR section of the SD questionnaire.

Order note. In VR, observation points ①–③ were set to daytime and ④–⑤ to nighttime, which effectively produced a day-then-night sequence; this may likewise introduce order effects, and we interpret VR day–night contrasts with caution.

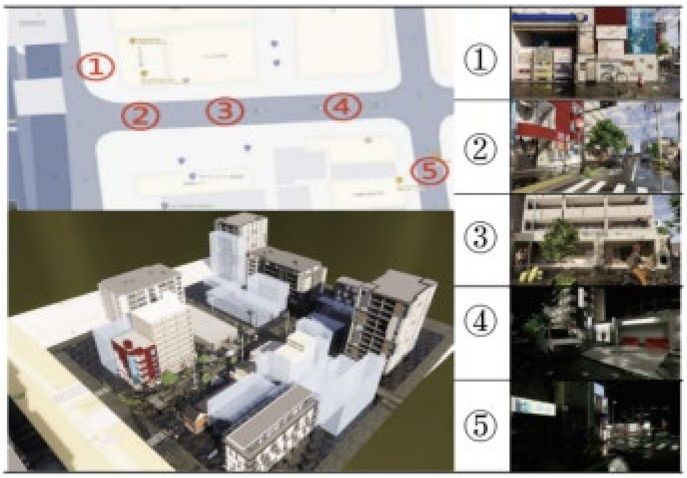


Figure 7. VR observation points (map source: Google maps).

(4) SD questionnaire

Applying the SD method to safety perception, we assessed impressions of architectural space. We consulted prior studies on spatial-interface descriptors and adjectives used for street-scape evaluation via SD, and selected 22 bipolar adjective pairs across three categories—affective, material, and spatial atmosphere (**Table 10**. and **Figure 8**.). We used a seven-point scale with verbal anchors (“very,” “quite,” “slightly,” “neither”), assigning values −3 to +3. At the end, participants additionally ranked the four most important factors among the seven proposed influences.

SD questionnaire and item selection.

We measured perceived safety using a Semantic Differential (SD) questionnaire composed of 22 bipolar adjective pairs. The item pool was developed from the semantic-differential tradition and widely used spatial/environmental descriptor sets in environmental psychology and urban design. From an initial list (compiled from prior SD studies and streetscape descriptors), we retained items that (a) align with our conceptual pathways (safety, normative order/guardianship, affective appraisal/comfort, visibility/sightlines) and (b) show clear face validity for street environments. Two faculty experts (urban design; environmental psychology) independently screened the list; discrepancies were resolved by discussion. A small pilot (n≈6) confirmed clarity of wording and anchors.

Scale and scoring.

Items were rated on a 7-point scale with labeled anchors at each pole (e.g., Dangerous—Safe, Unwatched—Watched). For analysis, responses were coded 1–7 such that higher values indicate the “safer/more positive” pole. Composite indices (e.g., Safety, Normative Order/Guardianship, Affective Comfort) were formed by averaging relevant items

Table 10. Semantic Differential (SD) adjective pairs used in the study (22 pairs; grouped by category).

Category	Adjective Pairs	Category	Adjective Pairs	Category	Adjective Pairs
Emotional Elements	Painful —— Pleasant	Material Elements	Intermittent —— Continuous	Spatial Atmosphere	Ordinary —— Novel
	Boring —— Enjoyable		Closed —— Open		Awkward —— Lively
	Resistant —— Attractive		Dark —— Bright		Monotonous —— Rich
	Worried —— Secure		Dirty —— Clean		Dangerous —— Safe
	Tense —— Relaxed		Ugly —— Beautiful		Passive —— Active
			Narrow —— Wide		Annoying —— Refreshing
			Old —— New		

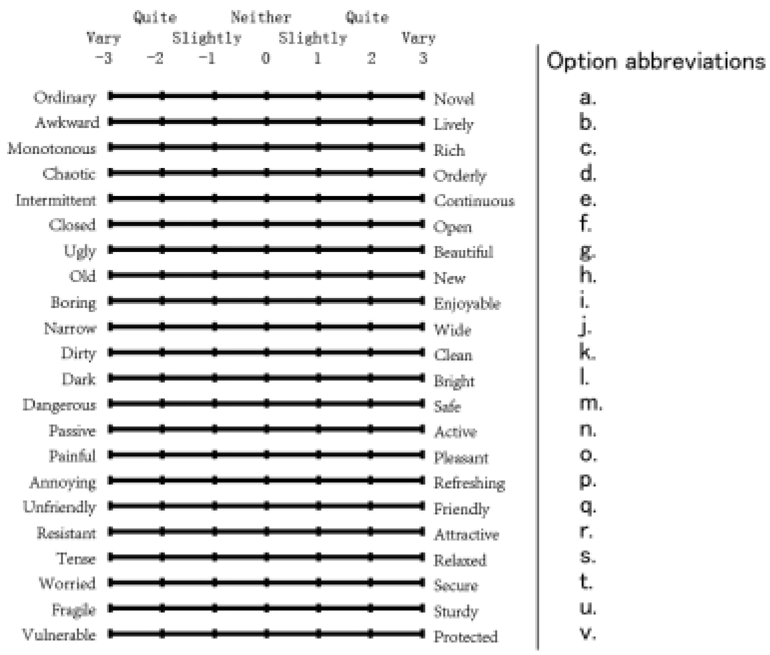


Figure 8. SD method questionnaire options.

3.2.1. Stimulus construction and validation

Photographic stimuli (day vs. night). All photographs were captured from typical sidewalk positions used by pedestrians, with viewpoint height fixed at 1.60 m and camera orientation aligned parallel to the curb (yaw), zero pitch/roll, and a constant horizontal field-of-view ≈ 63° (28–35 mm full-frame equivalent). For each daytime viewpoint we returned to the same geodetic position at night to hold composition constant (landmarks/signage aligned across pairs). Exposure was standardized via manual settings and bracket checks to avoid auto-gain artifacts; images were then normalized using histogram matching anchored on mid-gray to reduce residual global-luminance differences across scenes prior to display. Presentation on the lab display occurred in a light-controlled, windowless room described in Section 3.2, with monitor luminance calibrated (D65, gamma 2.2) to ensure comparable photometric output across sessions.

Operational increments for environmental factors. To systematically vary and code scene properties, we defined quantitative, scene-level increments:

− Clutter/untidiness (litter, fly-posting, graffiti): three levels based on counts per 10 m frontage within the primary field-of-view—None/Low (≤ 2 small items, 0 posters/graffiti), Medium (≈ 3–10 small items or 1–2 posters), High (≥ 11 items or ≥ 3 posters/graffiti tags).

− People (pedestrian activity): None/Low/Medium bands coded by visible head-counts in the main 63° cone at capture (e.g., 0–1 / 2–5 / 6–10 persons).

− Vehicles: analogous 0–1 / 2–3 / ≥ 4 counts in the primary view; parked vs. moving status recorded.

