

BUILDING HEIGHT MODULATES OPTIMAL PLAZA SCALE: A VIRTUAL REALITY AND PSYCHOPHYSIOLOGICAL STUDY ON SPATIAL PERCEPTION IN HIGH-DENSITY CONTEXTS

Wen Lu
Jian Zhang
Ning Li

Plaza scale is a critical determinant of human comfort in urban environments. However, traditional design guidelines often prescribe fixed Length-to-Height (L/H) ratios (e.g., 2:1 or 3:1) without accounting for the dramatic vertical variations in modern high-density cities. This study bridges neuroscience and urban physics to investigate how building height modulates the optimal plaza scale for psychological adaptation. Using Virtual Reality integrated with neurophysiological metrics (Electroencephalography and Galvanic Skin Response), we measured the immediate responses of 42 participants across 26 spatial configurations with building heights ranging from 3 m to 100 m. Contrary to conventional theories, our results reveal that the optimal L/H ratio is nonlinear and strictly height-dependent. Quantitative analysis derived an adaptive scale model, $\frac{L}{H} \approx 1.43 \times e^{-0.057H} + 1.92$ ($R^2 = 0.92$), demonstrating a decaying requirement for openness as height increases. While low-rise environments ($H \leq 9$ m) favor larger ratios (approximately 3.0) for relaxation, high-rise environments ($H \geq 54$ m) require significantly tighter enclosures (approximately 1.9) to mitigate spatial stress. Neurophysiological data confirmed this divergence: in high-rise settings with excessive openings, participants exhibited increased Beta wave activity (cognitive load) and elevated physiological arousal. These findings challenge the “one-size-fits-all” approach, providing a geometry-based, data-driven framework for designing resilient public spaces in vertically growing cities.

© The author(s) 2026. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license (<http://creativecommons.org/licenses/by/4.0/>).

INTRODUCTION

The conflict between classical theories and vertical urbanism

Public plazas serve as the "living rooms" of cities, playing a pivotal role in regulating the psychological well-being of urban residents (Carr et al., 1992; Gehl, 2011). Historically, the spatial quality of these environments has been governed by the relationship between the horizontal expanse of the plaza (L) and the vertical height of surrounding boundaries (H). Classical architectural theories, rooted in the human-scale urbanism of the pre-industrial era, have long sought to define the "ideal" proportion to ensure aesthetic harmony and psychological comfort. Vitruvius, for instance, argued that squares must be proportional to the population to avoid appearing as desolate wastelands (Vitruvius, 1914). Building on this, seminal theorists like Sitte and Ashihara established the foundational "one-tenth rule" and "external module theory," often prescribing fixed L/H ratios—such as the widely cited 2:1 or 3:1—as the gold standard for balanced spatial proportions (Ashihara, 1970; Sitte, 1965). These guidelines suggest that a specific degree of enclosure is universally optimal for creating a sense of place and preventing spatial anxiety.

However, the morphology of the modern city has fundamentally shifted from the horizontal to the vertical, challenging the applicability of these static canons (Ng, 2009). In the context of contemporary high-density urbanization, cityscapes are increasingly dominated by super-high-rise structures that far exceed the 9-18 meter scale typical of European historical centers (Gehl, 2010). While traditional guidelines effectively managed comfort in low-rise contexts, they fail to account for the dramatic psychological impact of vertical gigantism found in modern metropolises. Simply applying a 3:1 ratio to a 100-meter skyscraper results in a plaza of vast absolute dimensions, potentially triggering feelings of exposure or "urban agoraphobia" rather than comfort (Alexander et al., 1977; Carmona, 2010). Furthermore, existing research on this scaling problem has predominantly relied on subjective assessments, such as observational studies and self-reported questionnaires (Marcus & Francis, 1998; Whyte, 1980). While valuable, these methods capture post-hoc reflections rather than the immediate, subconscious neurophysiological reactions that occur the moment a pedestrian enters a space (Banaei et al., 2017; Higuera-Trujillo et al., 2021). Consequently, there remains a critical knowledge gap: how does the extreme verticality of modern building heights modulate the neural mechanisms of spatial perception, and do classical L/H ratios remain valid in these high-density contexts?

Literature review

Classical theories of spatial enclosure and their limitations. The perception of "enclosure" has long been a foundational metric in assessing the quality of urban squares. Early theorists established the geometric relationship between viewing distance (D) and building height (H) as the primary determinant of spatial comfort. Sitte (Sitte, 1965) and Maertens (Maertens, 1877) famously identified the 27° (ratio 2:1) and 18° (ratio 3:1) vertical viewing angles as critical thresholds for perceiving spatial definition without oppression. Building on this, Ashihara (Ashihara, 1970) formalized the "External Module Theory," positing that a D/H ratio between 1 and 2 creates the most balanced "positive space". Similarly, Lynch (Lynch, 1971) and Gehl (Gehl, 2011) emphasized human-scale dimensions (typically 12–25m) as essential for social interaction and psychological security.

However, these classical theories were largely derived from the morphological context of low-rise European cities. They inherently assume a "human-scale" vertical boundary (typically < 20m). Recent studies suggest that these static ratios may lose validity in contemporary high-density environments. For instance, Stamps (Stamps, 2005) demonstrated that visual permeability and sky view factors significantly alter the perception of enclosure, factors often ignored by simple L/H ratios. It should be noted that classical theories typically employ the viewing distance (D) from the observer to the boundary wall as their primary metric, expressed as

D/H ratios. In the present study, participants were positioned at the centre of each plaza, meaning that $D = L/2$. The study's L/H ratio therefore maps onto the classical D/H ratio as $D/H = (L/H)/2$. For example, the classical 'balanced' range of $D/H = 1-2$ (Ashihara, 1970) corresponds to $L/H = 2-4$ in the present experimental parameterisation. This conversion is applied consistently throughout the paper when comparing results to classical benchmarks. Furthermore, as cities densify, the "canyon effect" created by super-high-rise structures introduces new psychological stressors—such as reduced sky exposure and wind tunnel effects—that classical ratios fail to predict (Ng, 2009; Oke, 1988).

The "neurophysiological turn" in urban perception. Traditionally, urban design research relied on self-reported methodologies, such as surveys and interviews, to evaluate spatial comfort. While valuable, these subjective measures are prone to "recall bias" and cognitive filtering, often failing to capture immediate, subconscious emotional reactions (Banaei et al., 2017). To address these limitations, the emerging field of Neuroarchitecture advocates for the use of physiological markers to quantify the human experience of space. Theoretical frameworks like the Prospect-Refuge Theory (Appleton, 1975) have recently been re-examined using biometric data. For example, Ellard (Ellard, 2015) and Vecchiato et al. (Vecchiato et al., 2015) utilized Electroencephalography (EEG) to demonstrate that variations in architectural scale can trigger measurable changes in frontal alpha asymmetry, a marker of approach-withdrawal motivation. Similarly, Galvanic Skin Response (GSR) has been successfully employed to measure arousal levels in response to complex urban stressors, such as crowding and traffic (Aspinall et al., 2015). These studies confirm that the built environment directly modulates the autonomic nervous system, yet few have specifically isolated the variable of plaza scale in high-rise contexts.

Virtual reality as an empirical tool. The application of Virtual Reality (VR) has revolutionized the study of spatial perception by allowing for the rigorous control of environmental variables. Research by Kuliga et al. (Kuliga et al., 2015) and Higuera-Trujillo et al. (Higuera-Trujillo et al., 2017) confirmed that psychological and physiological responses in immersive VR environments are ecologically valid and comparable to real-world experiences. Specifically in urban design, VR allows researchers to manipulate building heights and plaza dimensions systematically—an experimental design impossible in the physical world. Recent VR-EEG studies have begun to explore the impact of urban geometry on brain activity. For instance, analyzing Beta-band activity (associated with active concentration and stress) has proven effective in identifying "cognitive load" in navigational tasks (Banaei et al., 2017). However, a critical gap remains: most existing studies focus on street canyons or green spaces (Tilley et al., 2017), with scant attention paid to the height-dependent optimal scaling of public plazas. This study aims to bridge this gap by integrating VR simulation with multi-modal physiological sensing (EEG/GSR) to revisit classical scale theories in the context of vertical urbanism.

Research objectives

To address these theoretical and methodological gaps, this study employs a multi-modal approach combining VR simulation with real-time biometric monitoring. The primary objectives of this research are threefold:

(1) *To verify the modulating effect of building height on optimal plaza scale.* We aim to empirically test whether the "ideal" L/H ratio is a static constant (as suggested by classical theories (Ashihara, 1970)) or a dynamic variable that shifts as the surrounding vertical enclosure increases from human-scale (3m) to super-high-rise scale (100m).

(2) *To quantify immediate spatial perception via neurophysiological metrics.* By integrating EEG and GSR, we seek to capture the subconscious, immediate cognitive and emotional responses to varying spatial scales. Specifically, this involves analyzing Beta-band activity (indicative of cognitive load (Antonenko et al., 2010; Banaei et al., 2017)) and skin conductance levels (indicative of emotional arousal (Boucsein, 2012)) to

objectively identify the thresholds of "spatial stress" or "urban agoraphobia."

