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Urban chronotypes as climate vulnerability indicators: Safety-modulated bioclimatic responses and adaptive behavior across diurnal urban contexts

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ABSTRACT

Urban heat adaptation strategies assume stable human bioclimatic potential responses across time and space, yet cities transform substantially between day and night: thermally, acoustically, visually, and in terms of perceived safety, fundamentally altering how populations sense and respond to environmental exposures. Laboratory-based thermal comfort frameworks miss this real-world contextual complexity. This study introduces urban chronotypes: four distinct patterns of physiological and behavioral response to urban climatic conditions emerging from the interaction of time of day and perceived safety and examines their implications for climate vulnerability and heat adaptation effectiveness. In Brussels Capital Region during summer 2025, 36 monitoring sessions were conducted across morning and night walks through validated high-safety and low-safety urban areas, generating 2132 validated exposure-physiology-behavior pathway observations using synchronized wearable environmental, physiological, and eye-tracking sensors. Three findings emerge. First, unsafe contexts reversed physiological-behavioral coupling from positive to near-zero, demonstrating that cooling strategies deployed in unsafe areas fail to produce protective behavioral responses despite intact physiological heat sensing, a climate adaptation failure disproportionately affecting urban dwellers. Second, thermal bioclimatic processing showed unique context-dependence (+24% coupling in nighttime conditions, Bonferroni-corrected), while air quality, acoustic, and visual processing remained stable across all contexts. Third, nighttime processing accelerated by 3.6 min regardless of safety context, establishing a universal 14–16 min adaptation window as the minimum duration urban climate interventions must persist to enable complete physiological-behavioral integration. Urban climate vulnerability is not solely determined by thermal exposure magnitude but is critically shaped by perceived safety and temporal context, demanding integrated climate-safety approaches to urban heat adaptation.

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1. Introduction

Urban bioclimatology research has increasingly moved beyond characterising thermal exposure thresholds toward understanding how contextual factors modulate human physiological and behavioral responses to those exposures (Malakar et al., 2023). Yet a critical gap persists: the role of perceived safety as a modulator of bioclimatic response has received no systematic empirical attention, despite overwhelming evidence that urban populations experience dramatically different safety conditions across time of day and neighbourhood type. **Cities transform substantially between day and night, thermally, acoustically, and visually, while simultaneously evoking different safety perceptions that change how people process environmental information.** While indoor laboratory comfort studies reveal extensive non-linear interactions across sensory modalities, the comfort research field faces a critical ecological validity problem where controlled experimental conditions fail to capture the real-world complexity of how humans experience real cities (Kihlstrom, 2021). Traditional human vulnerability frameworks, including the Intergovernmental Panel on Climate Change's (IPCC) vulnerability assessments, have primarily relied on static demographic scenarios and remote sensing data while overlooking the dynamic relationship between environmental conditions and human responses (Ishtiaque et al., 2022, Xu et al., 2025, Li et al., 2024). Recent evidence from large-sample studies demonstrates that individual genetic variations explain differential vulnerability to urban environmental factors, accounting for significant variance in brain volume differences related to affective symptoms (Mavros et al., 2022; Badakhshan et al., 2025). This finding suggests that environmental interventions may produce effects varying substantially depending on individual characteristics and timing, introducing a level of complexity that laboratory studies systematically overlook. Research shows inconsistent effects in laboratory settings compared to field studies. Context-specific effects on soundscape perception were highly significant in laboratory conditions but non-significant in field studies of identical environments (Tarlao et al., 2022). This 'inflation' of effects in controlled settings severely limits generalizability (Refinetti et al., 2016), with controlled experiments missing critical contextual factors including holistic sensory integration under actual urban conditions, and dynamic environmental changes.

1.1. *Temporal variation operates through multiple pathways*

Circadian rhythms modulate sensory sensitivity, with auditory sensitivity and visual processing efficiency exhibiting robust diurnal variations. Beyond physiological circadian effects, nighttime urban experience carries distinct psychological dimensions. Reduced visibility heightens reliance on non-visual sensory modalities and amplifies safety concerns (Jackson and Gouseti, 2012). Fear of crime peaks during evening hours, particularly in poorly lit or isolated areas (Peña-García et al., 2016). Environmental safety perception research highlights that lighting conditions significantly affect emotional responses and threat assessment, with optimal safety perception requiring specific illuminance levels during nighttime conditions (Shang et al., 2015). Physiologically, perceived danger activates sympathetic nervous system responses including elevated heart rate, increased electrodermal activity, and altered respiration patterns (Walker et al., 2020; Clauss et al., 2022), which may either enhance or impair environmental sensitivity depending on arousal intensity. These neurocognitive mechanisms indicate that threat perception may act as a sensory gating mechanism, selectively altering which environmental domains such as thermal, visual, acoustic, or air quality dominate perception-action coupling during human experience in urban environments (Izquierdo et al., 2020).

The nocturnal urban environment is further characterized by pervasive Artificial Light at Night (ALAN), with citizen science inventories revealing that advertising and aesthetic lights outnumber street lighting in city centers, approximately 78 million individual light sources remain illuminated at midnight across Germany alone (Team Nachtlichter, 2025). This heterogeneous lighting landscape creates dramatically different stimulus environments between safe corridors with diverse lighting and unsafe areas with inadequate or inappropriate illumination. These temporal gradients in urban environmental conditions suggest that static characterisations of urban climate vulnerability, which do not account for diurnal variation in either physical conditions or human physiological sensitivity may substantially misrepresent who is vulnerable, when, and where.

The Stimulus-Organism-Response (SOR) framework provides a structured approach to address this gap (Wang et al., 2025a, 2025b; Lu et al., 2025). SOR's three-component structure: external environmental factors (stimuli), internal physiological and psychological states (organism), and behavioral outcomes (response) can enable systematic mapping of how urban contexts modulate human-environment coupling (Zhao and Weng, 2024; Huang, 2023). By integrating wearable sensing technology with SOR framework, there is a potential to trace complete pathways from environmental exposure through physiological mediation to behavioral response in authentic urban settings (Fan et al., 2025). Beyond physiological circadian effects, recent controlled experiments demonstrate that light exposure timing fundamentally alters thermal physiological responses: bright morning light significantly suppresses skin temperature rise and shifts thermal sensation toward cooler votes under warm conditions, whereas midday exposure shows attenuated effects (Elkounni et al., 2025).

These time-dependent responses suggest environmental interventions may achieve differential effectiveness depending on when they are deployed and accessed. Capturing these dynamic exposure-response relationships requires methodological approaches that can trace complete pathways from environmental exposure through physiological mediation to behavioral outcomes in real urban settings. **This study addresses a fundamental question for climate adaptation: does threat perception fundamentally alter multisensory environmental processing across temporal urban contexts, or does the human perceptual system maintain functional integrity through adaptive response strategies?** To the best of our knowledge, this represents the first study to model human adaptations within a systematic experimental framework under various temporal and safety-perceived conditions, using advanced temporal precedence methods including bootstrap confidence intervals, Granger causality testing, and cross-correlation analysis (Trudeau et al., 2020; Rossetti, 2020) in real-world urban environments across diurnal cycles and safety gradients. The study deployed synchronized physiological and behavioral sensors to map multisensory processing across experimentally controlled temporal-safety gradients in Brussels Capital Region.