− Greening: percentage of visible façade/streetscape pixels covered by vegetation (binned at < 5% / 5–15% / > 15%), estimated from semantic masks prepared for subsequent SS work.

− Lighting/visibility: daytime vs. nighttime condition; at night we reference the field illuminance survey (Section 2.2) to maintain comparable ranges of horizontal illuminance across sites when feasible; VR lighting was subsequently tuned to the median readings per site (± tolerance) to approximate in-situ conditions.

VR scene realism and parameter matching. VR models were built from MLIT PLATEAU[37] base geometry and our site photographs, with ray-traced rendering to match material reflectance and light sources. For each VR viewpoint, we mirrored the photographic viewpoint height (1.60 m), FOV (≈ 63°), and yaw; dynamic agents (pedestrians/vehicles) were populated to the same count bands as in the corresponding photo scenes for the targeted increment level. Nighttime emissive signage and street-/building-mounted luminaires were adjusted so that average horizontal illuminance at the eye point fell within the field-measured range for that micro-location (Section 2.2).

Display calibration and presentation controls. All sessions used the same 1920×1080, 60 Hz monitor, calibrated with a hardware colorimeter; VR was presented on a Meta Quest 3 (per-eye 2064×2208, 90 Hz). Stimuli were shown in a constant ambient setting (no external light), as already described in Section 3.2. Equipment specifications appear in Table 6; stimulus sets are listed in **Table 7**.

Realism/presence checks (pilot). Prior to the main study, we conducted an informal pilot with a small convenience sample to verify scene recognizability, perceived realism of materials/lighting, and presence in VR (7-point ratings: “looks like the real place,” “lighting looks natural,” “I feel present in the scene”). Feedback informed minor adjustments to texture roughness, emissive signage intensity, and pedestrian animation speeds. A synopsis of the checklist and rating items is provided in Appendix A (**Table 5**).

3.2.2. Operationalization of the seven factors (CPTED & Social-psych mapping)

To align constructs, measures, and analyses, we operationalized seven CPTED-relevant factors—lighting, cleanliness, greening, retail/business type, people, vehicles, graffiti/fly-posting—as follows. Areas of Interest (AOIs) in photographs/VR scenes were labeled by the dominant factor; eye-tracking indices (fixation count, dwell time, time-to-first-fixation, pupil diameter) were then aggregated per AOI and normalized by AOI area where appropriate. Safety-perception outcomes were obtained from 7-point SD ratings (**Table 11**).

We computed AOI-level eye-tracking indices (fixation count, dwell time, time-to-first-fixation, pupil diameter) and linked them to 7-point SD ratings (brightness, visibility, cleanliness, safety, comfort) via linear mixed models with crossed random effects for participant and scene.

Table 11. Operational definitions, CPTED & social-psych mapping, measurements, and analysis entry points.

Factor	Operational definition (what is it in the scene?)	CPTED principle(s)	Social-psych pathway	Field data / VR control	Photo/VR measurement & coding	Eye-tracking linkage	How it enters analysis
Lighting	Luminaires/sightlines that increase nighttime visibility (streetlights, building-mounted lights, signage illumination).	Natural surveillance	Reduces ambiguity/threat appraisal; supports "eyes on the street".	Field: illuminance counts & positions; VR: day vs night lighting states.	SD *brightness*, *visibility*; AOI for light sources/sight lines.	AOI-level fixation count/dwell; TTFF to light AOIs.	Predictors in LMM: standardized gaze metrics on **Lighting AOIs**; covariates: scene size, AOI area.
Cleanliness	Absence/presence of litter, clutter, overflowing waste.	Territorial reinforcement	Injunctive norms / place management signals.	Field: "untidy locations" mapping; VR: clutter level adjustments.	SD *cleanliness*; AOI labeled "clean/untidy frontage/ground".	Dwell on untidy vs clean AOIs; pupil dilation events.	LMM terms: gaze to **Cleanliness AOIs**; SD cleanliness as mediator/moderator in robustness checks.
Greening	Visible trees, planters, verge greenery within pedestrian field.	Territorial reinforcement; (supporting) Natural surveillance when well-maintained	Affective restoration; lowers arousal.	Field: not used for site selection; observed qualitatively; VR: planted elements placed per reality.	Presence/area share of greening AOI; optional SD *comfort*.	Dwell on greening AOIs; TTFF to greenery.	LMM: greening AOI share × gaze metrics; check indirect via *comfort*.
Retail/Business type	Frontage activation (transparent facade, staff presence), hours (daytime retail vs nightlife venues), shuttered/vacant frontage.	Natural surveillance; Territorial reinforcement	Guardianship cues; normative clarity via active, visible uses.	Field: not in ArcGIS composite; catalogued from photos/Street View for AOI coding; VR: held as in base scene.	AOI categories: **active daytime retail / service**, **night-time entertainment**, **vacant/closed**; frontage transparency noted.	Fixations on storefronts/signage; TTFF to staff/entrances.	LMM: categorical contrasts (active vs nightlife vs vacant), with gaze metrics as continuous covariates.
People	Pedestrians visible in scene.	Natural surveillance	Capable guardianship vs anonymous crowding (context-dependent).	VR: controlled counts by point/time-of-day; field: not in composite.	Counts per scene; AOI for pedestrian clusters.	Dwell/TTFF to people AOIs; pupil responses to movement.	LMM: pedestrian count × gaze to **People AOIs**; day/night interaction.
Vehicles	Moving/parked vehicles encroaching on pedestrian space/visibility	Access control (negative when dominating	Traffic safety / livability cues; potential concealment.	VR: controlled counts/speeds; field: camera/waste/lighting	Counts; AOI for vehicle masses/headlights.	Dwell on vehicle AOIs; TTFF to oncoming headlights at	LMM: vehicle count × gaze to **Vehicle AOIs**; night

Factor	Operational definition (what is it in the scene?)	CPTED principle(s)	Social-psych pathway	Field data / VR control	Photo/VR measurement & coding	Eye-tracking linkage	How it enters analysis
	.	) / Natural surveillance (when slow/overseen).		composite only.		night.	interaction.
Graffiti / Fly-posting	Visible tags, stickers, bills on walls/poles.	Territorial reinforcement	Disorder → weaker injunctive norms.	Field: mapped as "untidy locations"; VR: increased for experimental contrast.	Binary presence; AOI segments on marked surfaces.	Dwell on disorder AOIs; TTFF to salient tags.	LMM: presence of **Disorder AOIs** × gaze metrics; expect negative association with safety.

Table 11. (*Continued*)

3.3. Participants

We tracked pupil and gaze movements to collect perception data for street photographs. Because tracking errors can yield inaccurate or missing eye-tracking data, we recruited participants with normal or corrected-to-normal vision. In total, 50 participants (undergraduates, graduate students, and working adults) took part: 27 male and 23 female. We defined an "architecture group" (n=20) and a "non-architecture group" (n=30).