(3) *To formulate an adaptive design framework for high-density contexts.* Based on the empirical data, we intend to propose a data-driven, height-dependent guideline for plaza design. This framework moves beyond the traditional "one-size-fits-all" approach, offering precise scaling strategies to enhance psychological resilience and safety in the vertically growing city.

MATERIALS AND METHODS

Participants

A total of 42 participants were recruited from a university (mean age = 25.3 years, SD = 2.4). The sample was specifically restricted to young adults with academic backgrounds in architecture or urban design. This selection criterion was based on two methodological considerations:

(1) *Neurocognitive Sensitivity.* Young adults typically exhibit peak spatial processing speeds and physiological stability, minimizing the confounding effects of age-related cognitive decline or hormonal fluctuations on EEG/GSR baselines (Hedden & Gabrieli, 2004; Salthouse, 2009).

(2) *Professional Acuity.* Participants with architectural training demonstrate significantly superior spatial cognition and visual acuity compared to laypeople. Their enhanced ability to decode complex spatial geometries ensures a more precise evaluation of the subtle scale variations presented in the VR scenarios (Hyde, 2007; Shemesh et al., 2017).

It should be noted, however, that restricting the sample to architecture-trained participants enhances measurement precision at the cost of demographic breadth. The resulting guidelines should therefore be understood as reflecting the spatial comfort thresholds of a spatially-literate population, and may require recalibration before direct application to general urban users.

All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. To ensure data quality, participants were instructed to abstain from caffeine, alcohol, and strenuous exercise for 24 hours prior to the experiment. The study was approved by the Institutional Review Board of the university, and written informed consent was obtained from all subjects in accordance with the Declaration of Helsinki. An a priori power analysis (G*Power 3.1) indicated that a sample size of 42 was sufficient to detect a medium effect size ($f = 0.25$) with a power of 0.90 at an alpha level of 0.05. Moreover, this sample size exceeds the typical range ($N \approx 15-30$) found in comparable neuro-architectural studies (e.g., Banaei et al., 2017; Vecchiato et al., 2015), ensuring robust statistical reliability.

Virtual environment and experimental design

To isolate the specific effects of spatial scale and exclude confounding variables such as architectural style, material texture, or commercial signage, the study employed abstract, uniform virtual environments. This simplified approach has been validated in previous neuro-architectural studies as an effective method to focus participants' cognitive attention on geometric properties without the distraction of decorative details (Banaei et al., 2017; Higuera-Trujillo et al., 2021).

(1) *Stimuli Construction.* The virtual plazas were constructed using SketchUp and rendered in Enscape. All scenarios featured a central viewing point surrounded by four boundary walls with uniform neutral textures. Lighting conditions were standardized to simulate a clear day at 13:30 (solar angle of Beijing winter solstice)

to avoid shadow variations affecting perception, as lighting distribution significantly influences spatial depth estimation and emotional appraisal (Chamilothori et al., 2019). Participants viewed each scenario from a fixed central viewpoint (no free locomotion permitted) at a standing eye height of 1.65 m above floor level. The HTC Vive Pro Eye headset provided a field of view of approximately 110° (diagonal) with a display resolution of 1440 × 1600 pixels per eye and a refresh rate of 90 Hz. This fixed-viewpoint design was chosen to ensure that all participants received identical geometric information and to prevent locomotion-induced EEG artifacts.

(2) *Parametric Design Matrix.* A full-factorial design was employed with two independent variables: Building Height (H) and Plaza Side Length (L).

Building Height: Six levels were tested, ranging from human scale to super-high-rise scale (H = 3, 9, 18, 33, 54, and 100 m).

Scale Ratio: For each height, plaza dimensions were adjusted to create varying L/H ratios (1:1, 2:1, 3:1), alongside fixed-width control groups (approx. 10m, 50m, 100m). This resulted in a total of 26 unique spatial scenarios (Table 1 and Figure 1). Figure 1(b) presents the complete experimental matrix, illustrating the distribution of tested L/H ratios and fixed-width controls across building heights. Note that the position of optimal comfort shifts with height, as quantitatively shown in Figure 1(a).

Table 1: Parametric design matrix of the 26 experimental scenarios

Building Height (H, m)	L/H = 1	L/H = 2	L/H = 3	Fixed ≈10 m	Fixed ≈50 m	Fixed ≈100 m	Total Scenarios
3m	●	●	●		●	●	5
9m	●	●	●			●	4
18m	●	●	●	●		●	5
33m	●	●	●	●			4
54m	●	●	●	●			4
100m	●	●	●	●			4
Total	6	6	6	4	1	3	26

Note: The symbol (●) indicates the specific configurations tested in the VR experiment. For high-rise conditions (H ≥ 33m), a fixed 10m side length was included to evaluate extremely low L/H ratios (high enclosure).

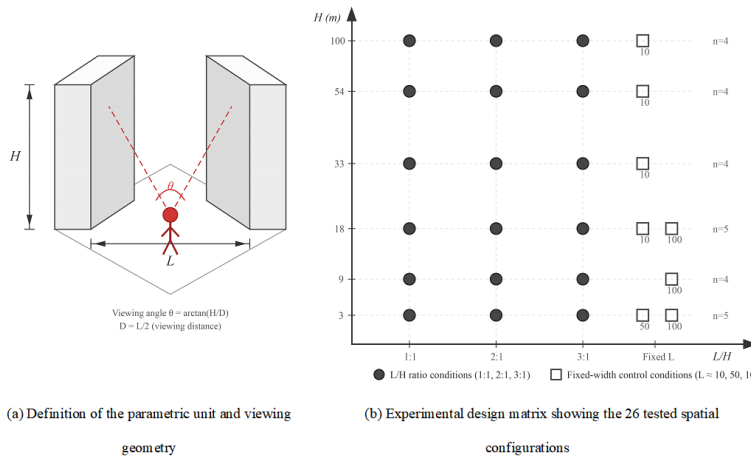


Figure 1: (a) Definition of the parametric unit and viewing geometry; (b) Experimental design matrix showing the 26 tested spatial configurations

Experimental procedure: rapid spatial assessment protocol

Unlike traditional dwell-time studies, this research utilized a rapid spatial assessment protocol designed to capture the instinctive, pre-cognitive physiological response to urban scale. This approach is grounded in the theory that affective responses to environments occur immediately, often preceding detailed cognitive processing (Ulrich, 1983).

The experiment consisted of two phases (Figure 2):

(1) *Preparation*. Participants were fitted with the VR headset (HTC Vive Pro Eye), EEG cap (Emotiv EPOC Flex, 32 channels), and GSR sensors (Shimmer3 GSR+). A 2-minute baseline recording was taken in a neutral "gray room" environment to establish individual physiological resting states (Boucsein, 2012).

(2) *VR Exposure*. The 26 scenarios were presented in a randomized order to prevent sequence effects. Each scenario was displayed for a duration of 10 seconds. This brief exposure window was specifically chosen to simulate the "initial scanning phase" of pedestrian navigation—the critical moment when a user first enters a space and forms an immediate subconscious judgment of safety and enclosure (Stamps, 2010). The total VR exposure phase lasted approximately 6.5 minutes (26 scenarios × 15 seconds per trial [10s stimulus + 5s ISI]), excluding equipment setup and baseline recording.

(3) *Inter-Stimulus Interval*. To prevent physiological carry-over effects and visual fatigue, a blank gray screen was presented for 5 seconds between scenarios, allowing electrodermal activity to return towards baseline levels (Braithwaite et al., 2013).

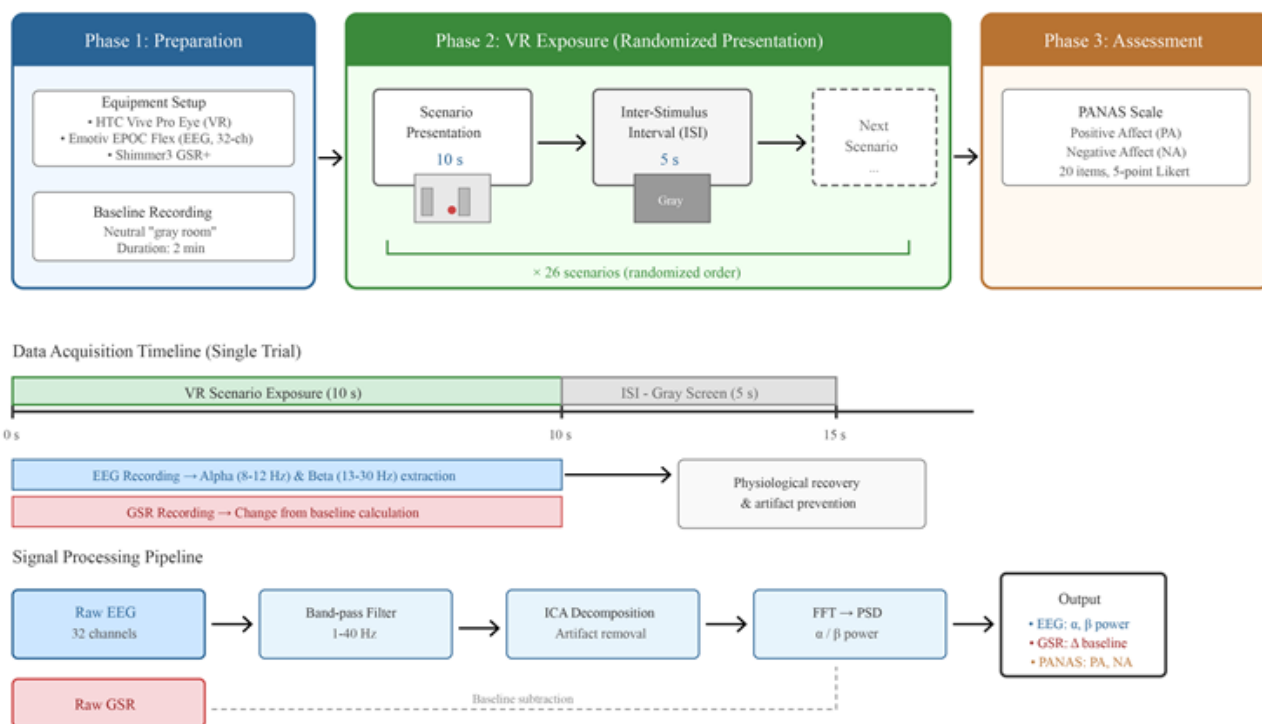


Figure 2: Flowchart of the experimental procedure

Data acquisition and signal processing

Physiological data were synchronized with the VR scenarios using a custom trigger system developed in Python. All signal processing was performed offline using MATLAB (MathWorks) and the EEGLAB toolbox to ensure artifact-free analysis (Delorme & Makeig, 2004).