We introduce the concept of 'urban chronotypes': distinct patterns of multisensory processing that emerge from the interaction between time of day and safety perception. Unlike circadian chronotypes that describe individual sleep-wake preferences, urban chronotypes describe context-dependent processing modes that any individual may experience depending on when and where they navigate the city. These patterns reflect adaptive recalibration of sensory-physiological-behavioral pathways rather than fixed individual traits. This research builds upon three central hypotheses collectively addressing a fundamental question for urban climate adaptation planning: whether human bioclimatic response capacity is uniform across urban contexts, or whether it varies systematically with the safety and temporal characteristics of the environment in ways that create differential climate vulnerability. First (H1), the study aims to answer whether threat perception modulates the strength of directed pathways linking environmental stimuli to behavioral responses via physiological states. Second (H2), we examine whether environmental domains show differential context-sensitivity: if some domains (e.g., thermal) reorganize across conditions while others (e.g., air quality) remain stable, this would indicate domain-specific versus universal processing mechanisms. Third (H3), we test whether unsafe contexts fragment temporal integration, producing delayed or erratic response timing or whether the perceptual system maintains consistent processing timescales despite threat.

2. Methods

2.1. Experimental design

To assess how perceived safety and temporal context modulate bioclimatic response under ecologically valid conditions, we deployed a wearable sensing protocol during pedestrian navigation in validated high and low-safety urban areas (Fig. 1). Initially, we deployed community-validated safety mapping with 100 residents to identify where people actually feel unsafe, then tracked physiological and behavioral responses in these authentic urban contexts. Online mapping (n = 100) classified safety concerns into threatening individuals, vulnerable situations, traffic hazards, poor ambient conditions, and inadequate lighting, informing route selection that balanced ecological validity with controlled comparisons (Fig. 3).

Field experiments deployed wearable sensing during pedestrian navigation, generating 6678 observations across four experimental conditions combining time of day (morning 10–11 AM vs. night 10–11 PM) and safety context (high-safety vs. low-safety areas) (See Table 1.) (Fig. 2). The study collected 6678 raw sensor measurements. *A preliminary examination using* 18 participants (10 men, 8 women; M_age = 28.8 years, SD = 4.2, range = 21–40). Eleven participants were aged 21–29 and seven were aged 30–39. In terms of national origin, participants represented 7 countries: Belgium, China, Greece, Iran, India, Spain and Turkey. All participants were residents of or regular commuters within the Brussels Capital Region at the time of the study. Clothing insulation was assessed at baseline using the standard Fanger clo index. Mean values were 0.42 ± 0.09 clo during morning sessions and 0.51 ± 0.12 clo during night sessions, consistent with light summer attire across both condition. After quality control filtering (removing movement artifacts, sensor failures, and incomplete measurement windows) and pathway validation (requiring statistically significant S → O and O → R relationships), 2132 complete stimulus-organism-response pathways met validation criteria for analysis. Sample size was determined a priori using three complementary methods namely, paired t-tests ($d = 0.5$, $\alpha = 0.05$, $1 - \beta = 0.80$), repeated measures ANOVA ($\eta^2 = 0.06$), and logistic growth curve modelling of physiological adaptation rates (Schweiker, 2022) converging on a recommended n = 20–25. The achieved sample of n = 18 reflects practical constraints of the five-system wearable protocol. Participants completed two

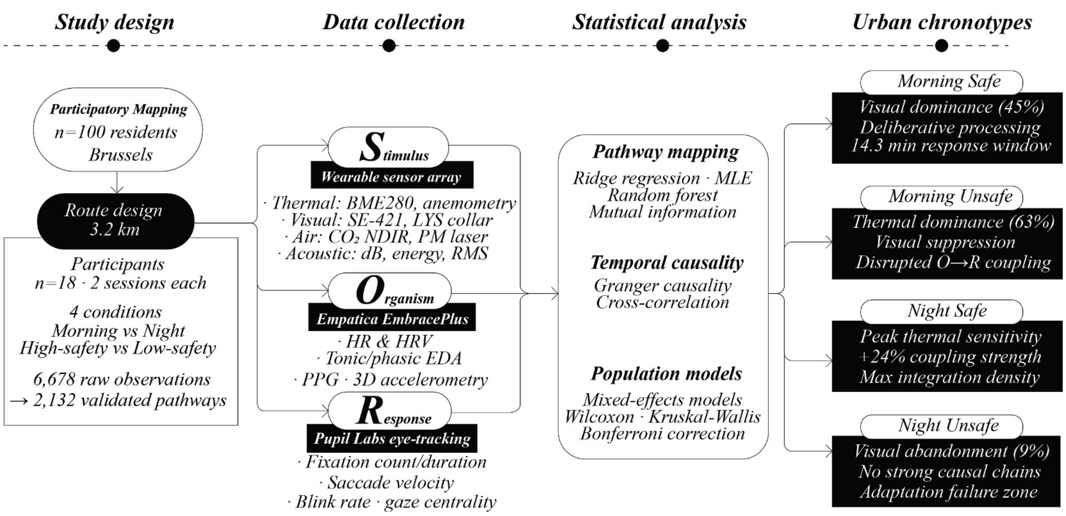

Fig. 1. Methodology overview.

Table 1
SOR Framework variables and measurement specifications.

Category	Variables ($n = 24$)	Measurement units	Sampling rate	Validation criteria
Stimulus (S)	Sound level (dB), Audio energy, Audio RMS, Temperature (°C), Humidity (%), CO_2 (ppm), Wind speed/direction, PM2.5/PM10/PM100 (μg/m^3), LUX levels, Color temperature (K), RGB components	Physical units	1-min intervals	FDR $p < 0.05$, Effect size ≥0.15
Organism (O)	Heart rate (BPM), Tonic EDA (μS), Phasic EDA (μS)	Physiological units	Continuous	Cross-validation $R^2 > 0.1$
Response (R)	Gaze position (X,Y pixels), Fixation duration/count (ms/n), Saccade velocity (°/s), Gaze spread (pixels)	Behavioral metrics	60–120 Hz	Bootstrap CI stability

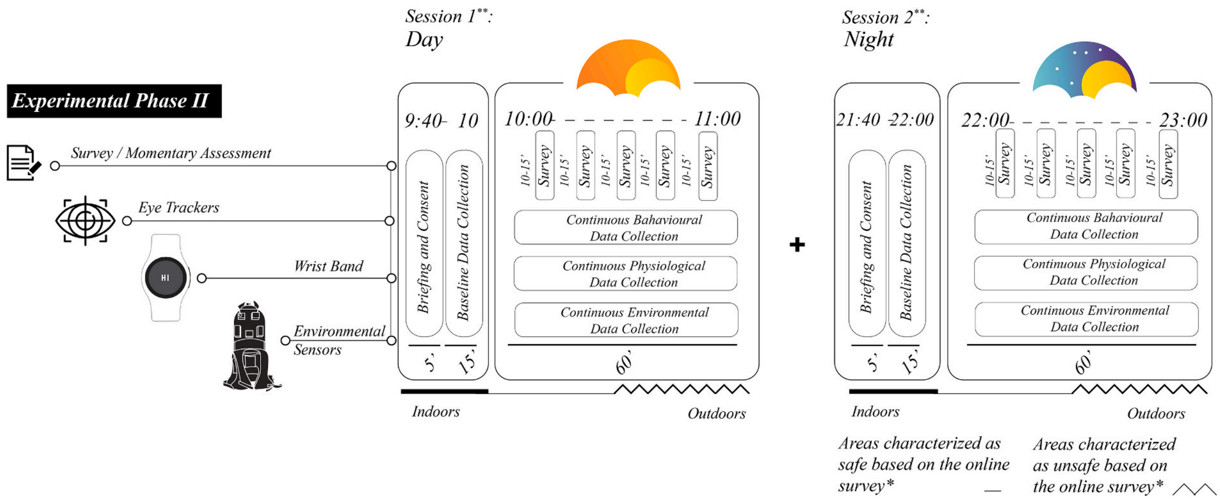

Fig. 2. Experimental Planning, each participant's involvement lasted approximately one hour per session, with two counterbalanced sessions conducted on separate days to minimize learning effects, recall bias, and other potential order effects.