Expanded participant profile. The sample comprised 50 individuals (27 male, 23 female) across architecture (n=20) and non-architecture (n=30) majors. Age distribution was: 15–19 years (n=2, 4%), 20–24 (n=18, 36%), 25–29 (n=25, 50%), 30–34 (n=4, 8%), and 55–59 (n=1, 2%). Regarding vision, 36 participants (72%) wore glasses (normal or corrected-to-normal vision), and 14 (28%) did not. Familiarity with the study area (Shinsakae) was high: 45 participants (90%) reported they knew the district, and among these, 8 (17.8%; 16% of the full sample) had previously resided there, while 37 (82.2%; 74% of the full sample) had not. Nationality composition reflected our recruitment context (Japanese, Chinese, and others), with Japanese (n=11) and Chinese (n=35) forming the majority; inferential tests reported in Section 4.2 found no significant between-group differences in perceived-safety ratings across sex, nationality, or academic background. This expanded profile clarifies that our target perspective is that of pedestrians—urban street users evaluating scenes from typical sidewalk viewpoints.

Sampling and recruitment. Participants were recruited via an open call circulated with a web registration link; volunteers self-enrolled on a first-come, first-served basis. This constitutes a non-probability convenience sampling (voluntary-response) approach. Eligibility required normal or corrected-to-normal vision and provision of informed consent under the approved protocol. Recruitment did not use random sampling or snowballing.

3.4. Statistical analysis

Data preparation and scoring. SD responses were coded on a 7-point bipolar scale (verbal anchors "very / quite / slightly / neither"), mapped to numeric values from −3 to +3. For the photograph-rating tasks, the five single-item evaluations ("brightness," "visibility," "cleanliness," "safety," "comfort") were likewise treated as 7-point ordinal ratings. Prior to analysis we screened for obviously invalid patterns (e.g., invariant responding across all items) and confirmed that no responses met exclusion criteria; hence N=50 were retained (see Section 4.2(1)). AOIs for eye-tracking were defined a priori by seven CPTED-relevant factors (lighting, retail type, greening, vehicles, people, cleanliness, graffiti/fly-posting); for each photo and participant we computed fixation count, total fixation duration, mean fixation duration, time-to-first-fixation, and pupil diameter, and then summarized by AOI.

Reliability. Internal consistency of the 22 SD adjective pairs was evaluated with Cronbach's α separately for daytime, nighttime, and VR data. As reported in the Results, internal consistency was good to excellent (day α=0.880; night α=0.908; VR α=0.947), supporting aggregation and comparative analyses.

Assumption checks. For comparisons based on SD items we inspected distributions, ran Shapiro–Wilk tests for normality and Levene's tests for homogeneity of variances. Parametric tests were used when assumptions were satisfied; if not, non-parametric counterparts were applied as sensitivity checks (Mann–Whitney U for independent samples; Wilcoxon signed-rank for paired samples). Unless otherwise noted, tests were two-tailed with α=0.05 and we report exact p-values.

Sensitivity analyses. To assess robustness, all primary between-condition and between-group inferences were re-checked using non-parametric counterparts (Mann–Whitney U and Wilcoxon signed-rank tests); conclusions were unchanged. Given the sample size, we also report exact p-values for transparency.

Between-group comparisons. To examine potential differences by sex (male/female), nationality (Japanese/non-Japanese; Chinese/non-Chinese), academic background (architecture/non-architecture), and VR group (A/B), we conducted independent-samples t-tests on each SD item; the corresponding t and p values are presented in **Table 12** in the Results. These analyses did not yield significant differences for the primary safety-perception measures, and we therefore did not stratify subsequent analyses by these factors.

Within-participant condition effects. For condition contrasts (daytime vs. nighttime, and VR vs. photographs), we summarized SD profiles by condition and compared paired means using paired t-tests (or Wilcoxon tests when indicated). For visual interpretability, we present profile curves of the 22 SD adjective pairs across the three conditions (Fig. 10) and discuss convergent patterns with eye-tracking metrics (Section 4.1 and 4.2).

Ranking data (factor importance). For the post-task ranking, we applied a point-weighted scheme (1st=4, 2nd=3, 3rd=2, 4th=1) to derive total and average points per factor, and summarized frequencies of selection within the top four. Group differences in the rank-point distributions (e.g., by nationality) were inspected descriptively and, when needed, assessed with Mann–Whitney U tests given the ordinal nature of ranks (see **Table 14** in the Results).

Software. Analyses were performed in IBM SPSS Statistics; figures were produced from the same environment.

AOI-level eye-tracking aggregation. For each participant we summed fixation durations within CPTED-relevant Areas of Interest (AOIs) and expressed each AOI's share of total time of interest (percentage). Aggregating across the 12 daytime and 12 nighttime photographs, retail/business frontages captured the largest share of overt attention (Day 17.1%, Night 21.9%), followed—at night—by lighting elements (Night 7.2%). During the day, cleanliness cues (e.g., litter/untidiness) accounted for 6.1% of attention, whereas people and vehicles drew smaller shares (≤1.3%). Complementary SD results showed higher brightness and cleanliness ratings in daytime (Dark–Bright: 0.20 vs −0.29; Dirty–Clean: −0.16 vs −0.76), paralleling the overall safety appraisal (Dangerous–Safe: −0.24 vs −0.67).

Table 12. Factor-specific descriptive contributions to perceived safety.

Factor	SD proxy item	SD Day mean	SD Night mean	ET attention share (Day, %)	ET attention share (Night, %)
Lighting	Dark — Bright	0.20	−0.29	N/A	7.16
Cleanliness	Dirty — Clean	−0.16	−0.76	6.05	N/A
Greening	—	—	—	2.73	0.81
Retail / business type	—	—	—	17.06	21.90
People	—	—	—	0.21	1.26
Vehicles	—	—	—	0.71	0.26
Graffiti / fly-posting	—	—	—	N/A	N/A

3.5. Ethical approval, consent, and participant safety

Ethics Statement. This study involved healthy adult volunteers and minimal risk procedures (photo-based appraisal tasks and an immersive VR task). All participants provided written informed consent and could pause or withdraw at any time without penalty. A safety briefing, motion-sickness screening, and rest breaks were provided; staff monitored adverse symptoms during VR and terminated sessions if discomfort occurred. Participants received a small honorarium (JPY 1,000 or a stationery set). No protocol was prospectively submitted to an institutional ethics committee for this pilot; we recognize that prospective review is best practice and acknowledge this as a limitation. All procedures adhered to the principles of the Declaration of Helsinki (2013).

4. Results of the safety-perception experiments

4.1. Eye-tracking analysis

Metrics and AOIs. We analyzed four standard indices—time to first fixation (shorter = attracts attention more readily), total fixation duration (longer = more sustained attention), fixation count (higher = more attention), and mean fixation duration (longer = deeper processing)[34][35]. Areas of interest (AOIs) were delineated for seven factors: lighting, retail/business type, greening, vehicles, people, cleanliness, and graffiti/fly-posting.

Heat-map results. Across the 24 scenes, daytime heat maps concentrated on shop signage/posters, building/store lighting, streetlights, vehicles, and pedestrians. Nighttime maps showed similar foci with stronger emphasis on illuminated elements (e.g., light-box advertisements and streetlights).

