Valentine *et al. Discover Cities* (2026) 3:14
https://doi.org/10.1007/s44327-025-00167-y

Discover Cities

RESEARCH Open Access

Measuring visual stress patterns in architectural façades in Seoul across different historic time periods

Cleo Valentine[1,7,8*], Heather Mitcheltree[1], Ian Hosking[2], Uemee Jung[3], Kyujin Choi[3], Daniel Lee[3], Kyungho Oh[3], Seoyoung Kim[3], Arnold Wilkins[4], Olivier Penacchio[5,6] and Leonard Schrage[7]

*Correspondence:
Cleo Valentine
crv29@cam.ac.uk
[1]Department of Architecture, University of Cambridge, Cambridge, UK
[2]Department of Engineering, University of Cambridge, Cambridge, UK
[3]Department of Architecture and Architectural Engineering, Yonsei University, Seoul, Korea
[4]Department of Psychology, University of Essex, Essex, UK
[5]Computer Vision Center, Universitat Autònoma de Barcelona, Bellaterra, Spain
[6]Department of Computer Science, Universitat Autònoma de Barcelona, Bellaterra, Spain
[7]Department of Urban Studies and Planning, Massachusetts Institute of Technology, Cambridge, MA, USA
[8]Division of the Built Environment, RISE Research Institute of Sweden, Stockholm, Sweden

Abstract
Architectural façades significantly influence human health as primary interfaces between individuals and urban visual environments, however neurophysiological responses to architectural features across historical periods and at varied viewing distances remains an area yet to be examined. This study identifies visual stressors in Seoul's building façades across five historical epochs and examines how design characteristics influence visual stress at different viewing distances. This study analyzed 77 façade samples using Visual Stress Analysis (ViStA) across five architectural periods: Late Joseon Dynasty, Japanese Colonial, Post-Korean War Reconstruction, High-Density Urban Expansion, and Digital-Transitional Era. Standardized photographs at three distances (10–15, 20–30, 40–60 m) were assessed using Fourier-based computational methods. In doing so, this research identifies specific design characteristics within each epoch that correlate with distinct patterns that may be visually stressful. Traditional Korean architecture demonstrates a spatial profile associated with organic surface variations and traditional screening systems, while Colonial period façades exhibit a spatial profile linked to systematic fenestration and regularized compositions. Post-war reconstruction architecture shows spatial features correlated with repetition and standardized building elements, whereas the Post-Industrial Transition period (1980–2000) displays the highest peak visual stress levels—associated with contrasting material juxtapositions and complex geometric arrangements. Contemporary architecture reveals visual stress characteristics linked to advanced glazing systems, perforated metal cladding, and computationally derived patterns; nonetheless, these systems afford fine-grained control over spatial frequency and contrast that can reduce predicted stress despite their complexity. The study integrates image-based computational analysis with architectural feature identification to offer insights into how specific design elements, rather than historical periods per se, influence neurophysiological responses in urban visual environments.

Keywords Visual stress, Architectural features, Seoul, Computational analysis, Façade design, Urban health

1 Introduction

The built environment exerts a profound influence on human health, with recent research revealing that architecture is not merely a backdrop to human life, but an active agent in shaping physiological and psychological responses [52, 54, 57]. Architectural façades in particular, represent a primary interface between individuals and the visual environment of cities, constituting a significant portion of the urban visual field experienced by inhabitants and visitors alike. While the symbolic, cultural, and functional aspects of façades have been extensively studied within architectural discourse, considerably less attention has been directed toward understanding the neurophysiological responses they may induce in observers.

Work in the vision sciences suggests that certain visual patterns—particularly those characterized by high contrast, spatial frequencies of around 3 cycles per degree, and repetitive motifs—may induce cortical hyperexcitability, leading to symptoms of visual stress [43]. These symptoms include eye strain, headaches, and cognitive fatigue, which can significantly impact urban experience and public health at scale. This phenomenon, known as visual stress or pattern-induced visual discomfort, occurs when the visual cortex encounters patterns it is not evolutionarily adapted to process efficiently, resulting in more energetically demanding neural activity [28]. In susceptible individuals, exposure to highly repetitive or statistically 'unnatural' spatial configurations has been shown to provoke significant physiological responses—including headaches, visual discomfort, and, in extreme cases, seizures—due to the overstimulation of the visual cortex and aberrant distribution of spatial frequencies [3, 39, 43, 45, 56, 57].