counterbalanced sessions on separate days. Prior to each session, participants received a standardized briefing covering the study purpose, the experimental route and its segments, the sensor systems they would wear, the frequency and format of the psychometric surveys, and their right to withdraw at any time. Written informed consent was obtained in accordance with the UCLouvain SST Ethical Committee approval, confirming that participants have been informed about the nature of physiological monitoring, data confidentiality, and anonymous storage procedures.A standardized 10-min indoor baseline period (seated, ~22 °C, ~300 lx, minimal stimulation) preceded each session to establish participant-specific physiological reference values and control for pre-existing autonomic differences. Routes (3.2 km, ~60 min) alternated between validated high-safety segments (<5% concern reports; well-lit commercial corridors) and low-safety segments (≥15% concern reports; poor lighting, isolation), spatially separated by ≥1 km. Psychological assessments included STAI-6 anxiety inventory (Perpiñá-Galvañ et al., 2011; Torres-Gomez et al., 2020), abbreviated NEWS walkability scale (Cerin et al., 2006), multidomain comfort (4-point scales), and safety perception (5-point scales) at 10–15 min intervals (Chinazzo et al., 2022). Environmental data collection by researchers maintained sufficient distance to avoid influencing natural behavior.

2.2. Study location

Experiments were conducted in Brussels Capital Region (BCR), Belgium (Köppen Cfb: temperate climate, warm summers, mild seasonal variation) during June–August 2025. Data collection occurred under moderate thermal conditions (15.7–30.1 °C, CV = 0.13) rather than extreme heat events. This methodological choice was intentional: existing literature demonstrates that extreme heat masks subtle multisensory interactions, reducing human sensitivity to non-thermal stimuli including acoustics, visual quality, and air pollution in indoors (Gnecco et al., 2023) and outdoors (Rosso et al., 2022). By conducting measurements during non-heatwave conditions with sufficient natural variation across all sensory domains (temperature range 14.4 °C; illuminance 387-fold variation; all $p < 0.001$), we enabled detection of domain-specific sensitivities and their context-dependent reorganization, patterns that would be obscured under thermal extremes where survival-oriented thermoregulation dominates perception. This temperate summer context provides ecological validity for understanding how multisensory urban design can support adaptive comfort under conditions representative of extending outdoor activity seasons in warming cities.

2.3. Data collection

2.3.1. Measuring environmental exposure (stimulus)

Environmental exposures were continuously monitored using a validated wearable monitoring system (Cureau et al., 2022), consisting of a modular backpack-mounted sensor array with GPS for spatial registration. Thermal conditions were measured via a BME280 sensor (air temperature ± 1 °C; relative humidity ±3% at 20–80% RH) and atmospheric pressure (±0.25% sensitivity), with wind speed and direction captured through ultrasonic anemometry (CV7-V). Visual exposure was quantified through SE-421 sensors (0–150,000 lx range), supplemented by personal light dosimetry using collar-mounted LYS button 1.0 sensors recording illuminance (0–100,000 lx), correlated color temperature (Kelvin), and RGB spectral components (350–750 nm). Air quality was monitored using TDS0037 NDIR sensors for CO_2 concentration (±2% accuracy) and PMS5003 laser-scattering sensors for particulate matter (PM1.0, PM2.5, PM10). Together, this configuration enabled high-resolution characterization of participants' environmental exposures across thermal, visual, and air quality domains, with direct spatial referencing to the urban fabric.

2.3.2. Physiological monitoring (organism layer)

Physiological responses were recorded continuously using Empatica EmbracePlus devices, certified for ambulatory cardiovascular monitoring (FDA 510(k), CE class IIa) (Chwalek et al., 2024). Heart rate variability (HRV) was derived from time-domain indices (root mean square of successive differences (RMSSD), standard deviation of NN intervals (SDNN)) and frequency-domain ratios (low frequency/high frequency (LF/HF)), providing markers of autonomic regulation. Sympathetic arousal was assessed through ventral electrodermal activity (EDA), capturing tonic and phasic components. Additional cardiovascular dynamics were captured with a 4-channel multiwavelength photoplethysmogram (PPG), while integrated 3D accelerometry and gyroscopic sensors corrected for movement artifacts. Together, these measures provided a multidimensional profile of organismic states, enabling assessment of physiological stress responses to environmental variation.

2.3.3. Behavioral monitoring (response layer)

Behavioral outcomes were assessed using Pupil Labs Act Natural eye-tracking glasses, offering gaze recordings. Data were processed through standardized pipelines to extract metrics of visual attention and stress-related gaze dynamics (Franěk and Petružálek, 2025). Two complementary indices were derived: (i) a composite stress indicator based on normalized fixation count and inversely scaled fixation duration (where higher frequency and shorter duration indicate increased cognitive load), and (ii) a rule-based multidimensional stress score integrating fixation dispersion, scan regularity, blink rate, saccade velocity, and gaze centrality. Blink rate was interpreted as a non-invasive marker of dopaminergic activity and attentional load (Maffei and Angrilli, 2019; Jongkees et al., 2017), while saccadic velocity captured fatigue and stress accumulation, with lower velocities indicating sustained challenge. These behavioral indicators linked sensory exposure and physiological state to observable engagement with the urban environment.

2.4. Statistical analysis

The study established temporal causality using established methods: Granger causality tests confirmed environmental changes preceded physiological responses, which then preceded behavioral adaptations (pathway). A 'pathway' represents a statistically validated causal chain where an environmental stimulus (S) predicts a physiological response (O), which in turn predicts a behavioral outcome (R). Pathway strength quantifies the combined correlation strength across both links (S → O and O → R), with values ranging from 0 (no relationship) to 1 (perfect coupling). Chain strength > 0.7 indicates strong integration where environmental changes reliably produce coordinated physiological and behavioral responses." Bootstrap resampling (1000 iterations, resampling participants with replacement to preserve within-person correlation structure) quantified statistical uncertainty in pathway strengths and generated 95% confidence intervals.

Analysis proceeded in two phases.

- Phase I (Pathway Mapping) systematically mapped relationships among environmental variables (thermal, acoustic, air quality, visual), physiological indicators (heart rate, electrodermal activity), and behavioral outcomes (attention, scanning patterns). Ridge regression captured time-delayed responses; Maximum Likelihood Estimation quantified how different sensory inputs contribute to final perceptual outcomes (Ronsse et al., 2009; van Dam et al., 2014). Random Forest regression tested generalizability beyond our sample; mutual information analysis detected nonlinear thresholds in physiological-behavioral coupling.
- Phase II (Network Validation) distinguished direct environmental-behavioral pathways (S → R) from physiologically-mediated pathways (S → O → R), testing whether safety impairs environmental monitoring, behavioral translation, or both. We applied stringent validation: false discovery rate correction ($p < 0.05$), meaningful effect sizes (≥ 0.15), cross-validation accuracy, and bootstrap confidence interval stability.

To address whether effects apply universally or vary by individual, we used two complementary approaches. Mixed-effects models (Silva et al., 2024) separated population-level patterns (fixed effects: safety, time, interaction) from individual differences (random effects), testing whether context effects are consistent enough for population-level design strategies. Distribution-free tests (Wilcoxon signed-rank, Kruskal-Wallis) on participant-aggregated data confirmed effects were reliable across individuals rather than artifacts of pooling. When comparing thermal processing's context-sensitivity against other sensory domains, Bonferroni correction ($\alpha = 0.0125$) ensured findings represent genuine effects rather than false positives from multiple testing.