Scan-path results. Scan paths corroborated the heat-map patterns, revealing frequent transitions among signage, lighting, and moving vehicles/pedestrians.

AOI-level summary. Advertising/textual elements generally drew more attention than background surfaces (ground/sky). At night, bright sources yielded the most fixations and the longest fixation durations, indicating strong attentional pull by lighting features(**Table 13**).

Table 13. Visualization of eye-tracking outputs (representation methods).

Type	Metric / color / form	Spatial representation
Heat map	Red	Red indicates areas with the longest fixation durations and the highest number of fixations.
	Area size	The larger the colored area, the longer the fixation time and the greater the

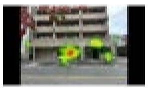
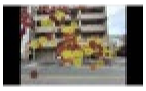
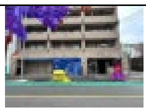
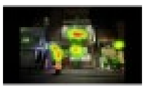
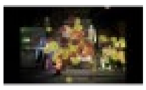
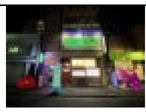
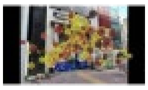
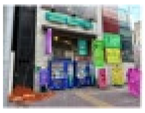
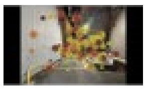
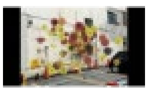
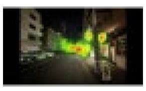
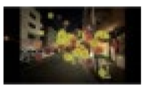
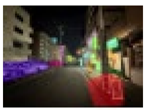
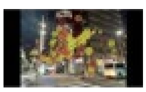
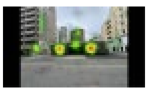
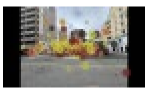
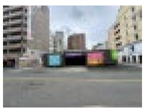
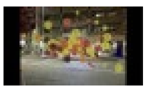
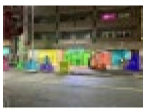
Type		**Metric / color / form**	**Spatial representation**
			number of fixations around its center within the same time window.
Scan-path diagram		Circle size	Represents fixation duration; the larger the circle, the longer the fixation at that point.
		Numbers	Indicate the order of fixations (1 = first).
Areas of interest (AOI)	Time to first fixation	shorter	Indicates the space attracts attention more readily.
	Total fixation duration	longer	Indicates the space attracts more attention.
	Number of fixations	higher	Indicates the space attracts more attention.
	Mean fixation duration	longer	Indicates the space attracts more attention.

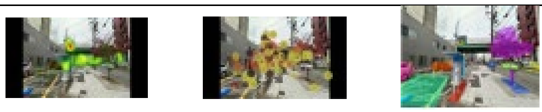
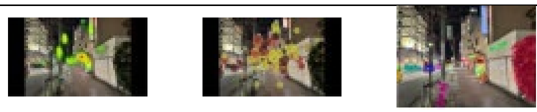
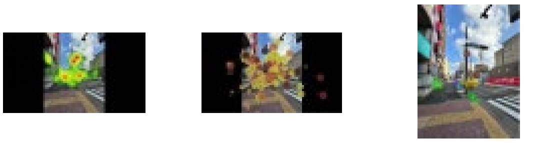
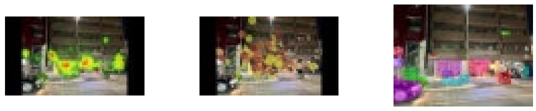
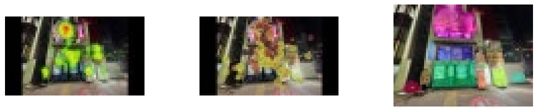
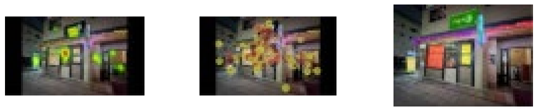
Table 13. (*Continued*)

(1) Heat-map results

Eye-movement heat maps visualize fixations; longer and denser fixations appear in red, whereas sparse or brief fixations appear in yellow/green; non-fixated regions remain uncovered (**Table 14**.). Across 24 locations, daytime heat maps concentrated on shop signs, wall posters, vending machines, waste collection sites, pedestrians, graffiti, parking-lot warning signs, traffic signals, walking direction, vehicles, and license plates—elements generally within parallel or slightly elevated lines of sight during walking. Nighttime heat maps showed similar concentration, with added emphasis on illuminated shop signs and bright sources. Overall, participants' gaze spread fairly widely, with primary foci on shop signage/posters, building/store lighting, streetlights, parking-lot lights, vehicles, and people.

Table 14. Visualizations from the eye-tracking experiment.

	Heat-map	**Scan-path diagram**	**AOI map**		**Heat-map**	**Scan-path diagram**	**AOI map**
1				13			
2				14			
3				15			
4				16			
5				17			

	Heat-map	Scan-path diagram	AOI map		Heat-map	Scan-path diagram	AOI map
6				18			
7				19			
8				20			
9				21			
10				22			
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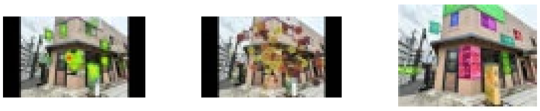
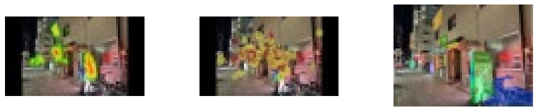
12				24			

Table 14. (*Continued*)

(2) Scan-path results

Scan-paths (**Table 14.**) corroborated heat-map findings: principal foci were shop signage/posters, building/store lighting, streetlights, parking-lot lights, vehicles, and pedestrians.

(3) Areas of interest (AOI)

AOI were defined by the seven environmental factors (**Table 14.**): lighting, retail type, greening, vehicles, people, cleanliness, and graffiti/fly-posting. We computed arithmetic means of the three eye-movement indices (fixation count, fixation duration, pupil diameter) for 50 participants across all 24 photos, and then by daytime vs. nighttime subsets. Objects containing advertising, signage, posters, and textual information attracted more attention. Ground and sky exerted weak visual pull. At night, illuminated areas yielded the most fixations, the longest fixations, and the largest pupil diameters—indicating that bright locations and light-box advertisements were especially attention-grabbing.

4.2. Questionnaire analysis

(1) Data Screening

Before formal analysis, we screened SD responses to remove extreme or flat patterns; no responses were excluded, leaving N=50 valid questionnaires. We converted items to numeric values (−3 … +3) and computed overall means for the three experimental parts (**Figure 9**).