Seoul presents a particularly compelling site for investigating these effects due to its extraordinarily rich architectural history and dramatic urban transformation over time. As one of the few cities in the world with approximately over two millennia of continuous urban history, Seoul embodies a high degree of continuity and layering of architectural forms shaped by shifting political regimes, cultural paradigms, and developmental pressures. Its built fabric spans centuries of development, from the intricately crafted hanok of the *Joseon Dynasty* to the vertical glass towers of contemporary financial districts. This research analyzes specific architectural design features across five key periods in Seoul's built environment to assess how particular façade characteristics may influence visual stress levels. This study segments buildings examined into five distinct epochs so as to examine a broad cross section of architectural facades within Seoul, and assess the design factors impacting on the presence of visual stressors over time and their corresponding neurophysiological implications.

Seoul's architectural landscape provides a unique case study for the identification of feature-specific sources of visual stressors due to its rich diversity of design approaches, from the traditional screening systems and organic materials of *Joseon Dynasty* 'hanok' to the advanced glazing technologies and computational patterns of contemporary architecture. Architecture shifts over time have produced distinctive design vocabularies with characteristic approaches to material application, pattern organization, construction systems, and a range of other factors that may influence visual comfort.

This research builds upon the methodological framework established by Mitcheltree et al. [37] and Valentine et al. [53], which demonstrated the efficacy of computational Fourier-based analysis for evaluating visual stress potential within architectural contexts. The present study extends this approach to examine how specific design features—including traditional Korean architectural motifs, regularized fenestration systems, utilitarian repetition, complex material arrangements, and advanced technological integrations—produce distinct visual stressor signatures that reflect their underlying compositional and material characteristics.

2 Research aims and objectives

This study aims to:

1. Identify visual stressors in building façades from five major historical periods in Seoul's architectural development:
    - Late Joseon Dynasty (Early twentieth century)
    - Modernization Period: Japanese Colonial (Early to mid-twentieth century)
    - Post-Korean war Reconstruction and Industrialization (Mid to late twentieth century)
    - High-Density Urban Expansion (Late twentieth century to early twenty-first century)
    - Digital-Transitional Era (twenty-first century onward)
2. Examine how particular design characteristics influence visual stress responses across different viewing distances to understand the spatial relationship of feature-specific perceptual effects
3. Analyze the relationship between architectural elements and visual stress indicators through computational assessment, identifying which specific features contribute to elevated or reduced stress predictions
4. Contextualize design features through architectural analysis, noting how different periods have employed distinct approaches to façade composition that may influence neurophysiological responses
5. Develop evidence-based insights regarding specific architectural design elements that inform human-centric design practices, focusing on feature characteristics rather than historical categorization

Through these objectives, the research seeks to establish an understanding of how specific architectural design elements influence human neurophysiological experience, and identify particular features that may contribute to visual discomfort. This approach provides targeted guidance for contemporary practice, facilitating the integration of beneficial design characteristics while identifying problematic features, irrespective of historical or stylistic origin.

3 Literature review

3.1 Visual stress and spatial patterning

Research in the vision sciences has identified a clear relationship between certain visual patterns and physiological discomfort. Wilkins et al. [57] demonstrated that spatial frequencies around 3 cycles per degree, combined with high contrast and repetitive regularity, can trigger visual discomfort in susceptible individuals. This phenomenon, known as pattern glare, is associated with cortical hyperexcitability—a condition where specific regions of the visual cortex exhibit increased reactivity to particular visual stimuli (Wilkins et al. 1984) [39].

The neurophysiological basis for visual discomfort relates to how efficiently the human visual system processes spatial information. Natural scenes typically exhibit a 1/f spatial frequency distribution, where amplitude decreases as spatial frequency increases [43]. This statistical property facilitates efficient neural processing through sparse coding, where only the necessary neurons activate to process visual information. By contrast, built environments frequently present visual stimuli that deviate from this natural distribution, particularly when architectural designs incorporate repetitive high-contrast motifs that concentrate energy around mid-range spatial frequencies [28].

Computational models developed by Penacchio and Wilkins [43] have established methods for quantifying the deviation of images from natural scene statistics, providing objective metrics that correlate with subjective discomfort ratings. Further research by Le et al. [28] has demonstrated that images of urban scenes that rate as uncomfortable show disproportionately greater amplitude at spatial frequencies within two octaves of 3 cycles per degree, producing measurable increases in haemodynamic responses in the visual cortex.

Individual differences in susceptibility to visual stress have been documented, with approximately 10% of the general population showing heightened sensitivity to pattern-induced discomfort [57]. This prevalence increases in certain neurodiverse populations, including individuals with migraine, photosensitive epilepsy, and autism spectrum conditions, suggesting important implications for inclusive design practices in the built environment [58].