3. Results

3.1. Experimental design, context

3.1.1. Route selection and safety assessment

Participatory mapping with 100 residents identified safety concerns concentrated in threatening individuals (28.7%), vulnerable situations (16.8%), and environmental factors including traffic hazards (10.9%), poor ambient conditions (9.9%), and inadequate lighting (8.9%). We designed an experimental route (Fig. 3) alternating between high-safety segments (<5% concern reports, well-lit commercial corridors) and low-safety segments (≥15% concern reports, characterized by poor lighting and social disorder cues).

3.1.2. Data collection

A preliminary examination using Mann-Whitney *U* tests revealed no gender differences across any safety dimension during daytime conditions (all $p > 0.25$; $n = 61$ female, $n = 43$ male), indicating comparable diurnal safety experiences. During nighttime, however, female respondents reported significantly higher personal unsafety (Mdn = 2.00 vs. 1.00; U = 1741.0, $p = 0.004$), nervousness/anxiety (Mdn = 2.00 vs. 1.00; U = 1756.5, $p = 0.003$), and tension (Mdn = 2.00 vs. 1.00; U = 1598.5, $p = 0.050$) on a 0–4 scale, while traffic-related unsafety showed no gender difference ($p = 0.602$). During the monitoring campaign, 2132 validated stimulus-organism-response observations were collected from 18 participants across four experimental conditions combining time of day (morning 10–11 AM vs. night 10–11 PM) and safety context (high-safety vs. low-safety urban areas) along the selected route. Data collection occurred during summer months (June–August 2025) under moderate temperature conditions (mean temperature: 18–24 °C, minimal precipitation) to ensure thermal comfort ranges conducive to outdoor activity while avoiding extreme heat that could confound physiological measurements. Each participant completed two counterbalanced walking sessions, generating synchronized environmental, physiological, and behavioral data streams analyzed for directed pathways linking stimuli to responses via organismic states. Environmental conditions showed substantial diurnal variation (Supplementary Material, Table S1). Illuminance decreased 387-fold (23,530 ± 26,614 lx morning vs. 61 ± 99 lx night), temperature decreased 10.5% (24.0 ± 2.5 °C vs. 21.4 ± 3.1 °C), humidity

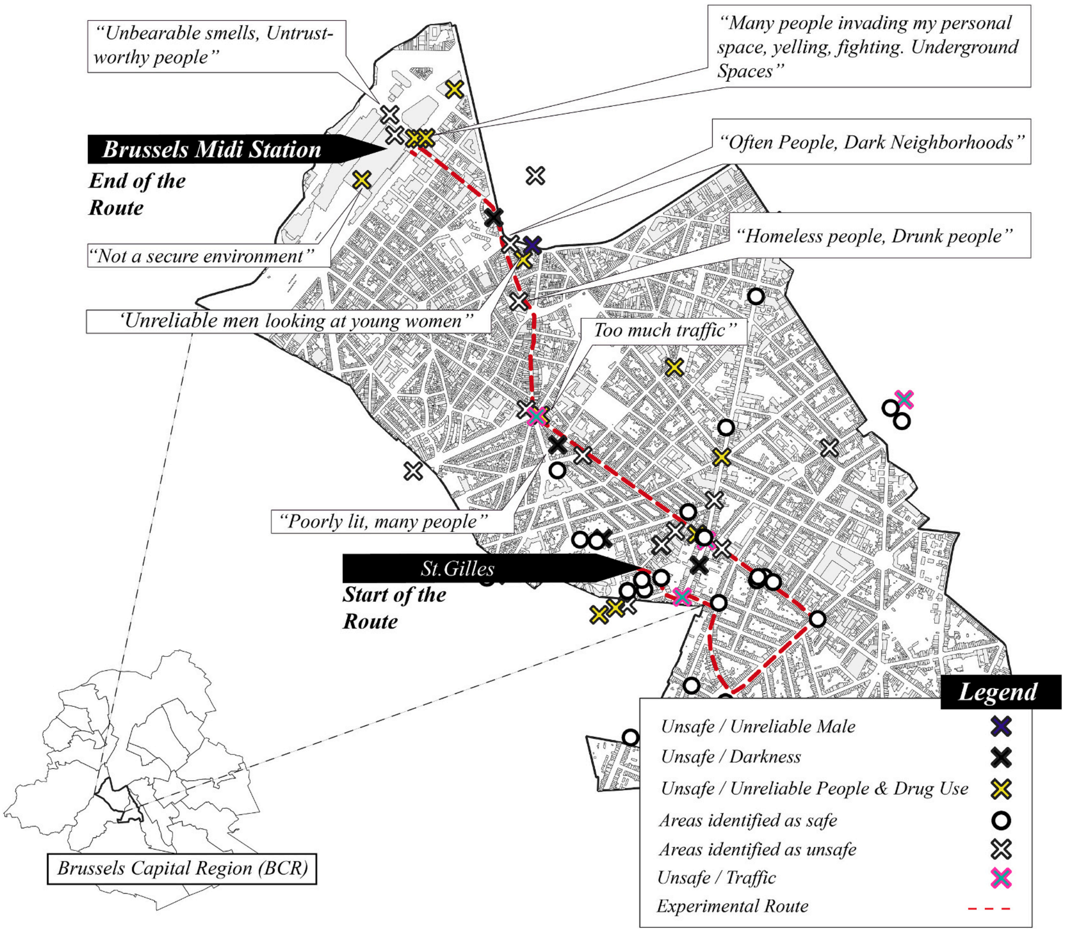

Fig. 3. Experimental route design.

increased 15.1% (48.6 ± 8.5% vs. 56.0 ± 9.3%), and particulate matter increased 11–17% at night (all $p < 0.001$). Coefficient of variation ranged from 0.13 (temperature) to 4.96 (color temperature).

3.2. Safety modulates pathway strength across conditions

3.2.1. Individual-level pathway patterns

Results from one randomly selected participant (Supplementary Material, Table S2) showed expected environmental differences between day and night conditions (Fig. 4): nighttime navigation occurred in conditions 4.4 °C warmer yet darker (22,968 versus 45 lx), with elevated $PM_{2.5}$ (+188%). Physiological arousal doubled (tonic EDA: 3.11 versus 1.56 μS), while visual behavior showed compensatory strategies, reduced fixation frequency and 15.4% slower eye movements under dim lighting.

Validated SOR pathways varied substantially across conditions (Fig. 5): Night Safe exhibited 68 complete validated pathways (meeting FDR $p < 0.05$, effect size ≥0.15 criteria), Morning Safe 21, while unsafe contexts showed reduced network density (Morning Unsafe: 14; Night Unsafe: 15). This reduction reflects both fewer statistically significant relationships and failure to meet effect size thresholds, indicating unsafe contexts disrupt multisensory integration quality, not just statistical detectability. Nine strong causal chains (chain strength >0.7, representing 8% of 117 pathways) emerged, with none in Night Unsafe conditions. Morning Safe contexts showed full visual comfort processing (Blue → Tonic EDA → Fixation Time: $\rho = 0.819$). Morning Unsafe contexts demonstrated complete switching to thermal processing (Temperature → Tonic EDA → Fixation Time: $\rho = 0.752$), a complete shift away from visual processing. Night Safe replicated RGB color processing but with faster integration (less than 1-min delays). A critical trade-off emerged between environmental sensitivity and behavioral coupling.