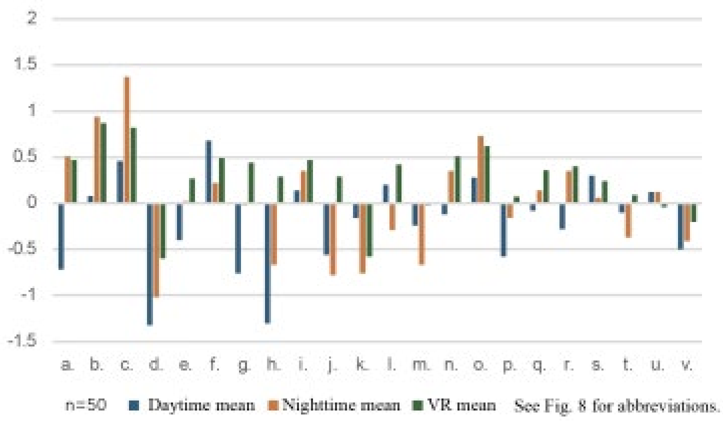


Figure 9. Mean scores (Daytime, Nighttime, and VR).

(2) Reliability (Internal consistency)

Table 15. Reliability (Cronbach's α)c

Condition	Cronbach's α
Daytime	0.880
Nighttime	0.908
VR experiment	0.947

Composite reliability rationale. The 22 SD adjective pairs were pre-selected to represent a single evaluative dimension of pedestrian-perceived safety/comfort within a CPTED framing (affective, material, and spatial-atmosphere cues converge on one latent appraisal). Accordingly, we treat the averaged SD profile as a reflective index and summarize its internal consistency using Cronbach's α. The coefficients indicate good-to-excellent reliability across conditions (Daytime α=.880; Nighttime α=.908; VR α=.947), supporting the use of a composite score for subsequent analyses (**Table 15**.).

(3) T-tests

Participants were Japanese, Chinese, and Mongolian; because Japanese (n=11) and Chinese (n=35) comprised the majority, we conducted independent-samples tests across sex (male/female), nationality (Japanese/non-Japanese), major (architecture/non-architecture), and VR groups (A/B). Between-group comparisons. We tested group differences on the primary safety item (Dangerous—Safe) and on the remaining SD items using independent-samples t-tests (two-tailed). No between-group differences were observed for the primary safety item (all $p > .40$), whereas a few secondary SD items (e.g., Closed—Open; Dirty—Clean) showed group differences; **Table 16** reports exact $t(df = 48)$ and p values for each item. Hence, subsequent analyses do not stratify by these factors (**Table 13**.).

Table 16. T-test analysis.

Adjective pair (SD item)	Japanese vs. non-Japanese		Male vs. female		Architecture vs. Non-Architecture		VR Group A vs. VR Group B		Chinese vs. non-Chinese	
	t	p	t	p	t	p	t	p	t	p
Ordinary — Novel	0.694	0.491	0.904	0.371	0.521	0.605	0.991	0.329	-0.983	0.330
Awkward — Lively	0.930	0.357	-1.294	0.202	0.878	0.385	0.261	0.796	-1.061	0.294

Monotonous — Rich	-0.841	0.405	-0.099	0.921	1.643	0.107	0.814	0.422	1.177	0.245
Chaotic — Orderly	-1.176	0.245	1.134	0.263	1.387	0.172	1.699	0.098	0.570	0.572
Intermittent — Continuous	-0.121	0.904	-0.302	0.764	1.210	0.232	0.714	0.480	0.343	0.733
Closed — Open	-2.890	0.006	0.224	0.824	2.818	0.007	1.802	0.082	2.335	0.024
Ugly — Beautiful	-0.890	0.378	1.545	0.129	1.644	0.107	0.878	0.386	0.952	0.346
Old — New	0.982	0.331	-0.763	0.449	-0.751	0.456	0.812	0.423	-1.390	0.171
Boring — Enjoyable	0.115	0.909	-0.881	0.382	-0.253	0.801	0.925	0.362	0.429	0.670
Narrow — Wide	-0.205	0.839	-0.430	0.669	0.165	0.870	1.479	0.149	-0.526	0.601
Dirty — Clean	-1.378	0.174	2.866	0.006	1.905	0.063	0.356	0.724	0.641	0.525
Dark — Bright	-0.330	0.743	0.139	0.890	1.637	0.108	0.852	0.401	-0.239	0.812
Dangerous — Safe	-0.788	0.435	0.489	0.627	0.833	0.409	0.785	0.439	0.194	0.847
Passive — Active	1.390	0.171	0.375	0.709	-0.962	0.341	0.389	0.700	-1.117	0.269
Painful — Pleasant	-0.617	0.540	0.881	0.383	-0.350	0.728	0.246	0.807	1.027	0.310
Annoying — Refreshing	-1.033	0.307	1.030	0.308	2.372	0.022	-0.166	0.869	0.659	0.513
Unfriendly — Friendly	-1.865	0.068	0.155	0.878	0.451	0.654	1.733	0.093	1.718	0.092
Resistant — Attractive	-1.512	0.137	0.611	0.544	1.398	0.168	-1.355	0.184	1.557	0.126
Tense — Relaxed	-0.076	0.939	0.233	0.817	1.088	0.282	0.354	0.726	0.457	0.650
Worried — Secure	-1.608	0.114	0.817	0.418	1.575	0.122	0.916	0.367	1.242	0.220
Fragile — Sturdy	-1.121	0.268	1.581	0.120	1.885	0.065	1.545	0.132	0.868	0.390
Vulnerable — Protected	-0.823	0.414	2.133	0.038	0.998	0.323	1.755	0.089	0.553	0.583

Table 16. (*Continued*)

Footnote. All comparisons used N=50 with no missing values; hence df = $n_1 + n_2 - 2 = 48$ *for each test (Male vs Female 27/23; Architecture vs Non-Architecture 20/30; Japanese vs non-Japanese 11/39; Chinese vs non-Chinese 35/15; VR Group A vs VR Group B totals sum to 50).*

(4) SD profile curves

We computed scores for the 22 bipolar adjective pairs for daytime, nighttime, and VR (Fig. 10.). Daytime scores on safety-related adjectives were higher than nighttime, indicating stronger safety perception in daylight. Items such as "dark–bright," "dangerous–safe," and "anxious–at ease" were notably lower at night, indicating greater perceived danger. VR profiles broadly resembled daytime but were slightly lower on some items. This suggests our VR setting approximated daytime cognition but did not fully reproduce nighttime safety perception; VR scores tended to exceed nighttime scores on many items, implying a general bias toward feeling safer in VR than in actual nighttime conditions—worthy of follow-up study. Items such as "disordered–orderly," "intermittent–continuous," and "dark–bright" showed pronounced differences, implying that controlled VR conditions mitigate some negative nighttime perceptions. In contrast, "ordinary–novel" and "awkward–lively" were stable across conditions. Items directly tied to safety, such as "dangerous–safe" and "anxious–at ease," showed the greatest variability, suggesting high environmental sensitivity.