3.2 Cultural–embodied perspectives on perception and place

While neurophysiological models account for the cortical mechanisms underlying visual discomfort caused by patterned stimuli [43, 53, 56], a complementary body of work in embodied cognition and cultural geography emphasizes that perception is not merely retinal but situated, motoric, and meaning-laden [12, 27]. Vision unfolds through the moving body within a socio-cultural field, where spatial rhythm, scale, and texture are continuously experienced through posture, motion, and culturally learned expectations of the built environment [9, 13, 55]. From this perspective, façades are not static optical surfaces but *perceptual interfaces* dynamically negotiated as individuals walk, glance, and dwell. This embodied view of perception provides a conceptual basis for analyzing architectural experience not as a static image, but as a temporally unfolding encounter between body and form.

Cultural geography further frames such embodied encounters as place-based, linking memory and identity to individual and collective narratives of urban form [8, 10, 58]. This orientation aligns with insights from urban sociology, which highlights the relational and communal dimensions through which people co-construct meaning in everyday urban space [36, 59]. In contrast, excessive repetition and homogeneity can diminish the legibility of, and attachment to, urban environments [21, 34], whereas material irregularity, texture, and proportional complexity can enhance perceptual comfort and foster symbolic belonging through physical and social dimensions of place attachment [21, 46]. This integration expands the visual stress framework beyond cortical responses, linking embodied perception and psychosocial meaning-making in how façades are sensed, interpreted, and retained within collective urban experience [6, 35, 46, 53]. This theoretical synthesis grounds architectural analysis in a *human-centered model of* *perception-in-place*, connecting neural sensitivity, embodied engagement, and cultural meaning within the urban visual experience [18, 44, 55].

3.3 Architectural façade design and material technologies

Historically, building façades have served not only as functional weatherproofing systems but as primary canvases for cultural expression, technological display, and socioeconomic signaling [7]. In Korea and more broadly in Asia, this symbolic role is especially visible—during the transition to modernity, facades evolved into a medium of architectural representation and identity [47], while design historians have shown that Korean architectural and design practices themselves actively engage in constructing national identity through the façade language [31]. Studies of traditional hanok façades show how materiality, asymmetry, and texture are organized not merely for utility but as visible carriers of cultural symbolism and logic [48]. Changes in façade design over time reflect socio-cultural shifts as well as broader shifts in aesthetic paradigms, material technologies, and construction methodologies across different architectural epochs. However, the neurophysiological implications of these design approaches remain largely under-examined within conventional architectural discourse. Korea presents a unique architectural trajectory shaped by a rapid transformation from a traditional agrarian society to an industrialized urban context within a relatively short timespan [20]. This accelerated historical and cultural transition has produced distinctive and period-specific shifts in architectural expression, with façade design playing a significant role in articulating shifting notions of identity across different eras [32]. Traditional Korean architecture, particularly during the Late Joseon, emphasized design approaches that strived to achieve harmony with natural surroundings, employing natural materials and proportional systems derived from human scales and environmental conditions [11, 40]. The façades of traditional hanok featured carefully balanced compositions of wooden structural elements, clay wall sections, and tiled roofing systems, and were characterized by subtle asymmetries and organic variations rather than strict repetition [11, 14, 22]. These elements often exhibited material tactility and visual irregularity, creating a nuanced sense of complexity that contrasted with the rigid symmetry typical of modern façades [41, 49]. Such façades frequently featured key design components—such as deep eaves, timber columns, and traditional doors—which have been shown to enhance perceived "Hanok-ness" and visual identity through rhythmic sequencing and balanced asymmetry [49]. These architectural characteristics not only reflect traditional construction logic but also embody visual qualities such as non-uniform patterns, textural richness, and scale-sensitive proportions that closely align with factors identified in neuroaesthetic research as conducive to positive affective responses. Recent findings in neuroaesthetics suggest that such visual irregularity**,** material tactility, and moderate complexity can elicit positive affective responses [1, 2] (Okamoto et al. 2013), particularly in environments dominated by natural irregularities and the use of materials with high tactile diversity. The Modernization period introduced Western and Japanese architectural influences, resulted in hybrid façade typologies that combined imported stylistic elements with local building practices. In major port cities and administrative centers, the Jōbo (条坊制, Japanese orthogonal urban grid) and Colonial planning regimes encouraged the adoption of standardized façade languages, often prioritized visual homogeneity and symbolic hierarchy [20]. This period saw the introduction of new materials such as reinforced concrete and structural steel, enabling larger glazed openings, modular construction, and increasingly rationalized window arrangements [33, 34]. These façades not only reflected advancements in construction methods but also operated as instruments of cultural hegemony—strategically designed to assert the visual dominance and symbolic authority of 'civilization' as defined by colonial ideology [20, 30]. The systematic approach to window placement and modular construction systems laid the groundwork for architectural standardization that would shape Korea's modern urban identity.