Conditions with highest environmental sensitivity (Night Unsafe S → O = 0.890; Morning Unsafe S → O = 0.887) paradoxically showed degraded behavioral coupling (O → R = 0.892 and 0.849). These O → R values, while numerically high, represent average coupling across all pathways, including many weak or negative relationships that cancel out, indicating inconsistent behavioral translation despite strong physiological monitoring. This represents a 13.9% efficiency loss under reduced safety. Enhanced environmental sensitivity in threatening contexts comes at the cost of coherent translation to behavior. Analysis of all 117 pathways revealed pronounced sensory reorganization: Morning Safe showed visual and light dominance (45%); Morning Unsafe shifted to thermal dominance (63%) with visual suppression; Night Safe (exhibited maximum diversity including unique auditory recruitment (26%), maintaining visual dominance (44%); Night Unsafe ($n = 11$) showed near-complete visual abandonment (9%), with air quality and thermal factors co-dominating but achieving no strong chains, indicating degraded integration under combined stressors. Granger causality testing confirmed temporal precedence (FDR-corrected $p < 0.001$) (Shojaie and Fox, 2022; Wang et al., 2023). From a climate vulnerability and urban design perspective, this dissociation is critical: populations navigating unsafe urban areas are physiologically sensing thermal and environmental stress at equivalent or higher intensity than those in safe areas, yet are systematically unable to convert that physiological awareness into protective adaptive behavior. This represents a previously uncharacterised mechanism of urban climate vulnerability, one that is invisible to exposure-only assessment frameworks and that disproportionately affects populations dwelling unsafe urban environments.

3.2.2. Population-level patterns

Analysis of all participants ($N = 18$, 2132 pathways) used two complementary approaches: participant-level aggregation with non-parametric tests and mixed-effects models accounting for nested data structure (Silva et al., 2024; Vanhöfen et al., 2025). Environmental sensitivity (S → O coupling) showed significant Safety × Time interaction ($\beta = 0.192$, $p = 0.016$): morning unsafe contexts exhibited reduced coupling versus safe contexts ($\beta = -0.140$, $p = 0.010$), but this reversed at night where safety effects diminished. The coupling between physiological states and behavioral responses (O → R) was strongly affected by threat perception regardless of time of day. In safe areas, physiological arousal positively predicted behavioral changes (M = 0.189), while in unsafe areas this relationship became negative (M = -0.037; W = 17.0, $p = 0.025$, $r = 0.162$). Critically, safety had a much stronger effect on how physiology translates into behavior ($\Delta = 0.226$) than on how the body initially responds to environmental stimuli ($\Delta = 0.002$ when averaging across times of day). This indicates safety primarily affects behavioral translation rather than sensory monitoring. This finding was reliable despite sparse pathway density, with 11 out of 18 participants showing consistent patterns (defined as O → R coupling difference between safe and unsafe contexts >0.15 in the predicted direction; binomial test against 50% null: $p = 0.033$).

3.3. Thermal processing shows unique context-sensitivity

Thermal processing showed unique context-sensitivity among four sensory domains (Table 2), with response timing revealing across-the-board nighttime acceleration. Nighttime responses across all pathways averaged 3.6 min faster than morning ($\beta = -3.58$, $p < 0.001$), independent of safety context (safety main effect: $\beta = -0.49$, $p = 0.374$; interaction: $p = 0.814$), with median times ranging 14.3–15.9 min. Within this general acceleration pattern, thermal sensitivity specifically peaked during safe nighttime navigation (M = 0.591, 95% CI [0.532–0.649]), representing 24% increase versus morning safe (M = 0.477, 95% CI [0.450–0.499]; H = 11.42, $p = 0.010$, $\eta^2 = 0.196$) the only modality surviving Bonferroni correction ($\alpha = 0.0125$) (Meidenbauer et al., 2024). This 24% increase in pathway strength indicates that thermal comfort interventions deployed during safe nighttime hours would produce substantially more reliable physiological-behavioral responses compared to identical interventions during morning hours, directly informing when cooling infrastructure achieves maximum behavioral effectiveness. Visual ($p = 0.194$), acoustic ($p = 0.338$), and air quality ($p = 0.495$) processing remained stable across contexts. The suppression of thermal sensitivity in unsafe contexts, where thermal pathway strength returns to morning-safe baseline levels (M = 0.476) despite nighttime circadian acceleration, indicates that safety perception acts as a

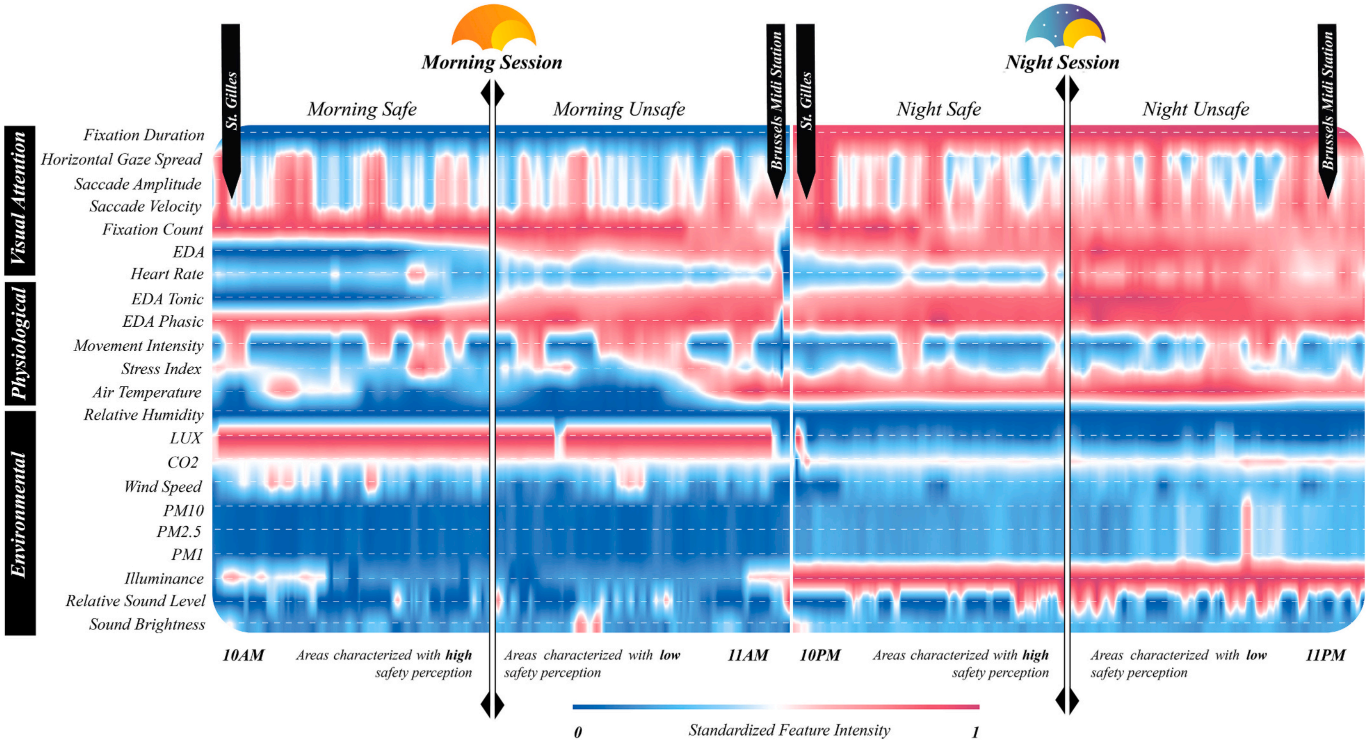

Fig. 4. Multisensory stress heatmap across diurnal and safety conditions. Heat maps display standardized intensity (blue = comfort, pink = discomfort) for 22 variables across morning (10–11 AM) and night (10–11 PM) sessions in high- and low-safety areas. Each time-step represents 15 s of data. Distribution analysis showed marked session differences: e.g., CO_2 stress rose from a median of 0.27 (morning) to 0.78 (night), and wind speed from 0.33 to 0.71, while fixation count dropped from 0.95 to 0.41, suggesting reduced visual engagement at night. Conversely, phasic EDA decreased from 0.88 to 0.48, pointing to lower physiological arousal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