EEG data processing

EEG signals were recorded from 32 scalp sites using the International 10–20 system (Jasper, 1958), see Figure 3.

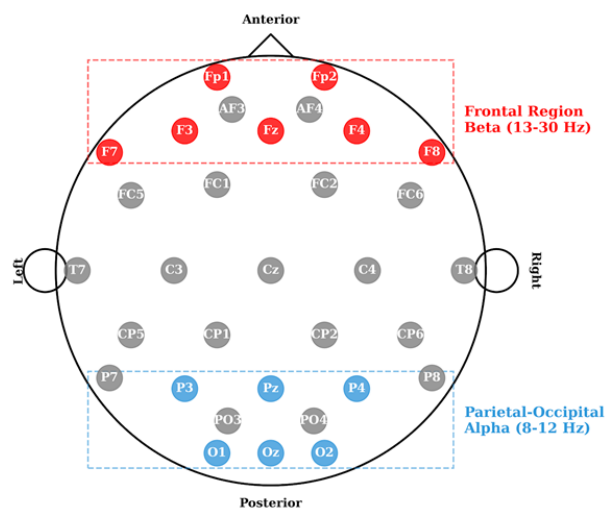


Figure 3: Electrode distribution map showing the 32-channel layout used in this study (International 10–20 system). Red-highlighted electrodes (Fp1, Fp2, F3, F4, F7, F8, Fz) in the frontal region were used to extract Beta-band power (13–30 Hz, indicative of cognitive load). Blue-highlighted electrodes (P3, P4, Pz, O1, O2, Oz) in the parietal-occipital region were used to extract Alpha-band power (8–12 Hz, indicative of relaxation). Remaining electrodes (grey) were retained for ICA artifact decomposition.

(1) *Preprocessing.* Raw EEG data were band-pass filtered between 1 Hz and 40 Hz to remove low-frequency drift and high-frequency muscle noise. Given that head movements in VR can introduce muscle artifacts in EEG data, we applied a strict rejection criterion. Epochs containing voltage fluctuations exceeding $\pm 100 \mu\text{V}$ were automatically rejected before ICA decomposition. This ensured that the Beta wave activity was purely neural and not contaminated by neck muscle tension from looking up at high buildings. To further address ocular (eye blink) and electromyographic (muscle movement) artifacts—which are common in VR studies—Independent Component Analysis (ICA) was applied to decompose the signals (Jung et al., 2000). Artifactual components were visually inspected and removed.

(2) *Feature Extraction.* Power Spectral Density (PSD) was computed using the Fast Fourier Transform (FFT) applied to 10-second epochs corresponding to each scenario exposure window. A Hanning window was applied prior to FFT to reduce spectral leakage. Baseline correction was performed by subtracting the mean PSD of the 2-minute pre-experiment resting period from each scenario epoch. The number of valid epochs retained per participant after artifact rejection ranged from 21 to 26 (out of 26 total), with a mean retention rate of 94.2% (SD = 4.1%) across participants. Based on previous neuro-urbanism literature, the analysis focused on two specific frequency bands:

Alpha Band (8–12 Hz): Extracted primarily from parietal and occipital regions (P3, P4, Pz, O1, O2, Oz). Increased Alpha power is inversely related to cortical activation, serving as a marker for relaxation and reduced visual processing load (Klimesch, 1999).

Beta Band (13–30 Hz): Extracted from frontal regions (Fz, Fp1, Fp2, F3, F4, F7, F8). Beta activity is associated with active concentration, alertness, and cognitive load, indicating the brain's effort to process complex spatial information (Ray & Cole, 1985).

GSR Data Processing. GSR was recorded using the Shimmer3 GSR+ unit with a sampling rate of 1 kHz.

(1) *Metric Calculation.* To normalize for individual variability in skin conductance, a "Change from Baseline" metric was calculated. The mean GSR value from the 2-minute baseline recording was subtracted from the average GSR value recorded during the full 10-second exposure window of each scenario, yielding a change-from-baseline score (Δ GSR) in microsiemens (μ S). To minimise motion artefacts, epochs in which raw GSR showed abrupt transients exceeding 3 SD of the participant's within-session mean were flagged and excluded from analysis. Complete GSR data across all six height conditions were obtained from $N = 4$ participants; one participant provided partial data (H=3m and H=18m only) and was excluded from inferential analysis, yielding a final GSR analytic sample of $N = 4$.

(2) *Interpretation.* A positive deflection or a smaller decrease relative to baseline indicates higher physiological arousal, serving as a proxy for emotional stress or vigilance in response to the spatial enclosure (Critchley, 2002).

Psychological assessment

To triangulate the physiological data with subjective experience, participants completed the Positive and Negative Affect Schedule (PANAS) immediately after the VR exposure (Watson et al., 1988). This validated 20-item scale assesses two primary dimensions: Positive Affect (PA) and Negative Affect (NA), rated on a 5-point Likert scale. This subjective layer ensures that the physiological "arousal" detected by GSR can be correctly interpreted as either distress (negative) or excitement (positive), aligning with the Circumplex Model of Affect (Russell, 1980).

Statistical analysis

Statistical analyses were conducted using SPSS 26.0 and Python (SciPy library).

(1) *Unit of Analysis and Repeated-Measures Structure.* Each of the 42 participants was exposed to all 26 spatial scenarios, constituting a fully within-subject repeated-measures design. To respect this structure, the unit of analysis was each participant's mean physiological or affective response per condition (averaged across the 10-second exposure window), yielding a participant \times condition data matrix prior to all inferential tests.

(2) *Normality Testing.* Shapiro-Wilk tests applied to the condition-level participant means indicated that EEG power, GSR change-from-baseline, and PANAS scores were not normally distributed ($p < 0.05$) (Shapiro & Wilk, 1965). Non-parametric methods were therefore employed throughout.

(3) *Primary Hypothesis Testing.* The Friedman test (a non-parametric repeated-measures rank-based test equivalent to a one-way within-subjects ANOVA) was used to examine the main effects of Building Height and L/H Ratio on EEG power, GSR arousal, and PANAS scores across all conditions (Friedman, 1937). Effect size was quantified using Kendall's W ($W = 0$ indicates no agreement; $W = 1$ indicates perfect agreement across ranked conditions).

(4) *Post-hoc Pairwise Comparisons.* Following a significant Friedman test, pairwise post-hoc comparisons were conducted using the Wilcoxon signed-rank test. To control the family-wise Type I error rate, Bonferroni correction was applied across all pairwise comparisons. Effect sizes for individual comparisons were calculated as $r = Z / \sqrt{N}$, where Z is the standardized test statistic and N is the number of participants (Cohen, 1988).

(5) *Correlation Analysis.* Spearman’s rank correlation coefficients were calculated to quantify the relationship between L/H ratios and neurophysiological indicators (Alpha/Beta power). The significance level was set at $\alpha = 0.05$ for all tests. All analyses were conducted in SPSS 26.0 and Python (SciPy library).

RESULTS

Subjective and behavioral results

Subjective emotional responses were assessed using the PANAS scale. (N = 26 participants with complete repeated-measures data across all 26 scenes). The Friedman test revealed significant within-subject differences in Positive Affect scores across L/H ratio categories ($\chi^2(4) = 42.26$, $p < 0.001$, Kendall’s $W = 0.41$, indicating a medium-to-large effect), and across Building Height categories ($\chi^2(2) = 10.65$, $p = 0.005$, Kendall’s $W = 0.21$). Negative Affect scores showed an even stronger within-subject effect across L/H categories ($\chi^2(4) = 61.61$, $p < 0.001$, Kendall’s $W = 0.59$).