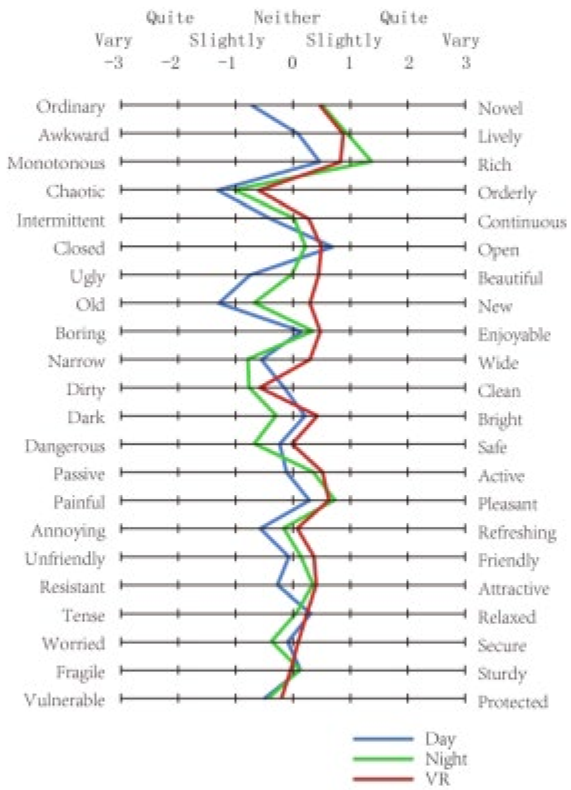


Figure 10. SD profile curves.

5) Factor importance

At the end of the survey, participants ranked the four most important influences among the seven factors (lighting, cleanliness, people, graffiti & fly-posting, vehicles, retail type, greening). **Table 17**. shows overall rankings and separate analyses for Japanese and Chinese participants. Broadly, Japanese participants prioritized brightness, likely because cleanliness is already high in Japanese cities and thus taken for granted; brightness more directly signals safety. Chinese participants prioritized cleanliness, plausibly reflecting urban-cleanliness challenges in some regions of China, where cleanliness is a salient criterion in environmental evaluation.

Table 17. Rankings by nationality.

Nationality	Rank	Factor	Total points	Frequency	Average points
Chinese n=35	1	Cleanliness	85	30	2.833
	2	Brightness	66	24	2.75
	3	People	59	23	2.565
	4	Graffiti & fly-posting	37	15	2.467
	5	Vehicles	34	14	2.429
	6	Retail type	50	25	2
	7	Greening	11	6	1.833

Nationality	Rank	Factor	Total points	Frequency	Average points
Japanese n=11	1	Brightness	27	9	3
	2	People	22	8	2.75
	3	Retail type	26	10	2.6
	4	Cleanliness	31	12	2.583
	5	Graffiti & fly-posting	18	8	2.25
	6	Vehicles	4	3	1.333
	7	Greening	2	2	1
Total n=50	1	Brightness	93	33	2.818
	2	Cleanliness	116	42	2.762
	3	People	81	31	2.613
	4	Graffiti & fly-posting	55	23	2.391
	5	Vehicles	38	17	2.235
	6	Retail type	76	35	2.171
	7	Greening	13	8	1.625

Table 17. (*Continued*)

※*Frequency = number of times selected within the top four.*

※*1st place = 4 points, 2nd = 3, 3rd = 2, 4th = 1; Total points are the sum based on these weights.*

5. Discussion and implications

5.1. Lighting and visibility: Convergence with prior evidence

Consistent with classic urbanism and CPTED claims, we found lighting/sightlines to be among the strongest positive contributors to perceived safety; eye-tracking also showed that illuminated areas and luminous signage attracted the most fixations and the longest dwell times, especially at night. These patterns align with evidence that better pedestrian lighting improves reassurance and often reduces crime (Jacobs, 1961; Newman, 1972; van Rijswijk & Haans, 2018; Cozens & Love, 2015; Cozens, 2022). They are also consistent with Japanese studies reporting that appropriate residential street lighting lifts feelings of security, particularly among women (Monma, 2014[40]). Our heat maps and scan-paths thus provide an attentional mechanism for these perceptual and behavioral effects.

5.2. Access control

Our SD ratings and gaze data indicate that cleanliness is a major positive driver while visible disorder (e.g., litter, graffiti/fly-posting) lowers safety appraisals; untidy cues captured attention in ways associated with lower safety ratings. This dovetails with research on “incivilities” and cross-norm effects showing that visible norm violations can legitimize further violations and depress reassurance (Keizer, Lindenberg, & Steg, 2008). It also resonates with community-maintenance and territorial-reinforcement strands within CPTED. By mapping AOIs to disorder cues, we add fine-grained evidence of how such cues draw attention and shape appraisals moment-to-moment.

5.3. Greening and place maintenance

We observed that greening/maintenance is positively associated with perceived safety (though typically with smaller effect sizes than lighting and cleanliness), consistent with trials showing greening and blight remediation reduce fear and, in some cases, violence (e.g., Philadelphia vacant-lot greening; Branas et al., 2018). Our results extend this literature by coupling safety ratings with gaze measures, suggesting that greenery may contribute via ambiguity reduction and affect regulation rather than by capturing overt attention to the same extent as bright light sources.

5.4. Human activity, vehicles, and context-dependent effects

Participants' attention frequently concentrated on people and vehicles, yet their effects on safety perception were context-dependent. This is consistent with findings that "eyes on the street" raise reassurance when uses are well managed and sightlines remain clear, whereas dense/anonymous crowds or certain facility types can reduce comfort (Jacobs, 1961; subsequent CPTED syntheses). In our nighttime scenes, bright vehicle lights and moving traffic strongly pulled gaze yet did not uniformly increase safety ratings—underscoring that visibility must be coupled with positive social signals and manageable flows.

5.5. Eye-tracking indices as objective correlates of safety appraisals

We interpret higher fixation counts/durations and larger pupil diameters on AOIs (e.g., lighting, signage, disorder cues) as indices of attentional priority and information load, which—when integrated with SD ratings—clarify whether the captured attention is reassuring or concerning. This logic and our metrics are in line with established eye-tracking methodology (Holmqvist et al., 2011; Duchowski, 2017) and with recent transportation/VR eye-tracking studies on pedestrian behavior recommended by the reviewer. Our study adds to this work by linking AOI-level gaze to a multi-factor CPTED framework in real urban scenes.

5.6. VR replication: Approximating daytime, diverging at night

VR safety judgments broadly resembled daytime profiles but did not fully reproduce nighttime perceptions; VR scores tended to exceed actual nighttime scores on safety-related items. This complements prior work showing that VR affords high experimental control and presence, yet lighting reproduction, dynamic range, and peripheral darkness cues can remain challenging, especially for scotopic/low-luminance conditions (Pan & Hamilton, 2018; Cummings & Bailenson, 2016; Slater, 2009). Our finding suggests that VR is suitable for modeling many daytime street attributes but may under-represent certain nighttime risk signals—an issue to be addressed in future VR pipelines (e.g., calibrated luminance, HDR tone-mapping, and ambient-noise modeling).