Post-war reconstruction and rapid industrialization precipitated standardized approaches to building design, with prefabricated elements and modular systems becoming prevalent in façade compositions. Early apartment blocks and low-rise public buildings constructed during the Korean War and recovery period were often characterized by brick façades, modular repetition, and minimal ornamentation—reflecting a utilitarian ethos that prioritized functionality over aesthetics [26, 38]. These façades typically featured flat roofs, straight horizontal lines, and standardized units reminiscent of modernist rationalism [38]. Architectural surfaces commonly employed raw or exposed materials such as unpainted concrete, bricks, and glass blocks, reinforcing a modernist visual grammar while simultaneously reducing production costs [23, 26]. Notable public buildings, such as Swoo-Geun Kim's 1963–65 medical ward, further reflected this ethos, employing exposed concrete and pilotis to create dramatic tension between compressed and open spaces [23]. In contrast, temporary structures and informal settlements that emerged during this period often exhibited ad-hoc material use and visual arrangements, adding layers of visual "noise" to the urban fabric [4, 25]. Wartime facilities like the Walker House in Busan exemplified bricolage construction, using rubble stones and Japanese-style roofs, which, though lacking ornamental detailing, now serve as a visual archive of examples of the types of construction improvisation employed during times of constraint [4].

With the onset of rapid industrialization in the late 1960 s and 1970 s, architectural production shifted toward mass housing developments and commercial towers, especially in newly developed districts such as Gangnam. Mass-produced high-rise apartment complexes adopted standardized façade logics that prioritized efficiency, cost reduction, and construction speed over aesthetic differentiation [23, 38]. Their visual composition commonly employed modular grids, vertically ordered window fields, and iterative balcony modules [15, 16, 50]. In parallel, high-density residential schemes emerged with minimal ornamentation and recurrent façade typologies driven by economic rationalization [17]. This utilitarian paradigm produced regular geometries and pronounced material contrasts that, in certain urban contexts, heightened perceptual tension and visual intensity [5, 23]. Contemporary commercial towers consolidated these tendencies, coupling structural and spatial optimization with serial curtain-wall systems that reinforced façade repetition at scale [18, 32]. In areas like Apgujeong Rodeo, façades evolved into expressive surfaces decoupled from structural logic, acting as symbolic interfaces for commercial identity. However, the accumulation of eclectic materials, signage, and surface treatments along commercial corridors has been found to contribute to visual overstimulation and potential cognitive stress [32].

Contemporary architectural practice in Seoul has embraced global design trends, incorporating advanced material technologies, parametric design strategies, and performance-oriented façade systems. While these approaches have produced visually distinctive buildings, they have also introduced unprecedented levels of pattern regularity, material reflectivity, and contrast relationships through computer-aided design and manufacturing processes [19]. Empirical analyses of Seoul's recent high-rise apartment and commercial developments indicate that while modular clarity and formal precision offer efficiency, their repetitive nature may lead to perceptual fatigue or emotional neutrality [17, 19]. However, contemporary design tools may also enable architects to optimize visual patterns, potentially mitigating some visual stress factors through more nuanced control over material relationships and geometric composition. Façade strategies such as rhythmic segmentation, twisted forms, and curvature modulation have been shown to enhance perceptual engagement, offering cognitive stimulation and visual relief in dense urban environments [14, 42]. Projects like Dongdaemun Design Plaza exemplify how digital fabrication and curvature mapping technologies can generate fluid, non-repetitive surface geometries while maintaining a sense of formal continuity [29]. These trends suggest a dual trajectory in contemporary practice, where technological regularity and expressive complexity coexist, shaping both the sensorial intensity and perceptual quality of Seoul's architectural landscape.

3.4 Urban morphology and architectural evolution in Seoul

Seoul's urban fabric reflects successive waves of cultural influence, political transformation, economic development, and technological change. Seoul has served as the capital of the Korean Peninsula for over two millennia, leaving distinct traces of each historical era—from the premodern Joseon Dynasty through the Japanese Colonial period to postwar industrialization and its transformation into a contemporary global city—on the city's urban form and architectural styles, shaped by successive political, economic, and technological changes. Each historical phase has left distinctive architectural imprints on the city, creating a layered urban landscape that encompasses multiple design approaches and building typologies. This morphological diversity provides a valuable spectrum for analyzing the relationship between architectural design approaches and their potential neurophysiological impacts, particularly regarding visual stress and perceptual comfort in the urban environment.