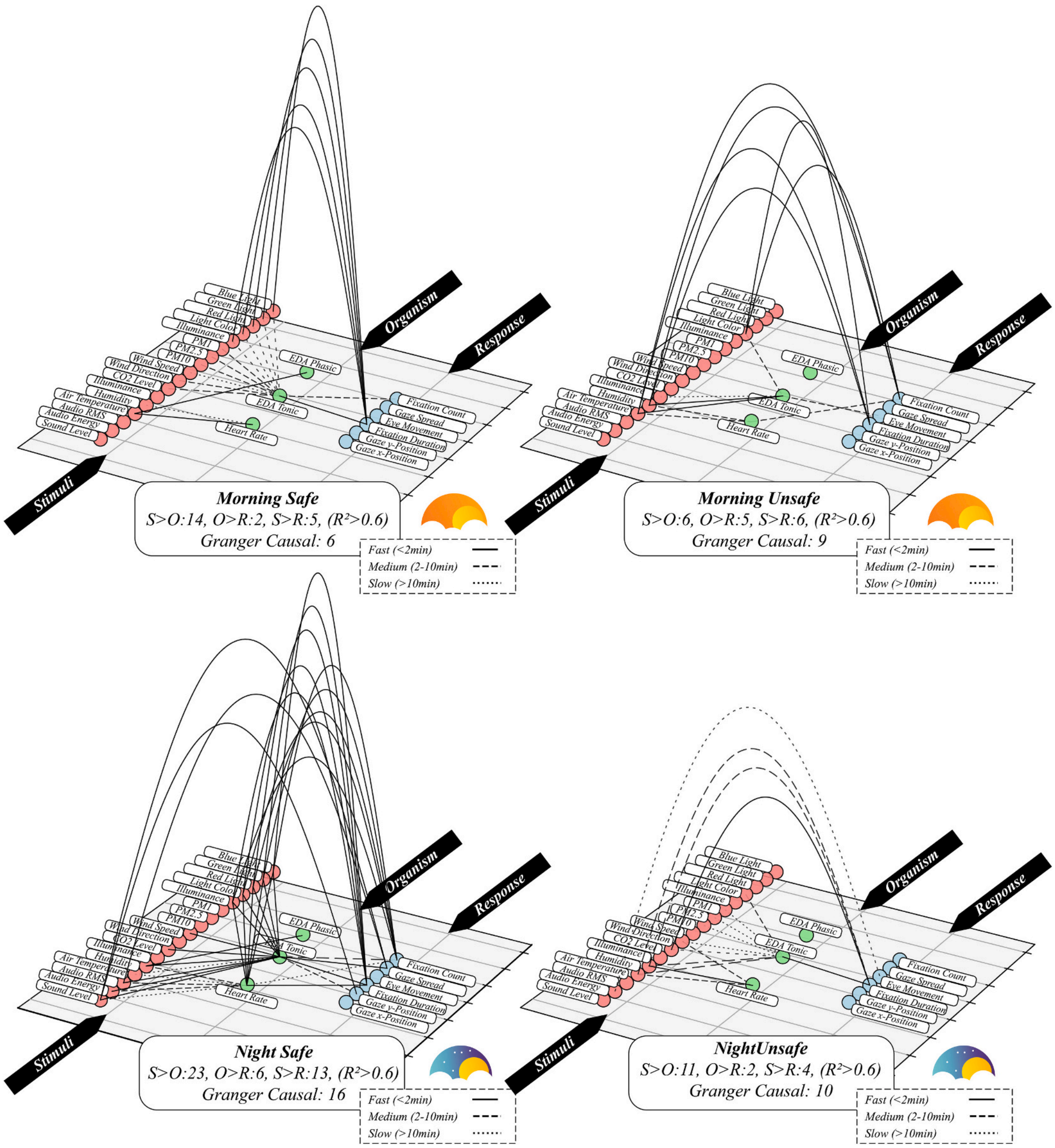

Fig. 5. Safety and Time Modulate Multisensory Integration Networks. Representative participant's Stimulus-Organism-Response pathways across four urban contexts. Nodes represent environmental inputs (red), physiological states (green), and behaviors (blue); edges show validated causal connections (chain strength >0.6, FDR $p < 0.05$). Line type indicates response speed. Night Safe conditions enable densest integration; Morning Safe produces distributed processing patterns. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Environmental domain processing across urban contexts.

Domain	Morning safe	Morning unsafe	Night safe	Night unsafe	Statistical test
Visual	*0.541 [0.498–0.589]*	*0.474 [0.430–0.521]*	*0.510 [0.453–0.566]*	*0.480 [0.423–0.553]*	$H = 4.71, p = 0.194$ *ns*, $\eta^2 = 0.034$
Thermal	*0.477 [0.450–0.499]*	*0.509 [0.472–0.544]*	*0.591 [0.532–0.649]*	*0.476 [0.444–0.512]*	$H = 11.42, p = 0.010^{**}$, $\eta^2 = 0.196$
Air Quality	*0.420 [0.378–0.468]*	*0.400 [0.360–0.452]*	*0.428 [0.398–0.464]*	*0.435 [0.389–0.477]*	$H = 2.39, p = 0.495$ *ns*, $\eta^2 = -0.016$
Acoustic	*0.412 [0.364–0.465]*	*0.401 [0.378–0.422]*	*0.445 [0.418–0.472]*	*0.419 [0.381–0.450]*	$H = 3.37, p = 0.338$ *ns*, $\eta^2 = 0.011$

Values show average pathway strength (ranging 0–1, where higher values indicate stronger coordination between environmental stimuli, physiological responses, and behavioral outcomes) with 95% confidence intervals calculated using bootstrap resampling (1000 iterations). We compared domains across contexts using Kruskal-Wallis tests (H statistic) applied to individual participant averages (n = 18). Effect sizes reported as eta-squared (η^2), representing the proportion of variance explained. **p < 0.01; ns = not significant (p > 0.05).

gating mechanism on thermal bioclimatic adaptation capacity.

This domain-specific reorganization occurred despite comparable environmental variability across domains (CV: visual = 1.79–4.96, thermal = 0.13–0.68, air quality = 0.22–0.83; Supplementary Material, Table S1). Building upon the second hypothesis of this study, these results demonstrate that the relative importance of environmental domains changes substantially between contexts but only for thermal processing. Thermal processing uniquely reorganizes across conditions (24% increase in Night Safe contexts), while visual, acoustic, and air quality processing remain stable. The thermal domain's unique context-sensitivity (24% increase Night Safe vs. morning) while other domains remained stable aligns with evidence from both controlled human experiments and urban ecosystem studies demonstrating thermal systems' particular susceptibility to temporal and circadian reorganization (Elkounni et al., 2025; Wang et al., 2025a, 2025b). The context-independence of air quality processing ($H = 2.39$, $p = 0.495$) contrasts sharply with thermal processing and suggests that exposure to $PM_{2.5}$ and CO_2 produces consistent physiological-behavioral responses regardless of safety context or time of day. This domain-specific contrast has direct implications for urban climate adaptation prioritisation: while heat interventions require co-occurring safety conditions to achieve full behavioral effectiveness, air quality improvements deliver consistent benefits across all urban chronotype contexts.

3.4. Response timing reveals adaptive processing, not fragmentation

3.4.1. Circadian acceleration across all pathways

Response timing analysis revealed consistent circadian acceleration independent of safety context. Nighttime responses averaged 3.6 min faster than morning ($\beta = -3.58, p < 0.001$), with safety showing no main effect ($\beta = -0.49, p = 0.374$) or interaction with time ($p = 0.814$). Median response times ranged from 14.3 to 15.9 min across conditions, identifying a critical 14–16 min adaptation window. This temporal threshold has direct design implications: environmental improvements (e.g., misting systems, shade structures, cooling zones) must persist for at least 15 min to enable complete stimulus-organism-response integration; shorter-duration interventions may trigger physiological responses but fail to produce coordinated behavioral adaptation.