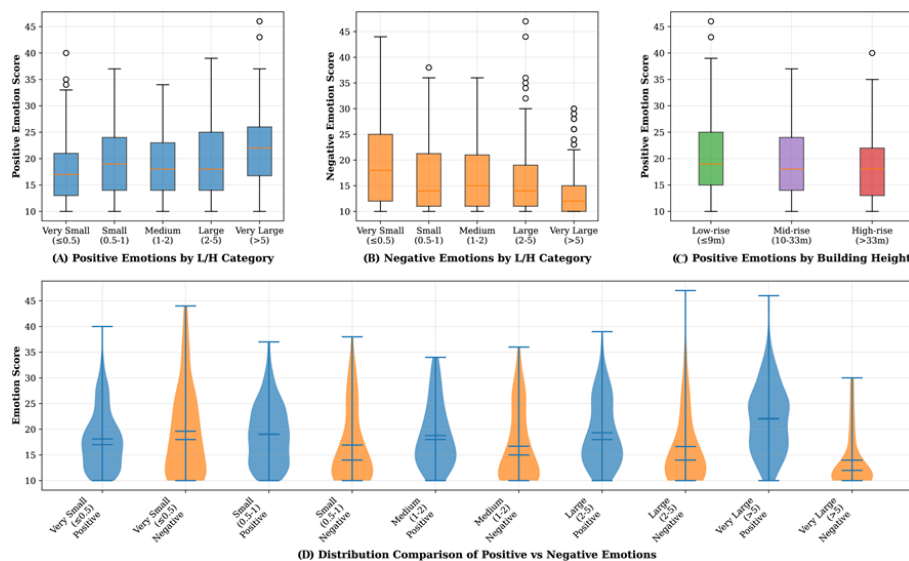


Figure 4: Distribution analysis of emotional responses (PANAS; N = 26). (A) Positive Affect scores by L/H ratio category (Very Small ≤ 0.5 ; Small 0.5–1; Medium 1–2; Large 2–5; Very Large > 5); higher scores indicate greater positive affect. (B) Negative Affect scores by L/H ratio category; lower scores indicate less negative affect. (C) Positive Affect scores grouped by building height category (Low-rise $\leq 9\text{m}$; Mid-rise 10–33m; High-rise $> 33\text{m}$). (D) Violin plots comparing the full distribution of Positive (blue) and Negative (orange) Affect across L/H categories. Box plots show median, interquartile range, and outliers.

Post-hoc Wilcoxon signed-rank tests with Bonferroni correction ($\alpha = 0.005$ for 10 L/H pairwise comparisons) confirmed that the "Very Large" L/H category (> 5) elicited significantly higher Positive Affect than all other categories (vs. Very Small: $p < 0.001$, $r = 0.87$; vs. Small: $p < 0.001$, $r = 0.83$; vs. Medium: $p < 0.001$, r

= 0.85; vs. Large: $p < 0.001$, $r = 0.66$). The "Small" and "Large" categories also differed significantly ($p = 0.002$, $r = 0.60$).

For Building Height, post-hoc comparisons (Bonferroni $\alpha = 0.017$ for 3 comparisons) showed that Low-rise contexts ($H \leq 9\text{m}$; $M = 20.48$) elicited significantly higher Positive Affect than High-rise contexts ($H > 33\text{m}$; $M = 18.35$; $p = 0.003$, $r = 0.61$) and marginally higher than Mid-rise contexts ($M = 18.98$; $p = 0.025$, $r = 0.48$). No significant difference was found between Mid-rise and High-rise ($p = 0.237$, ns). Group means for Positive Affect by building height were: Low-rise $M = 20.48$, $SD = 3.21$; Mid-rise $M = 18.98$, $SD = 2.34$; High-rise $M = 18.35$, $SD = 2.91$ ($N = 26$).

As illustrated in Figure 4, there is a general positive correlation between plaza openness and emotional well-being. Panel (A) shows that as the L/H ratio increased from 'Very Small' (≤ 0.5) to 'Very Large' (> 5), Positive Affect scores trended upward ($M = 18.23$, $SD = 2.51$; 17.24 , $SD = 4.01$; 18.41 , $SD = 2.99$; 19.99 , $SD = 3.94$; and 23.79 , $SD = 2.27$, respectively; $N = 26$ participants with complete data). Panel (A) shows that as the L/H ratio increased from "Very Small" (≤ 0.5) to "Very Large" (> 5), Positive Affect scores trended upward ($M = 18.23$, 17.24 , 18.41 , 19.99 , and 23.79 , respectively). Panel (B) shows the parallel decrease in Negative Affect with increasing L/H. Panel (C) reveals the effect of building height on Positive Affect.

Physiological evidence: arousal and spatial stress (GSR)

GSR data were available for $N = 4$ participants with complete recordings across all six building height conditions (3m, 9m, 18m, 33m, 54m, 100m); one additional participant provided partial data (3m and 18m only) and was excluded from inferential analysis. Given this limited sample size, the Friedman test yielded a non-significant result ($\chi^2(5) = 5.43$, $p = 0.366$, Kendall's $W = 0.27$), indicating insufficient statistical power to confirm within-subject differences at the group level. The following interpretation is therefore primarily descriptive and should be interpreted with caution.

While subjective reports provided a general trend, GSR captured the immediate, subconscious physiological reactions. Figure 5 illustrates the physiological response patterns across different building heights. The analysis revealed two key findings:

(1) *Universal Arousal*. All spatial scenarios elicited a negative change from baseline (values < 0), confirming that entering any plaza environment triggers a degree of physiological vigilance compared to a resting state.

(2) *Height Sensitivity*. The magnitude of this arousal is significantly modulated by building height. As shown in Figure 5, the strongest physiological responses (largest deviations) were observed in the transition zones ($H=33\text{m}$ and 54m), suggesting that these scales create the most ambiguous and stressful spatial definitions.

(3) *Interaction Effect*. Further post-hoc analysis indicated that this stress is exacerbated by inappropriate scale ratios. Specifically, in high-rise settings, expanding the plaza scale (increasing L/H) failed to induce relaxation, contrasting with low-rise settings where openness was physiologically soothing. This confirms that "spatial stress" is a tangible physiological reaction to the scale mismatch. Descriptive statistics for GSR change-from-baseline by building height ($N = 4-5$ participants with valid recordings) were as follows: $H=3\text{m}$: $M = -0.187$, $SD = 0.122$; $H=9\text{m}$: $M = -0.130$, $SD = 0.093$; $H=18\text{m}$: $M = -0.224$, $SD = 0.075$; $H=33\text{m}$: $M = -0.262$, $SD = 0.089$; $H=54\text{m}$: $M = -0.214$, $SD = 0.020$; $H=100\text{m}$: $M = -0.142$, $SD = 0.095$.

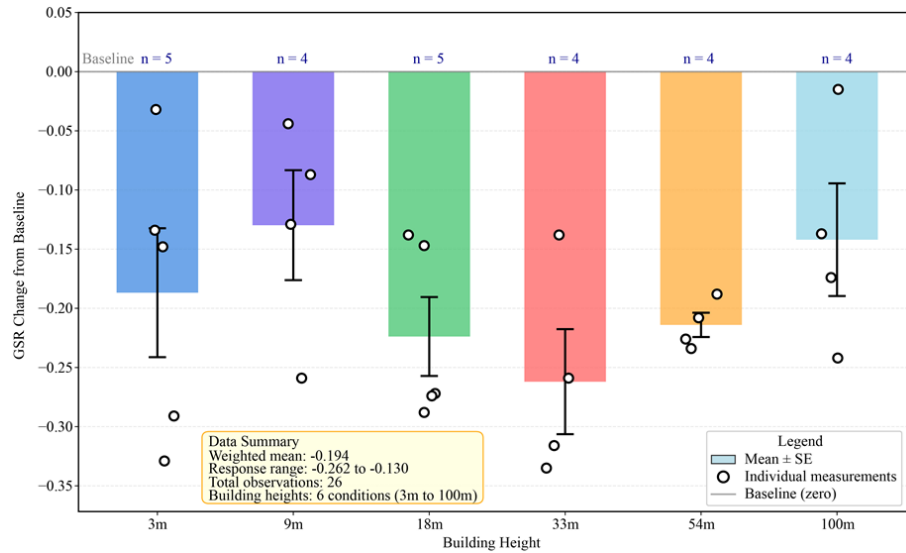


Figure 5: GSR change-from-baseline (ΔGSR , μS) across six building height conditions ($N = 4\text{--}5$ participants per condition). Each bar represents the group mean \pm standard error; open circles show individual participant values. All values are negative, indicating physiological arousal relative to resting baseline. The weighted mean across all conditions is -0.194 (range: -0.262 to -0.130 μS). Bar colours distinguish the six height conditions (3m = blue; 9m = purple; 18m = green; 33m = red; 54m = orange; 100m = cyan) and are for visual separation only. Note: Friedman test was non-significant ($p = 0.366$) due to small sample size; results are descriptive only.

Neurocognitive mechanisms: cognitive load (EEG)

EEG data further elucidated the neural mechanisms underlying this stress response.

(1) *Spatial Distribution of Activation.* Topographic mapping (Figure 6) showed that as building height increased from 3m to 100m, neural activity shifted systematically from posterior regions (Alpha band, associated with visual relaxation) to frontal regions (Beta band, associated with cognitive processing).