5.7. VR vs. real-world validity (day vs. night).

Using the scene-level mean SD safety scores (22 items averaged per scene), we quantified cross-modal correspondence between real-photo and VR conditions. The correlation between daytime photos and VR across the 12 matched scenes was $r = 0.71$ (95% CI 0.23–0.91, $p \approx 0.009$, $n=12$), indicating that VR closely approximated daytime judgements. By contrast, the correspondence between nighttime photos and VR was $r = 0.27$ (95% CI −0.36–0.73, $p \approx 0.39$, $n=12$), i.e., non-significant. For completeness, day vs. night photo judgements correlated at $r = 0.68$ (95% CI 0.17–0.90, $p \approx 0.017$, $n=12$). These patterns suggest that our VR pipeline reproduced daytime safety appraisals well, but under-captured nighttime cues (e.g., luminance gradients, glare/veiling, shadow contrast, and the social meaning of lit signage and human activity).

Implications. (i) VR-derived factor weights for daytime conditions can be translated directly to design guidance; (ii) for nighttime interventions (lighting placement, spectrum, vertical illuminance, contrast management), we treat VR findings as screening-level and calibrate them with targeted field measurements (illuminance/vertical luminance mapping) and/or nighttime photo-based panels before implementation; (iii) future work will improve fidelity by adding physically-based lighting (IES profiles), dynamic glare models, and higher-contrast tone-mapping to narrow the night-gap.

5.8. Contributions and practical implications

Methodologically, combining AOI-mapped eye-tracking with SD ratings allowed us to quantify the relative weight of seven CPTED-relevant factors and to propose an attentional pathway linking physical cues to perceived safety. Substantively, the convergence with prior evidence on lighting and order, together with our AOI results, supports integrated interventions that pair pedestrian-scale lighting and sightline improvement with place maintenance and guardianship—especially at night and at activity nodes. For planners in regional cities, this implies prioritizing (i) uniform, pedestrian-oriented lighting; (ii) persistent maintenance/cleanliness programs; and (iii) place management that sustains visibility without generating unmanaged density.

6. Policy roadmap for Shinsakae: Prioritized CPTED interventions, costs, and evaluation

6.1. Prioritization logic

Our empirical results show that lighting and cleanliness contributed most positively to pedestrians' perceived safety, whereas visible disorder (graffiti/fly-posting) and vehicle activity at night lowered safety appraisals; the VR replication approximated daytime judgments but not nighttime ones. These findings guide the ordering of interventions for Shinsakae's mixed entertainment–commercial streets (e.g., Higashi-Shinmachi near Hirokōji-dōri).

6.2. Ranked intervention package for Shinsakae

Rank	Intervention	CPTED principle(s)	Scope / typical unit	Indicative cost	Feasibility	Primary day/night effect	Key metrics for impact
1	**Pedestrian-scale lighting upgrade & dark-spot remediation** (target ≥10–15 lx sidewalks; ≥20 lx crossings; reduce glare)	Natural surveillance	1 block-front + intersection nodes	$$–$$$	High (ROW works)	**Night ↑↑**, Day ↑	Min/avg lux; SD safety score change; complaints; eye-tracking AOI to lighting (subset)
2	**Cleanliness & place-maintenance program** (litter removal, tamper-proof bins, frontages tidiness)	Territorial reinforcement	Micro-district "beat"	$–$$ (opex)	High (operations)	Day ↑, **Night ↑↑**	Litter pieces/100 m; re-inspection pass rate; SD score change
3	**Graffiti/fly-posting rapid-removal + anti-poster coatings** (24–72 h SLA; property-owner MOUs)	Territorial reinforcement	Hotspots from kernel maps	$–$$	High	**Night ↑↑**, Day ↑	New tags per 30 days; time-to-removal; SD score change
4	**Traffic calming around nightlife streets** (30 km/h zone, raised crossings, curb-extensions, side-street filtering)	Access control / Natural surveillance	Per intersection cluster	$$$	Medium	**Night ↑**, Day ↑	85th-percentile speed; pedestrian yield rate; SD score change (night)
5	**Waste-collection site upgrades** （netted→boxed）+ consolidated locations & screening	Territorial reinforcement	Per collection point	$–$$	High（with Ward sanitation）	Day ↑, Night ↑	Share of "boxed" sites; spill events/week; complaints; perceived cleanliness score
6	**Retail frontage transparency &**	Natural surveillance /	Frontage design	$–$$ (per frontage)	Medium	Day ↑, Night ↑	% compliant frontages; footfall;

Rank	Intervention	CPTED principle(s)	Scope / typical unit	Indicative cost	Feasibility	Primary day/night effect	Key metrics for impact
	lighting guidance （≥60% clear glazing, avoid opaque shutters; balanced sign luminance）	Territorial reinforcement	guideline + incentives				SD score change along compliant segments
7	**Micro-greening with maintenance** （trees/planters placed to preserve sightlines）	Territorial reinforcement / Affect regulation	Per block-front	$$	Medium	Day ↑, Night ↔/↑	Canopy/planter count; maintenance pass; SD calm/safety items
8	**Steward/ambassador presence & merchant “eyes-on-the-street” program** （weekend nights）	Capable guardianship	Nightlife cluster	$– $$ (opex)	High (stakeholder program)	**Night ↑**	Steward hours; incident/complaint rate; SD safety after 22:00

Cost classes: $ ≤ ¥1 million (per block-front or intersection); $$ ¥1–5 million; $$$ ≥ ¥5 million. Ranges are indicative and depend on site conditions and procurement.

Rationale by local conditions. Fieldwork in Shinsakae identified dense signage lighting, litter/graffiti hotspots, and distinct nightlife blocks; cameras were numerous but largely on private property (574 total with only 34 in public areas), so we emphasize lighting, maintenance, and place management over public-space cameras as near-term tools.

6.3. Implementation phasing & city partners

- Phase 0 (0–3 months): Clean-up blitz; rapid-removal SLA; boxed-type waste sites at hotspots; draft frontage/lighting guidance; identify dark spots; temporary beacons at crossings. Partners: Naka Ward (sanitation), Roads/Construction Bureau, merchants’ association.
- Phase 1 (3–12 months): Permanent pedestrian lighting retrofit; first traffic-calmed intersection; ambassador pilot (Fri–Sun evenings).
- Phase 2 (12–24 months): Scale traffic calming to priority side-streets; incentive program for transparent frontages; micro-greening with maintenance contracts.
- Phase 3 (24–36 months): Program consolidation; refresh of hotspots using updated kernel maps.

6.4. Monitoring and evaluation

To avoid over-interpreting VR validity (especially at night), we propose a pre-post, treated vs control design anchored in perception and objective indices, with two follow-ups (6 and 12 months):

- Perception: Intercept SD surveys (replicating our items) at treated and matched control blocks; nighttime oversampling; target ≥100 respondents/wave. Primary outcome: Δ in mean SD safety score (day; night) at block level.
- Objective environment: Illuminance (min/avg lx) at sidewalk/crossing; litter pieces/100 m; graffiti recidivism within 30 days; share of “boxed” waste sites; frontage transparency compliance; 85th-percentile speed.
- Analytic approach: difference-in-differences with cluster-robust CIs; Holm–Bonferroni where multiple corridors are tested.
- Learning loop: Update hotspot kernel maps and re-prioritize segments annually using the same layers we used for site selection.