Addressing the third hypothesis of this study, the results demonstrate that response timing patterns in unsafe conditions do not reflect fragmented processing as predicted by threat-related accounts of disrupted sensory integration. Instead, circadian acceleration operates independently of safety (3.6-min nighttime acceleration regardless of safety context), and response times in unsafe conditions (14.8–15.9 min) fall within the normal 14–16 min adaptation window observed across all conditions. This suggests adaptive processing flexibility rather than disruption.

3.5. Universal mechanisms and individual variation

Despite substantial individual variation in pathway strength and response speed (Table 3), core pathways appeared consistently: RGB light pathways (86–93% of participants) and thermal pathways (86%) connecting through tonic EDA to fixation behavior (Supplementary Material, Table S3). Test-retest reliability exceeded $r = 0.78$, confirming these as fundamental urban navigation mechanisms. Tonic EDA appeared in 93% of participants, mediating 56% of all pathways, confirming skin conductance as the primary mechanism translating environmental exposures into behavior (Chwalek et al., 2024). Heart rate appeared in only 23% of pathways, exclusively under stress, representing an auxiliary arousal channel (Walker et al., 2020). Dual-route processing architecture remained invariant across contexts: 59% partial mediation (direct + physiological), 41% complete mediation ($p = 0.536$). However, strong coupling (>0.7) was rare (4% of pathways) and concentrated in Night Safe contexts (48% of strong chains; 24% of Night Safe pathways vs. 1–3% elsewhere), indicating that circadian optimization combined with safety may enable higher multisensory integration efficiency, directly informing when urban climate interventions achieve maximum effectiveness.

4. Discussion

The findings challenge fundamental assumptions underlying current climate adaptation investments. Threat perception doesn't just reduce comfort: it blocks the body's ability to translate environmental awareness into protective behavior. The term "climate vulnerability indicators" framed by this study follows the IPCC AR5/AR6 interpretation, where vulnerability denotes "the propensity

Table 3
Temporal processing modes across urban contexts.

Context	n (pathways)	Median response time	IQR	Processing mode	Key characteristics
Morning safe	568	14.3 min	11.7–16.5	Extended integration	Deliberative processing
Morning unsafe	467	15.9 min	12.4–17.0	Intermediate	Moderate latency
Night safe	675	14.9 min	12.6–16.0	Rapid transduction	Accelerated processing
Night unsafe	422	14.8 min	13.2–16.8	Intermediate	Moderate latency

*Median response latencies from participant-level data (n = 18). Mixed-effects models revealed significant circadian acceleration ($\beta = -3.58$, $p < 0.001$): nighttime responses averaged 3.6 min faster than morning responses, independent of safety context (safety: $p = 0.374$; interaction: $p = 0.814$). Processing modes defined as follows: Extended integration = deliberative processing with longer latencies allowing full sensory evaluation; Rapid transduction = accelerated processing with maintained coupling strength; Intermediate = moderate processing speed with context-dependent coupling quality. These modes reflect adaptive recalibration rather than processing deficits.

or predisposition to be adversely affected," encompassing sensitivity and lack of adaptive capacity as properties intrinsic to a system and explicitly decoupled from hazard magnitude (Sharma and Ravindranath, 2019). Behavioral and perceptual mechanisms underlying heat vulnerability including thermoregulatory behavior, psychological adaptation, and thermal sensitivity, operate continuously across the thermal gradient and are most diagnostically revealing under moderate conditions, where they are not masked by acute physiological stress (Nikolopoulou and Steemers, 2003; Schlader et al., 2010; de Dear and Brager, 1998). This approach is consistent with established vulnerability assessment methodology, which routinely measures adaptive capacity and sensitivity indicators under typical summer conditions rather than exclusively during extreme events (Valois et al., 2017). Neuroscientific evidence suggests urban stress hyperactivates fear centers like the amygdala (Lederbogen et al., 2011), yet these results show adaptive flexibility: core sensory-physiological pathways remain stable even in unsafe contexts, but their translation into behavior changes dynamically (Grapas et al., 2025; Taufer et al., 2025). This frames resilience as processing mode flexibility rather than environmental optimization (Kolling and Scholl, 2024). Threat perception and circadian state interact to produce four distinct urban 'chronotypes' (Stefani and Golombek, 2025), each with unique sensory-physiological-behavioral configurations. Current urban planning maintains artificial separation between climate adaptation, public safety, and health equity. The four urban chronotypes are products of systems that create differential vulnerability. Addressing them requires synchronized cooling infrastructure, safety improvements, and accessible public space as integrated investments, not separate objectives.

4.1. Safety modulates behavioral translation, not physiological sensing

Paradoxically, unsafe contexts showed the strongest physiological sensitivity to environmental changes, yet this heightened monitoring failed to produce coherent behavioral responses. Preliminary evidence from the online participatory mapping study showed that gender disparities in perceived safety were more pronounced during nighttime and for personal rather than traffic-related dimensions. Given that perceived safety functions as a gating mechanism on thermal adaptive capacity in this framework, female urban residents may face systematically reduced capacity to translate physiological environmental stimuli into protective behavior during evening hours, precisely the Night Safe context where thermal sensitivity peaks. This represents a gender asymmetry in adaptive capacity that future research with adequately powered monitoring samples should quantify directly (te Braak and van Tienoven, 2025).Positive coupling in safe areas reversed to negative coupling in unsafe areas. This occurs because environmental sensing uses automatic brain pathways, while translating signals into action requires conscious processing that threat disrupts (Walker et al., 2020; Clauss et al., 2022). Morning unsafe contexts showed reduced coupling, reversing at night when circadian rhythms constrain attentional resources for threat monitoring. The behavioral translation disruption may reflect how lighting infrastructure shapes safety perception. Only 48% of streetlights are fully shielded, and 58% of floodlights are unshielded, creating glare that may enhance rather than reduce perceived threat (Nachtlichter et al., 2025). This could explain why Night Unsafe pathways showed degraded coupling despite adequate absolute light levels.

Urban populations who disproportionately inhabit unsafe environments such as lower-income communities without private transport, women navigating nighttime public spaces, residents of underserved neighbourhoods, and individuals experiencing housing insecurity, face compounded climate vulnerability. Not only do these populations experience higher thermal exposures due to urban heat island patterns and green space inequities, but unsafe conditions actively suppress the physiological-to-behavioral translation required for heat-protective response. Current vulnerability indices based on thermal exposure and demographics miss this mechanism, systematically underestimating climate risk for populations navigating unsafe contexts. This represents a previously uncharacterised environmental justice dimension where protective capacity is unevenly distributed not only by physical exposure but by perceptual safety.

4.2. Thermal processing shows unique context-sensitivity

Among four sensory domains tested, only thermal processing showed significant context variation, surviving conservative Bonferroni correction (Table 2). Thermal sensitivity peaked during safe nighttime conditions (24% increase versus safe morning), while remaining suppressed in unsafe contexts. This uniqueness likely reflects thermal comfort's dual nature, both physiological regulation and psychological appraisal making it sensitive to circadian rhythms and attentional state. Thermal processing may require sustained attention competing with threat monitoring, whereas visual and acoustic cues process more automatically (Ding et al., 2024; Izquierdo et al., 2020). Air quality's invariance reflects its status as continuous background determinant operating through less conscious pathways (Chinazzo et al., 2022). Despite comparable environmental variability across domains (Supplementary Material Table S1), thermal processing exhibited strong context-sensitivity while air quality remained invariant. This has critical implications: air quality interventions deliver context-independent benefits (Cureau et al., 2022), while thermal interventions require strategic timing and spatial targeting. Cooling achieves maximum effectiveness during safe nighttime hours but minimal benefit in unsafe contexts without concurrent safety improvements.