(2) *Cognitive Load Correlation.* As an exploratory analysis, Spearman’s correlation between mean Beta power (averaged across frontal electrodes Fz, Fp1, Fp2, F3, F4, F7, F8; $N = 42$ participants contributing to condition-level means) and L/H ratio across the six height-level aggregated conditions yielded a large positive effect ($r = 0.929$, 95% CI $[-0.10, 0.998]$, $p = 0.071$, $k = 6$ height conditions), which did not reach the pre-specified significance threshold of $\alpha = 0.05$ given the small number of aggregated data points. This result should therefore be interpreted with caution as a directional trend only: larger plaza-to-height ratios were associated with higher frontal Beta activity, suggesting a potential increase in cognitive load, but this association requires replication with a larger range of conditions before causal inference can be drawn.

(3) *Interpretation.* The exploratory trend toward elevated Beta activity in large, high-rise plazas is consistent with the hypothesis that these spaces may impose a higher cognitive load, though this interpretation remains tentative pending replication. The brain is actively scanning for boundaries and safety cues, preventing the "default mode" relaxation typically associated with public parks.

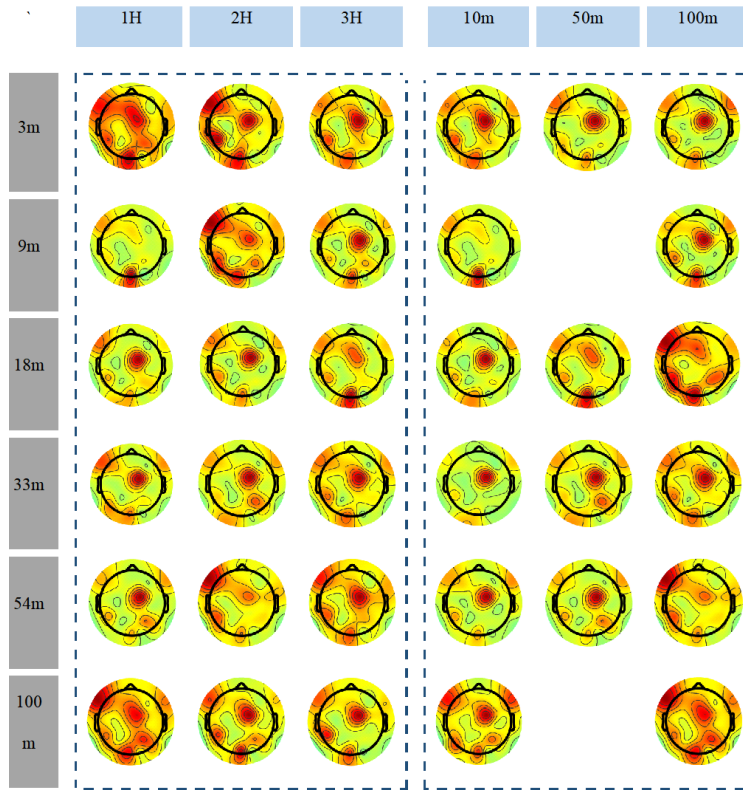


Figure 6: EEG topographic power spectrum maps for all 26 spatial scenarios. Rows correspond to building heights (3m, 9m, 18m, 33m, 54m, 100m); columns correspond to plaza conditions ($L/H = 1H, 2H, 3H$; fixed-width $L \approx 10m, 50m, 100m$). Colour scale represents relative EEG power (μV^2): warm colours (red/orange) indicate higher power; cool colours (green/blue) indicate lower power. In lower building heights, warm activation is concentrated in posterior regions (parietal-occipital, indicating Alpha/relaxation); as building height increases, activation shifts toward anterior frontal regions (indicating Beta/cognitive load). Empty cells indicate scenarios not included for the corresponding height level

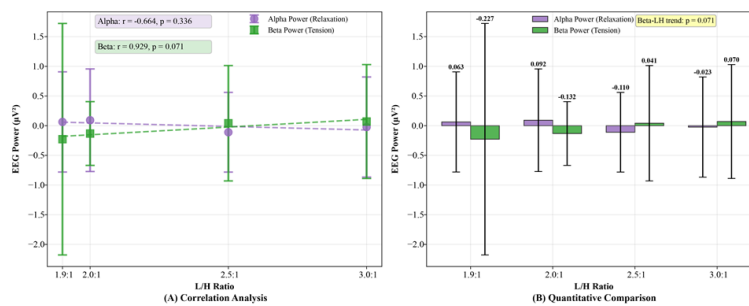


Figure 7: (A) Spearman's correlation between L/H ratio and EEG power (aggregated across six height-level conditions, $k = 6$): Beta power (green squares, $r = 0.929$, $p = 0.071$) shows a directional positive trend; Alpha power (purple circles, $r = -0.664$, $p = 0.336$) shows a negative trend. Neither correlation reached the pre-specified significance threshold of $\alpha = 0.05$; results are exploratory. Error bars represent 95% confidence intervals. (B) Mean EEG power (μV^2) \pm SD at four representative L/H ratios (1.9:1, 2.0:1, 2.5:1, 3.0:1) for Alpha (purple) and Beta (green) bands.

Derivation of the adaptive scale model

The optimal L/H ratio for each building height was defined as the spatial scale at which participants perceived the plaza as neither too enclosed nor too expansive — operationalised as the interpolated zero-crossing of the mean Spatial Perception Score (SPS), a bipolar 7-point scale anchored at -3 ("extremely narrow/small") and +3 ("extremely wide/large"), with 0 denoting perceptual neutrality. For each height level, the SPS was measured at all tested L/H configurations. Where no tested scenario yielded SPS = 0 exactly, the optimal L/H was linearly interpolated between the adjacent negative and positive values. This threshold was corroborated by the convergence of two secondary indicators: (a) the local minimum of mean GSR change-from-baseline (indicative of lowest physiological arousal), and (b) the point of transition from Alpha-dominant to Beta-dominant EEG topography. No composite weighting was applied; the SPS zero-crossing served as the primary criterion, with GSR and EEG providing directional corroboration. The full set of outcome values for all tested scenarios and the resulting optimal L/H selections are presented in Table 2.

Table 2: Decision Criteria for Optimal L/H Ratio at Each Building Height Level

H (m)	Tested L/H	Spatial Perception Score (mean)	Positive Affect (mean)	Negative Affect (mean)	GSR Change (height mean)	Selection
3	1.0	-2.28	17.00	23.72	-0.187	—
	2.0	-1.45	18.55	15.83		—
	3.0	-0.07	20.76	14.24		✓ SPS = -0.07 ≈ 0; adopted as L/H = 3.0 (interpolated zero-crossing = 3.38; nearest tested value used)
	16.3	+2.34	24.17	13.55		—
	33.0	+2.76	23.00	13.24		—
9	1.0	-2.00	17.93	19.93	-0.130	—
	2.0	-0.83	17.45	16.03		—
	3.0	+0.24	19.86	14.24		✓ nearest to zero; interpolated optimum = 2.77
	11.0	+1.89	24.07	13.04		—
18	0.5	-2.45	18.07	22.97	-0.224	—
	1.0	-1.45	17.55	19.17		—
	2.0	-0.24	18.21	16.14		—
	3.0	+0.55	20.21	14.00		—
	5.8	+1.31	23.35	12.04		✓ interpolated optimum = 2.30
33	0.3	-2.24	17.86	21.62	-0.262	—
	1.0	-1.00	17.28	19.79		—
	2.0	-0.14	17.66	18.72		—
	3.0	+0.45	21.28	15.10		✓ interpolated optimum = 2.24
54	0.19	-2.41	18.86	22.00	-0.214	—
	1.0	-0.86	16.62	18.59		—
	2.0	+0.07	18.76	15.55		✓ interpolated optimum = 1.93
	3.0	+0.86	19.72	14.69		—
100	0.1	-2.32	18.25	24.61	-0.142	—
	1.0	-0.93	17.31	19.76		—
	2.0	+0.03	18.66	16.31		✓ interpolated optimum = 1.96
	3.0	+1.00	19.48	15.17		—

Note: Spatial Perception Score (SPS) is a bipolar 7-point scale (-3 = extremely narrow; 0 = just right; +3 = extremely wide). Optimal L/H is defined as the linearly interpolated zero-crossing of SPS between adjacent tested values. PA = Positive Affect (PANAS); NA = Negative Affect (PANAS). GSR values represent height-level means across all L/H conditions (N = 4–5 participants with valid recordings). The SPS zero-crossing serves as the primary decision criterion; GSR minimum and EEG Alpha/Beta transition provide corroborating directional evidence.

Synthesizing the subjective, physiological (GSR), and neurological (EEG) data, we derived the optimal L/H ratio for varying building heights. As shown in Figure 8, the relationship is nonlinear. The optimal plaza side length does not follow a fixed linear progression (e.g., L = 3H) as suggested by traditional theories. Instead, the curve demonstrates a decaying ratio:

- For Low-rise contexts (H=3m), the optimal ratio is approximately 3.0, maximizing openness.
- For Mid-rise contexts (H=18-33m), the optimal ratio drops to 2.2 – 2.5.

- For Super-high-rise contexts (H=100m), the optimal ratio converges to 1.9.

These interpolated optimal values — $L/H \approx 3.03$ (H=3m), 2.77 (H=9m), 2.30 (H=18m), 2.24 (H=33m), 1.93 (H=54m), and 1.96 (H=100m) — are summarised with their supporting outcome metrics in Table 2, and were used as the six empirical data points for the subsequent curve fitting.