6.5. Translating lab insights to street practice

Because VR approximated daytime judgments but not nighttime ones, nighttime evaluation should rely on real-world audits and intercept surveys, using VR mainly to prototype lighting layouts before field pilots. We therefore pair the above nighttime metrics with staggered pilots (e.g., one intersection at a time) to confirm gains prior to scaling.

7. Conclusion

Conclusion—Summary. This study examined how seven CPTED-related street-environment features—cleanliness, lighting, retail/business type, greening, people, vehicles, and graffiti/fly-posting—shape pedestrians' perceived safety in Nagoya's Shinsakae district. We combined eye-tracking with Semantic Differential (SD) ratings using 24 day/night photographs and a VR replication with 50 participants to link overt visual attention to safety appraisals. Across methods, lighting and cleanliness consistently elevated perceived safety, whereas visible disorder cues lowered it; the VR condition approximated daytime judgments more closely than nighttime. These results support CPTED strategies that pair lighting and maintenance with place management to strengthen natural surveillance, normative clarity, and perceived guardianship in public streets.

7.1. Findings

From a social-psychological perspective, the observed importance of lighting, cleanliness, graffiti/fly-posting, and visible human activity is consistent with mechanisms of normative cues, collective efficacy/guardianship, and affect-based appraisal. In practice, this means that physical interventions work best when they also shape the social meaning of a place—signaling expected behavior, visible oversight, and a welcoming but legible public realm.

Grounded in CPTED, we analyzed how various street-environment factors influence safety perception in Nagoya's Shinsakae district using eye-tracking, VR, and SD-based questionnaires. Lighting, cleanliness, retail type, vehicles, people, graffiti/fly-posting, and greening all affected safety perception to varying degrees. In particular, brighter lighting and cleaner environments substantially improved perceived safety, whereas poor lighting and dirty conditions markedly reduced it. Appropriate greening and business mix also contributed positively. These findings provide empirical support for urban design that prioritizes lighting and cleanliness while situating greening and business types to optimize perceived safety in public space. We thus offer a groundwork of evidence to guide urban design toward safer streets.

7.2. Limitations and future work

Additionally, because recruitment relied on a voluntary, convenience sample drawn via an open web link, the sample may be subject to self-selection bias and is not statistically representative; future work should employ probability-based or stratified recruitment strategies.

Fixed block order (potential order effects). The SD-rating and VR tasks presented daytime before nighttime, which may have induced priming/fatigue/contrast effects and thus inflated the observed day–night differences in perceived safety. Future work should counterbalance the order across participants (day→night vs night→day) and/or interleave scenes by time of day; adaptive breaks and attention checks can further mitigate fatigue. The eye-tracking task mitigated this concern by using mixed random order.Transferability and cultural context. Our findings derive from a single district in Nagoya (Shinsakae), within a Japanese urban context characterized by comparatively high baseline cleanliness and strong social norms of order. As such, factor weights may shift in cities with different urban forms or cultural norms—for example, where disorder cues are more prevalent, cleanliness may weigh more heavily than lighting, whereas in highly illuminated contexts lighting may show diminishing returns. Consistent with this possibility, our nationality-split ranking data suggest cross-context variation in salience (Japanese participants prioritized brightness slightly more; Chinese participants prioritized cleanliness)(**Table 14**). Future work should replicate across multiple districts/cities and cultural settings to assess how urban form and social norms moderate factor weights

We did not record participants' current municipality of residence; instead, we documented familiarity with and residence history in the Shinsakae district. Future work should collect finer-grained residential context (e.g., current neighborhood, commuting patterns) to test for potential place-based differences in perceived safety.

This study has limitations. First, experimental scenes and sample size were limited, which may affect generalizability. Second, reliance on self-report introduces potential subjective bias. Future work should expand samples across more areas, seasons, and times, and incorporate additional psychophysiological indicators. Although we identified safety-perception factors via CPTED and evaluated real streets with eye-tracking and VR, further steps remain: diversify and enlarge datasets; adopt advanced deep-learning algorithms and multi-domain training to improve the accuracy and robustness of semantic-segmentation models; and incorporate video and real-time data to capture dynamic and long-term effects. Integrating subjective and objective evaluations is also crucial—e.g., fusing survey/interview data with semantic-segmentation outputs.

Locomotion in VR was local rather than full room-scale. Although participants could translate within a predefined zone using the controller and head tracking, they did not physically walk long distances. This constraint may attenuate vestibular and proprioceptive cues and could contribute to the observed differences between VR and nighttime field appraisals. Future studies could adopt room-scale walking, treadmill/redirected-walking techniques, or mixed-reality augmentation to better approximate real nighttime conditions.

For practical application, we should strengthen collaboration with planners and policymakers to address implementation challenges. Integrating drones, IoT, and AI cameras with SS-based analytics can improve precision and efficiency in road-safety perception assessment. Addressing these issues will contribute to safer, more reassuring urban environments.

A key limitation is the absence of prospective institutional ethics approval. While our institution did not require formal review for this type of minimal-risk study, we recognize that prospective review is best practice and will seek prospective committee review and (pre-)registration for follow-up studies. We also note the volunteer sample and modest compensation (¥1,000 or stationery) may influence participation willingness; future work will include standardized adverse-event logging and pre-registered stopping rules.

7.3. Data, materials, and reproducibility

Availability. All anonymized data and study materials are available in an open repository [link blinded for peer review; DOI to be added upon acceptance]. The repository contains: (i) raw and processed datasets for eye-tracking (per-fixation and per-AOI metrics) and SD ratings (per participant × per stimulus), plus participant profile variables in banded form (age band, eyewear yes/no, local familiarity); (ii) AOI masks for all 24 stimuli (vector files); (iii) the 24 photographic stimuli used in the lab tasks with faces and vehicle plates blurred; (iv) the VR scenes used in the experiment (Unity project export/.unitypackage and the Meta Quest 3 build); and (v) a data dictionary (codebook) and variable-derivation sheet describing all fields and composite indices.

Reproducibility. No bespoke analysis code was written; all analyses used standard statistical procedures. To enable exact regeneration of the reported results, we provide a replication guide (PDF) detailing the analysis steps and settings, together with a spreadsheet that reproduces all summary tables from the shared datasets. File-level provenance and checksums are listed in the repository README.

Restrictions and licensing. The stimuli images are released with faces and license plates redacted to protect privacy; unredacted originals can be provided for non-commercial academic use under a data-use agreement. Unless otherwise noted, materials are shared under a CC BY-NC 4.0 license; software packages are redistributed under their original licenses. Repository contents will be made public upon article acceptance.

Notes

Note 1. Eye-tracking enables detailed analysis of which parts of the road space pedestrians attend to and which factors most strongly influence safety perception.

Note 2. Photo-site selection ensured coverage of all seven safety-perception factors.

Conflict of interest

The authors declare no conflict of interest.

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