4.3. Adaptive processing maintains integration despite threat

Response timing refutes H3's prediction of fragmented processing under threat: timing remains within normal adaptation windows across all conditions (Table 3). Nighttime processing accelerated regardless of safety context, with safety showing neither independent effect nor interaction with time of day. This indicates distinct neural mechanisms: circadian rhythms modulate processing speed through physiological arousal (Silva and Duffy, 2008), while threat affects behavioral coupling through executive functions (Kolling and Scholl, 2024). Median response times fell within a narrow 14–16 min range, establishing a consistent adaptation window. Unsafe contexts preserve fundamental integration timescales despite disrupting behavioral translation effectiveness. This reframes resilience from preventing disruption to maintaining processing flexibility: dynamic recalibration of perception-action coupling while preserving core integration mechanisms (Franěk and Petružálek, 2025).

4.4. Chronotypes for climate-adaptive urban design

The four urban chronotypes challenge deploying uniform cooling infrastructure without accounting for contexts determining behavioral uptake. Morning Safe contexts' visual dominance suggests conventional daylight-oriented strategies remain effective. Morning Unsafe contexts shifted to thermal dominance despite adequate lighting, implying co-located safety interventions are prerequisites. Night Safe contexts showed peak thermal sensitivity, indicating maximum return-on-investment for thermal interventions in safe areas. Night Unsafe contexts showed near-complete visual abandonment, representing a design failure zone where cooling infrastructure remains unused. While large-scale heat mitigation can decrease peak temperatures by 2–3 °C and reduce heat-related mortality (Santamouris, 2020), such benefits materialize only where safety enables behavioral translation of thermal comfort. This represents a previously uncharacterized climate vulnerability dimension intersecting built environment quality, social stress, and adaptive capacity (Gruebner et al., 2017; Tonne et al., 2021).

At the governance level, these findings demand dissolving institutional separation between climate adaptation, public safety, and health equity. Effective adaptation requires co-designed interventions where cooling zones deploy simultaneously with safety improvements including lighting quality, sightlines, and pedestrian activation. Performance metrics must shift from temperature reduction to behavioral uptake across demographic groups, times, and neighbourhood contexts. The 24% thermal sensitivity peak during safe nighttime conditions coincided with 387-fold illuminance reduction and documented nighttime safety decline (Navarrete-Hernandez et al., 2025), suggesting lighting quality acts as enabling condition for thermal adaptive capacity. Optimising thermal and visual conditions as independent targets risks undermining the perceptual foundation thermal adaptation requires. The 14–16 min adaptation window establishes minimum temporal standards, a critical design parameter for outdoor and transitional spaces. Climate-adaptive monitoring requires: physiological measures as tonic electrodermal activity mediates 56% of pathways (Section 3.5); 15-min or finer temporal resolution; and dynamic safety perception layers.

This framework enables scalable implementation: cities classify spaces by multisensory context using participatory safety mapping combined with 15-min environmental monitoring, then apply chronotype-specific interventions validated through population-level indicators. Implementation faces institutional barriers (Pellerey et al., 2025) including fragmented datasets, insufficient sensor infrastructure, and separated planning mandates, but recent advances in distributed sensing and participatory approaches (Tarlao et al., 2022; Trudeau et al., 2020) demonstrate pathways forward. The fundamental barrier is institutional: integrating climate adaptation with safety planning and health equity requires an integrative approach toward urban microclimate in cites which are far more complex and 'emotional' than what a controlled study may offer (Adli et al., 2017). This connects to the neurourbanism framework (Adli et al., 2017), which emphasises that urban populations experience the city's stressors and resources unequally depending on where and when they navigate it. Research within this framework demonstrates that the built environment's impact on human physiology and behavior is fundamentally context-dependent shaped by morphology, lighting, density, and environmental quality as interacting determinants rather than independent variables (Ancora et al., 2022; Bonifácio et al., 2023). The present study operationalises this unevenness at the perceptual-physiological level: in unsafe chronotype contexts, the body senses thermal stress but cannot translate that awareness into protective behavior, meaning that climate adaptation benefits are distributed not by exposure but by the perceptual safety conditions of the environment. The chronotype framework provides experimental specification of when and where thermal-visual interventions achieve effective physiological-behavioral integration, enabling transition from reactive heat response to proactive design for human adaptive capacity in warming cities requiring expanded evening outdoor activity as daytime temperatures become increasingly inhospitable.

5. Conclusions

Are we designing cities for bodies that do not exist? Current urban climate adaptation assumes stable, uniform human bioclimatic responses, an abstraction misaligned with how humans actually experience urban thermal environments. This study demonstrates that thermal response capacity is context-dependent, shaped by safety perception and diurnal conditions. Three findings emerge. First, safety operates as a gating mechanism: unsafe contexts maintain intact physiological heat sensing yet disrupt translation into protective behavior. Populations navigating unsafe areas, disproportionately lower-income communities, women, and residents of underserved neighbourhoods sense thermal stress equivalently but cannot convert awareness into adaptive behavior, a climate vulnerability mechanism invisible to exposure-only frameworks. Second, thermal processing shows unique context-sensitivity while air quality, visual, and acoustic processing remain stable. Air quality interventions deliver universal benefits; thermal interventions require co-located safety improvements. Deploying cooling infrastructure in unsafe environments constitutes design failure if perceptual safety conditions are absent. Third, bioclimatic processing maintains consistent temporal integration, establishing a universal adaptation window with direct implications for microclimate design.

How do we design urban microclimates, in transitional spaces that compel dwellers to stay long enough for thermal adaptive responses to emerge? Current design prioritizes engineering metrics over temporal persistence and perceptual safety conditions determining whether cooling interventions translate into adaptive behavior. Implementation demands dissolving institutional separation between climate adaptation, public safety, and health equity. Performance metrics must shift from temperature reduction to behavioral uptake across demographic groups, times, and neighbourhood contexts. Critical limitations constrain generalizability. Brussels' temperate climate and moderate summer temperatures may not represent tropical megacities, arid environments, or rapidly urbanising contexts where informal settlements concentrate vulnerable populations. Safety thresholds and thermal context-sensitivity likely vary substantially across climate zones and cultures. Validation in cities experiencing severe thermal stress is essential. How do we integrate climate science with qualitative data on safety perception and lived experience to build integrative datasets for healthier cities? Current approaches treat thermal exposure, safety perception, and behavioral response as separate domains.

This study demonstrates they operate as an integrated system and that both physiological sensing, perceptual safety assessment, and behavioral translation are interdependent components of thermal adaptive capacity. Future research must combine environmental monitoring with participatory safety mapping, physiological sensors, and behavioral observation to characterize how populations experience thermal environments across diverse urban contexts. The chronotype framework provides foundation for comparative research, enabling systematic characterization of how climate vulnerability emerges from interactions between physical exposure, temporal context, and perceived safety. Only by understanding cities as experienced, not as abstracted thermal environments independent from safety, time, and human perceptual capacity, can adaptation move from reactive infrastructure deployment to proactive design for human adaptive capacity in an era of intensifying urban heat.

CRediT authorship contribution statement

Christos Grapas: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maider Llaguno-Munitxa:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Anna Laura Pisello:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ahmadreza Irajpour:** Writing – review & editing, Investigation.

Ethical approval

This study was approved by the Ethical Committee of the Sector of Sciences and Technologies (SST), Université catholique de Louvain (UCLouvain) (n. 03–25) on the 05.05.2025. All participants provided written informed consent and voluntary participated. Data were anonymized and stored in compliance with General Data Protection Regulation (GDPR).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2026.102906.

Data availability

Data will be made available on request.

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