This fitted curve ($R^2 = 0.92$) in Figure 8 challenges the "One-Size-Fits-All" guidelines, proposing a new, height-dependent standard for determining plaza scale in high-density cities.

The relationship was well approximated by an exponential decay model:

$$\frac{L}{H} \approx 1.43 \times e^{(-0.057H)} + 1.92 (R^2 = 0.92),$$

where L/H is the optimal plaza side-length-to-building-height ratio (dimensionless) and H is the surrounding building height (m). The three fitted parameters are: amplitude $a = 1.43$ (95% CI [0.91, 1.94]), representing the difference between the low-rise and high-rise optimal ratios; decay rate $b = 0.057 \text{ m}^{-1}$ (95% CI [0.005, 0.110]), reflecting the rate at which the optimal ratio decreases with building height; and lower asymptote $c = 1.92$ (95% CI [1.60, 2.23]), representing the minimum enclosure ratio required under extreme high-rise conditions. Parameters were estimated by nonlinear least squares regression (`scipy.optimize.curve_fit`, Python 3.11) applied to the six empirically derived optimal L/H data points ($H = 3, 9, 18, 33, 54, 100 \text{ m}$), capturing the nonlinear shift toward greater enclosure with increasing vertical scale.

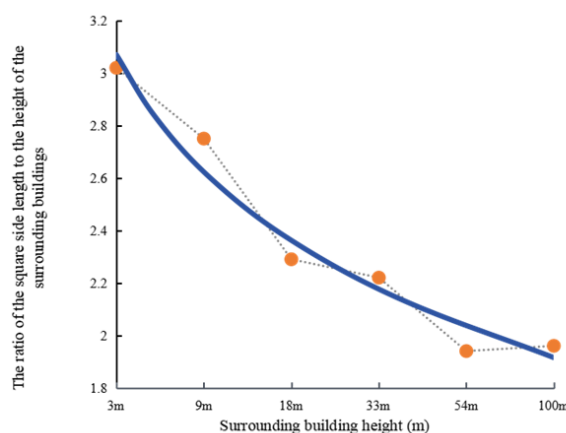


Figure 8: The adaptive model of optimal L/H ratios across different building heights. Orange dots represent the six empirically derived optimal L/H data points (one per building height: $H = 3, 9, 18, 33, 54, 100 \text{ m}$); the dotted line connects observed values. The solid curve shows the fitted exponential decay model: $L/H \approx 1.43 \times e^{(-0.057H)} + 1.92$ ($R^2 = 0.92$). As building height increases, the optimal L/H ratio decreases, indicating that greater enclosure is required to maintain psychological comfort in taller environments. The lower asymptote (≈ 1.92) represents the minimum enclosure ratio under extreme high-rise conditions.

DISCUSSION

Theoretical interpretation: the "vertical enclosure" paradox

Our findings reveal a critical paradox in urban spatial perception: while openness is generally associated with psychological relief in low-rise contexts, it triggers "spatial stress" in high-rise environments. This divergence

challenges the conventional wisdom that "bigger is always better" for public plazas and can be interpreted through the lens of Prospect-Refuge Theory (Appleton, 1975) and Visual Scale Theory (Thiel, 1961).

The failure of refuge in vertical gigantism. According to Prospect-Refuge Theory, human psychological comfort relies on a balance between the ability to observe (prospect) and the feeling of safety (refuge).

In Low-Rise Settings ($H \leq 9m$). A large plaza ($L/H \approx 3$) offers expansive prospect without diminishing the sense of refuge. The building boundaries are human-scaled, acting as "permeable edges" that frame the sky without dominating the viewer (Stamps, 2005). Consequently, the openness is perceived as liberty and relaxation (as confirmed by our elevated Alpha waves).

In High-Rise Settings ($H \geq 54m$). The vertical scale of the boundaries radically alters this dynamic. When a plaza is too large ($L/H \geq 3$) relative to a 100-meter skyscraper, the absolute horizontal distance becomes vast (e.g., >300m wide). In this scenario, the building walls are too distant to provide a sense of "enclosure" or "shelter," while the sheer height of the structures creates a looming "panoptic" effect. The pedestrian feels exposed in an "urban desert"—a space with excessive prospect but zero refuge. This triggers the observed "urban agoraphobia," manifested physically as increased GSR arousal.

The "visual anchor" hypothesis. Why does reducing the ratio to 1.9:1 alleviate stress in high-rise contexts? We propose a "Visual Anchor" Hypothesis. In super-high-rise environments, the human eye struggles to find a resting point in a vast open plaza. A tighter enclosure (1.9:1) brings the boundary walls closer to the viewer's effective visual field (within the 18° - 27° vertical viewing angle threshold proposed by Ashihara (Ashihara, 1970). This proximity transforms the towering facade from a distant, abstract object into a tangible "defensible boundary" (Newman, 1972). By compressing the space, the design artificially restores a sense of containment, allowing the brain to define the territory and reducing the subconscious vigilance required to scan a boundless environment (S. Kaplan, 1995).

Neurophysiological interpretation: the cost of spatial ambiguity

While Prospect-Refuge theory explains the psychological motivation for enclosure, our EEG results provide the mechanistic evidence for how the brain processes these spatial scales. Specifically, the exploratory positive trend between L/H ratio and Beta-band activity ($r = 0.929$, $p = 0.071$, ns) in high-rise contexts is consistent with the existence of a hidden cognitive cost (Antonenko et al., 2010), though this association did not reach statistical significance under our pre-specified $\alpha = 0.05$ threshold and should be treated as hypothesis-generating.

The "searching brain" hypothesis. In human-scale environments (e.g., typical parks), the brain often enters a "Default Mode," characterized by Alpha wave dominance (relaxation) (Knyazev et al., 2011; Ulrich et al., 1991). However, our data shows that in super-high-rise settings ($H=100m$) with large plazas ($L/H=3$), frontal Beta activity shows a directional increase.

We interpret this as the "Searching Brain" response. When the vertical scale is overwhelming and the horizontal boundaries are too distant, the environment lacks immediate "visual anchors" (Lynch, 1960). Consequently, the brain cannot rely on peripheral vision to define safety; instead, it must allocate top-down cognitive resources to actively scan the environment for boundaries and depth cues. This transforms a passive experience (relaxing in a square) into an active, cognitively demanding task (spatial mapping), leading to the observed rise in cognitive load (Banaei et al., 2017).

Spatial ambiguity and vigilance. This neurological state aligns with the concept of "Spatial Ambiguity." In high-density cities, a plaza that is too open relative to the towering skyscrapers creates a scale mismatch—the

pedestrian feels miniscule, and the space feels "placeless" (Relph, 1976). The elevated Beta waves, combined with increased GSR arousal (Section 3.2), suggest that the brain interprets this ambiguity as a potential threat. This aligns with Kaplan's Information Processing Theory, which posits that environments lacking "coherence" or "legibility" induce stress because they require excessive effort to comprehend (R. Kaplan & Kaplan, 1989). The reduction of Beta power at the 1.9:1 ratio indicates that tighter enclosure resolves this ambiguity. By bringing the "walls" within a cognitively graspable distance, the design offloads the brain's processing burden, allowing the transition from "vigilance" back to "relaxation."

Practical implications: towards an adaptive design framework

The derivation of the nonlinear optimal scale curve (H-dependent L/H ratio) provides actionable criteria for revising current urban design codes. Unlike the static guidelines of the past (e.g., Ashihara's universal 2:1 rule), our findings advocate for a "Height-Adaptive" design framework that responds to the vertical density of the site (Ashihara, 1970).

Differentiated zoning guidelines. Urban planners should adopt distinct scaling strategies based on the dominant vertical morphology of the district:

Low-Rise Zones (Residential/Historical, $H \leq 9m$). Prioritize Openness ($L/H \approx 3$). In these human-scale environments, designers should maximize horizontal viewing corridors. Wide plazas function as "urban lungs," inducing relaxation (Alpha wave dominance) without triggering agoraphobia. Over-enclosing these spaces is unnecessary and may reduce their restorative potential (S. Kaplan, 1995).

High-Rise Zones (CBD/Financial Districts, $H \geq 54m$). Prioritize Enclosure ($L/H \approx 1.9$). In dense vertical cores, the primary design goal should be to mitigate "spatial stress." Plazas should be more compact to form a clear "defensible space" (Newman, 1972). If a large gathering capability is required, the space should be subdivided into smaller, human-scaled clusters rather than a single vast expanse (Alexander et al., 1977).

Remediation strategies for "oversized" plazas: visual layering. A critical challenge in modern Asian cities is the prevalence of existing "mega-plazas" surrounded by skyscrapers, which our data identifies as high-stress environments (High Beta/GSR). Since moving buildings is impossible, we propose a "Visual Layering" strategy to artificially correct the scale ratio. For existing mega-plazas that cannot be structurally altered, we propose "soft-intervention" strategies. For instance, placing a row of deciduous trees or temporary art installations at the 1.9H mark can create a "psychological ceiling" (psychological boundary), effectively reducing the perceived scale without changing the physical footprint (Whyte, 1980). This tricks the brain into perceiving a tighter, safer enclosure, thereby reducing the cognitive load required to scan the distant building facades (Cullen, 1961).

Alignment with sustainable development goals (SDGs). Finally, optimizing plaza scale is not merely an aesthetic pursuit but a component of social sustainability (United Nations, 2015). Public spaces that induce high cognitive load or physiological stress discourage long-term dwelling and social interaction (Dempsey et al., 2011). By implementing these neuro-ergonomic guidelines, cities can transform "hostile" high-rise voids into "restorative" places, enhancing the psychological resilience of the urban population in an era of densification (Roe & McCay, 2021).

Limitations and future directions

While this study provides novel neurophysiological insights into urban scaling, several limitations must be acknowledged to contextualize the findings:

(1) *Exposure Duration.* The use of a 10-second "Rapid Spatial Assessment" protocol focused exclusively on immediate, instinctive perception. While this effectively captured the "first impression" mechanism critical for pedestrian navigation, it does not account for long-term physiological adaptation or "dwelling" experiences (e.g., sitting on a bench for 30 minutes). This limitation is consistent with Stamps' findings that initial environmental judgments stabilize within seconds (Stamps, 2010). Future studies should employ longitudinal designs to examine how these stress responses evolve over time.

(2) *Ecological Validity and Generalizability of the Simplified VR Environment.* To isolate the geometric variable of L/H ratio and maximise internal validity, the virtual plazas were rendered as abstract enclosures with uniform, untextured boundary walls and standardised lighting. While this approach is well-established in controlled neuro-architectural research (Banaei et al., 2017; Higuera-Trujillo et al., 2021), it introduces several important constraints on the generalisability of the recommended ratios to real-world plazas.

First, the "building height" in our simulation represents a uniform, unbroken wall surface. Real facades are typically articulated with windows, recesses, balconies, podium setbacks, and varying materials, all of which alter the perceived visual weight and enclosure of a boundary (Stamps, 2005). Facade permeability in particular — the degree to which a boundary feels visually porous rather than solid — has been shown to modulate enclosure perception independently of geometric height (Stamps, 2005). Buildings with highly transparent ground-floor facades or articulated upper-floor setbacks may effectively reduce the perceived height, implying that the recommended L/H thresholds could be somewhat relaxed in such contexts.

Second, the simulated environments contained no vegetation, street furniture, human activity, or ground-level programming. In real plazas, trees and planting are known to provide intermediate-scale visual anchors that partially substitute for architectural enclosure, potentially reducing spatial stress even at L/H ratios that our model identifies as suboptimal (S. Kaplan, 1995; Ulrich, 1984). Similarly, active ground-floor uses (cafés, retail, pedestrian movement) provide social stimuli that may buffer the agoraphobic response to oversized open spaces (Gehl, 2011; Whyte, 1980). This suggests that the recommended ratio of $L/H \approx 1.9$ for high-rise contexts could be partially offset by soft-landscape and programming interventions — a direction already proposed in Section 4.3.2 as the "Visual Layering" strategy.

Third, the simulation did not include sky exposure variation, wind effects, ambient noise, or time-of-day lighting changes, all of which are known to influence perceived comfort in real urban spaces (Chamilothori et al., 2019; Oke, 1988). The optimal L/H ratio may therefore shift under different microclimatic conditions, particularly in contexts with strong solar exposure or wind channelling effects typical of high-rise districts.

Taken together, these factors suggest that the proposed adaptive scale model should be interpreted as a geometric baseline — a necessary but not sufficient condition for spatial comfort — rather than a universal prescription. Future studies should systematically reintroduce these real-world variables, either through higher-fidelity VR simulations or controlled field experiments, to quantify how façade articulation, vegetation, and activity levels interact with L/H ratio to shift the comfort threshold. In the interim, practitioners applying the 1.9:1 guideline to high-rise contexts should treat it as a conservative lower bound, recognising that enriched facade design and active programming may permit somewhat larger ratios without triggering the spatial stress responses documented here.

(3) *Demographic Generalizability.* The sample consisted primarily of young adults. Since spatial perception and glare sensitivity can vary with age (Moffat, 2009), the specific threshold values (e.g., the 1.9:1 optimal ratio) may differ for children or the elderly. Expanding the demographic scope is a necessary next step for creating inclusive urban design guidelines.

(4) *Participant Sampling and External Validity.* The study sample was intentionally restricted to young adults with academic training in architecture or urban design. As noted in Section 2.1, this choice was motivated by

two methodological goals: maximising neurocognitive sensitivity to spatial stimuli and minimising noise in the physiological baseline. However, this decision has important implications for the external validity of the proposed guidelines.

Individuals with professional spatial training are known to perceive and evaluate architectural scale differently from the general public. Research on spatial expertise suggests that trained observers are more sensitive to subtle geometric variations, more capable of abstracting geometric properties from decorated or complex facades, and potentially more tolerant of extreme enclosure ratios due to familiarity with spatial conventions (Hyde, 2007; Shemesh et al., 2017). Conversely, they may exhibit reduced agoraphobic responses to large open plazas, as their professional framework provides cognitive anchors that laypersons lack.

As a consequence, the optimal L/H thresholds derived in this study — particularly the 1.9:1 lower bound for high-rise contexts — should be interpreted as reflecting the comfort range of a spatially-literate population. For general urban users, who represent the primary occupants of public plazas, the comfort threshold for enclosure may be somewhat higher (i.e., requiring a tighter ratio at any given height), suggesting that our recommendations may represent a conservative estimate for the broader public. Future studies should replicate the experimental design with demographically diverse samples — including non-specialist adults, older residents, and users from different cultural backgrounds — to establish whether the exponential decay model holds across populations and to determine the direction and magnitude of any systematic bias introduced by the current sampling strategy.

In the interim, practitioners should treat the proposed ratios as geometry-based reference points derived from a spatially-trained cohort, and consider applying a modest adjustment factor when designing plazas intended primarily for general public use.

CONCLUSION

Paradigm shift: from static canons to adaptive resilience

This study challenges the centuries-old architectural canon that prescribes a fixed "Golden Ratio" (e.g., 2:1 or 3:1) for all public plazas (Ashihara, 1970; Sitte, 1965). By integrating Virtual Reality with multi-modal psychophysiological metrics (EEG/GSR), we provide empirical evidence that the optimal plaza scale is not a static constant but a dynamic variable strictly modulated by vertical urbanism. Our derivation of the Adaptive Scale Model demonstrates a nonlinear decay: as building heights soar from human-scale (3 m) to super-high-rise (100 m), the optimal L/H ratio contracts from 3.0:1 to 1.9:1 among spatially-trained observers to maintain psychological comfort, providing a geometry-based reference point for design practice. This finding signals a fundamental paradigm shift from "One-Size-Fits-All" rules to "Height-Adaptive" design frameworks.

The neurophysiological cost of "empty" space

Beyond behavioral preferences, this research elucidates the neural mechanisms underlying urban comfort. We identified "Spatial Ambiguity" as a distinct stressor in high-density environments. When plazas are too open relative to skyscraper boundaries, the brain is forced out of its default relaxation mode and into a high-cost "Searching Mode" (characterized by elevated frontal Beta activity and GSR arousal) to define spatial limits. This confirms that in the vertical city, enclosure is not merely an aesthetic choice, but a cognitive necessity for reducing mental load.

Implications for sustainable cities (SDG 11)

In the context of rapid global urbanization, these findings offer a practical toolkit for achieving Sustainable Cities and Communities (SDG 11) (United Nations, 2015). By applying the proposed 1.9:1 guideline and visual layering strategies, urban planners can diagnose and remediate "hostile" public spaces, transforming them from anxiety-inducing voids into restorative sanctuaries (Roe & McCay, 2021). Ultimately, this study bridges the gap between neuroscience and urban planning, establishing a rigorous, data-driven foundation for the design of psychologically resilient high-density cities.

AUTHOR CONTRIBUTIONS

Wen Lu: Conceptualization, Methodology, Software (VR environment development), Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Jian Zhang: Funding acquisition.

Ning Li: Conceptualization, Methodology, Supervision, Project administration, Formal analysis, Funding acquisition, Writing – review & editing, Investigation, Resources, Data curation, Correspondence.

All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

The VR scenario stimuli, anonymised participant-level PANAS scores, and the curve-fitting script used to derive the Adaptive Scale Model are available from the corresponding author upon reasonable request. Raw EEG and GSR signals are not publicly archived due to participant privacy constraints, but de-identified condition-level summary data are available upon request. No external data repositories were used for this study.

REFERENCES

- Alexander, C., Ishikawa, S., & Silverstein, M. (1977). *A pattern language: Towns, buildings, construction*. Oxford University Press.
- Antonenko, P., Paas, F., Grabner, R., & van Gog, T. (2010). Using electroencephalography to measure cognitive load. *Educational Psychology Review*, 22(4), 425–438. <https://doi.org/10.1007/s10648-010-9130-y>
- Appleton, J. (1975). *The experience of landscape*. John Wiley & Sons.
- Ashihara, Y. (1970). *Exterior design in architecture*. Van Nostrand Reinhold.
- Aspinall, P., Mavros, P., Coyne, R., & Roe, J. (2015). The urban brain: Analysing outdoor physical activity with mobile eeg. *British Journal of Sports Medicine*, 49(4), 272–276. <https://doi.org/10.1136/bjsports-2012-091877>
- Banaei, M., Hatami, J., Yazdanfar, A., & Gramann, K. (2017). Walking through architectural spaces: The impact of interior forms on human brain dynamics. *Frontiers in Human Neuroscience*, 11, 477. <https://doi.org/10.3389/fnhum.2017.00477>
- Boucsein, W. (2012). *Electrodermal activity* (2nd). Springer. <https://doi.org/10.1007/978-1-4614-1126-0>

- Braithwaite, J. J., Watson, D. G., Jones, R., & Rowe, M. (2013). *A guide for analysing electrodermal activity (eda) & skin conductance responses (scr) for psychological experiments* (tech. rep.). University of Birmingham.
- Carmona, M. (2010). Contemporary public space: Critique and classification, part one: Critique. *Journal of Urban Design*, 15(1), 123–148. <https://doi.org/10.1080/13574800903435651>
- Carr, S., Francis, M., Rivlin, L. G., & Stone, A. M. (1992). *Public space*. Cambridge University Press.
- Chamilothori, K., Wienold, J., & Andersen, M. (2019). Adequacy of immersive virtual reality for the perception of daylight spaces: Comparison of real and virtual environments. *LEUKOS*, 15(2-3), 203–226. <https://doi.org/10.1080/15502724.2017.1404918>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd). Lawrence Erlbaum Associates.
- Critchley, H. D. (2002). Electrodermal responses: What happens in the brain. *The Neuroscientist*, 8(2), 132–142. <https://doi.org/10.1177/107385840200800209>
- Cullen, G. (1961). *The concise townscape*. Architectural Press.
- Delorme, A., & Makeig, S. (2004). Eeglab: An open source toolbox for analysis of single-trial eeg dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134(1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>
- Dempsey, N., Bramley, G., Power, S., & Brown, C. (2011). The social dimension of sustainable development: Defining urban social sustainability. *Sustainable Development*, 19(5), 289–300. <https://doi.org/10.1002/sd.417>
- Ellard, C. (2015). *Places of the heart: The psychogeography of everyday life*. Bellevue Literary Press.
- Friedman, M. (1937). The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the American Statistical Association*, 32(200), 675–701. <https://doi.org/10.2307/2279372>
- Gehl, J. (2010). *Cities for people*. Island Press.
- Gehl, J. (2011). *Life between buildings: Using public space*. Island Press.
- Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the ageing mind: A view from cognitive neuroscience. *Nature Reviews Neuroscience*, 5(2), 87–96. <https://doi.org/10.1038/nrn1323>
- Higuera-Trujillo, J. L., Llinares, C., & Macagno, E. (2021). The cognitive-emotional design and study of architectural space: A scoping review of neuroarchitecture and psychology techniques. *Sensors*, 21(6), 2193. <https://doi.org/10.3390/s21062193>
- Higuera-Trujillo, J. L., López-Tarruella Maldonado, J., & Llinares Millán, C. (2017). Psychological and physiological human responses to simulated and real environments: A comparison between photographs, 360° panoramas, and virtual reality. *Applied Ergonomics*, 65, 398–409. <https://doi.org/10.1016/j.apergo.2017.05.006>
- Hyde, W. (2007). A stitch in time: Gender issues explored through contemporary textiles practice in a sixth form college. *International Journal of Art & Design Education*, 26(3), 296–307. <https://doi.org/10.1111/j.1476-8070.2007.00540.x>
- Jasper, H. H. (1958). The ten-twenty electrode system of the international federation. *Electroencephalography and Clinical Neurophysiology*, 10, 371–375.
- Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., McKeown, M. J., Iragui, V., & Sejnowski, T. J. (2000). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology*, 37(2), 163–178. <https://doi.org/10.1111/1469-8986.3720163>
- Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press.
- Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, 15(3), 169–182. [https://doi.org/10.1016/0272-4944\(95\)90001-2](https://doi.org/10.1016/0272-4944(95)90001-2)
- Klimesch, W. (1999). Eeg alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews*, 29(2-3), 169–195. [https://doi.org/10.1016/S0165-0173\(98\)00056-3](https://doi.org/10.1016/S0165-0173(98)00056-3)

- Knyazev, G. G., Slobodskoj-Plusnin, J. Y., Bocharov, A. V., & Pylkova, L. V. (2011). The default mode network and eeg alpha oscillations: An independent component analysis. *Brain Research, 1402*, 67–79. <https://doi.org/10.1016/j.brainres.2011.05.052>
- Kuliga, S. F., Thrash, T., Dalton, R. C., & Hölscher, C. (2015). Virtual reality as an empirical research tool — exploring user experience in a real building and a corresponding virtual model. *Computers, Environment and Urban Systems, 54*, 363–375. <https://doi.org/10.1016/j.compenvurbsys.2015.09.006>
- Lynch, K. (1960). *The image of the city*. MIT Press.
- Lynch, K. (1971). *Site planning* (2nd). MIT Press.
- Maertens, H. (1877). *Der optische-maassstab: Oder die theorie und praxis des ästhetischen sehens in den bildenden künsten*. Max Cohen & Sohn.
- Marcus, C. C., & Francis, C. (1998). *People places: Design guidelines for urban open space*. John Wiley & Sons.
- Moffat, S. D. (2009). Aging and spatial navigation: What do we know and where do we go? *Neuropsychology Review, 19*(4), 478–489. <https://doi.org/10.1007/s11065-009-9120-3>
- Newman, O. (1972). *Defensible space: Crime prevention through urban design*. Macmillan.
- Ng, E. (2009). *Designing high-density cities for social and environmental sustainability*. Earthscan.
- Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and Buildings, 11*(1-3), 103–113. [https://doi.org/10.1016/0378-7788\(88\)90026-6](https://doi.org/10.1016/0378-7788(88)90026-6)
- Ray, W. J., & Cole, H. W. (1985). Eeg alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. *Science, 228*(4700), 750–752. <https://doi.org/10.1126/science.3992243>
- Relf, E. (1976). *Place and placelessness*. Pion.
- Roe, J., & McCay, L. (2021). *Restorative cities: Urban design for mental health and wellbeing*. Bloomsbury Publishing.
- Russell, J. A. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology, 39*(6), 1161–1178. <https://doi.org/10.1037/h0077714>
- Salthouse, T. A. (2009). When does age-related cognitive decline begin? *Neurobiology of Aging, 30*(4), 507–514. <https://doi.org/10.1016/j.neurobiolaging.2008.09.023>
- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika, 52*(3-4), 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Shemesh, A., Talmon, R., Karp, O., Amir, I., Bar, M., & Grobman, Y. J. (2017). Affective response to architecture — investigating human reaction to spaces with different geometry. *Architectural Science Review, 60*(2), 116–125. <https://doi.org/10.1080/00038628.2016.1266597>
- Sitte, C. (1965). *City planning according to artistic principles* (G. R. Collins & C. C. Collins, Trans.) [Original work published 1889]. Random House.
- Stamps, A. E. (2005). Visual permeability, sky, and enclosure. *Environment and Behavior, 37*(5), 587–619.
- Stamps, A. E. (2010). Use of static and dynamic media to simulate environments: A meta-analysis. *Perceptual and Motor Skills, 111*(2), 355–364. <https://doi.org/10.2466/04.22.24.PMS.111.5.355-364>
- Thiel, P. (1961). A sequence-experience notation for architectural and urban space. *The Town Planning Review, 32*(1), 33–52. <https://doi.org/10.3828/tpr.32.1.w211603036412678>
- Tilley, S., Neale, C., Patuano, A., & Cinderby, S. (2017). Older people’s experiences of mobility and mood in an urban environment: A mixed methods approach using electroencephalography (eeg) and interviews. *International Journal of Environmental Research and Public Health, 14*(2), 151. <https://doi.org/10.3390/ijerph14020151>
- Ulrich, R. S. (1983). Aesthetic and affective response to natural environment. In *Human behavior and environment* (pp. 85–125, Vol. 6). Plenum Press.
- Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science, 224*(4647), 420–421. <https://doi.org/10.1126/science.6143402>

- Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*(3), 201–230. [https://doi.org/10.1016/S0272-4944\(05\)80184-7](https://doi.org/10.1016/S0272-4944(05)80184-7)
- United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development* [A/RES/70/1].
- Vecchiato, G., Tieri, G., Jelic, A., De Matteis, F., Maglione, A. G., & Babiloni, F. (2015). Electroencephalographic correlates of sensorimotor integration and embodiment during the appreciation of virtual architectural environments. *Frontiers in Psychology, 6*, 1944. <https://doi.org/10.3389/fpsyg.2015.01944>
- Vitruvius, M. P. (1914). *The ten books on architecture* (M. H. Morgan, Trans.) [Original work published ca. 15 BC]. Harvard University Press.
- Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The panas scales. *Journal of Personality and Social Psychology, 54*(6), 1063–1070. <https://doi.org/10.1037/0022-3514.54.6.1063>
- Whyte, W. H. (1980). *The social life of small urban spaces*. Conservation Foundation.

AUTOBIOGRAPHICAL SKETCHES

Wen Lu, Beijing Historical Building Protection Engineering Technology Research Center, Beijing University of Technology, Beijing, China.

Jian Zhang, Beijing Historical Building Protection Engineering Technology Research Center, Beijing University of Technology, Beijing, China.

Ning Li, Beijing Historical Building Protection Engineering Technology Research Center, Beijing University of Technology, Beijing, China; ning_li11@bjut.edu.cn.

Manuscript revisions completed 20 January 2026.