To systematically examine these relationships, this study employs a chronological framework that divides Seoul's architecture into five distinct epochs, each representing a specific historical period with characteristic architectural expressions and façade treatments. This approach enables systematic comparison of visual stress indicators across different historical and stylistic contexts (Table 1; Fig. 1).

Table 1 Epoch classification of Seoul's architectural development and building count by period

Epoch	Era	Historical period	Count	Ratio
Epoch 1	Early twentieth century	Late Joseon dynasty	60,948	10.84%
Epoch 2	Early to mid-twentieth century	Modernization period: Japanese colonial	2944	0.52%
Epoch 3	Mid to late twentieth century	Post-Korean war reconstruction and industrialization	96,528	17.17%
Epoch 4	Late twentieth century to early twenty-first century	High-density urban expansion	273,470	48.65%
Epoch 5	twenty-first century onward	Digital-transitional era	128,241	22.81%

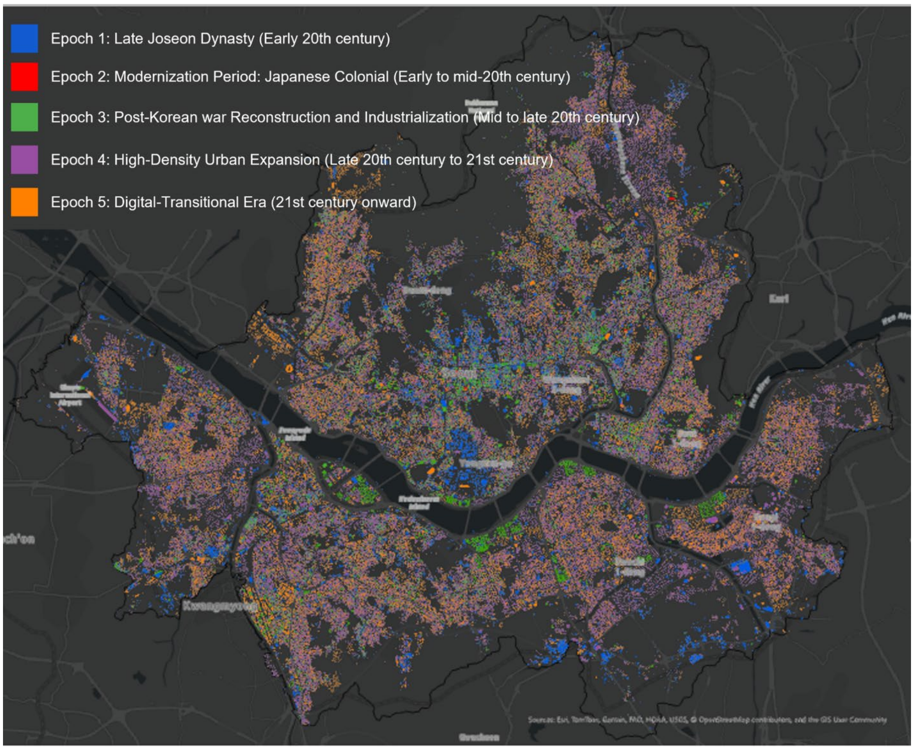


Fig. 1 Chronological distribution of building epochs in Seoul based on construction period

3.4.1 Late Joseon period (early twentieth century)

The Late Joseon Period encompasses traditional Korean architecture before significant Western or Japanese influence. Representative structures include buildings, Gyeongbokgung Palace complex, and surviving vernacular structures that maintain traditional construction techniques and proportional systems. The façades of this period typically feature wooden structural elements, clay wall sections, and tiled roofing systems with organic textures and balanced compositional arrangements that emphasize craftsmanship and natural materials (Fig. 2).

3.4.2 Modernization period: Japanese colonial (early to mid-twentieth century)

Characterized by Japanese Colonial influence and early modernization, this period introduced hybrid architectural approaches that combined Western and Japanese elements with Korean traditions. Significant examples include Myeongdong Cathedral, the Old Seoul Station, and Colonial-era administrative buildings. While some of these structures, such as Myeongdong Cathedral and Jeongdong Church, were completed before 1900, they are classified within this epoch due to their architectural vocabulary and historical associations with Korea's early modernization. Façades from this period often display symmetrical compositions, regularized fenestration patterns, and decorative elements derived from Western classical or Japanese modernist architectural vocabularies, marking the introduction of systematic approaches to façade organization (Fig. 3) [24].

3.4.3 Post-Korean war reconstruction and industrialization (mid to late twentieth century)

Following extensive destruction during the Korean War, this period was defined by pragmatic reconstruction efforts and rapid urbanization under challenging economic

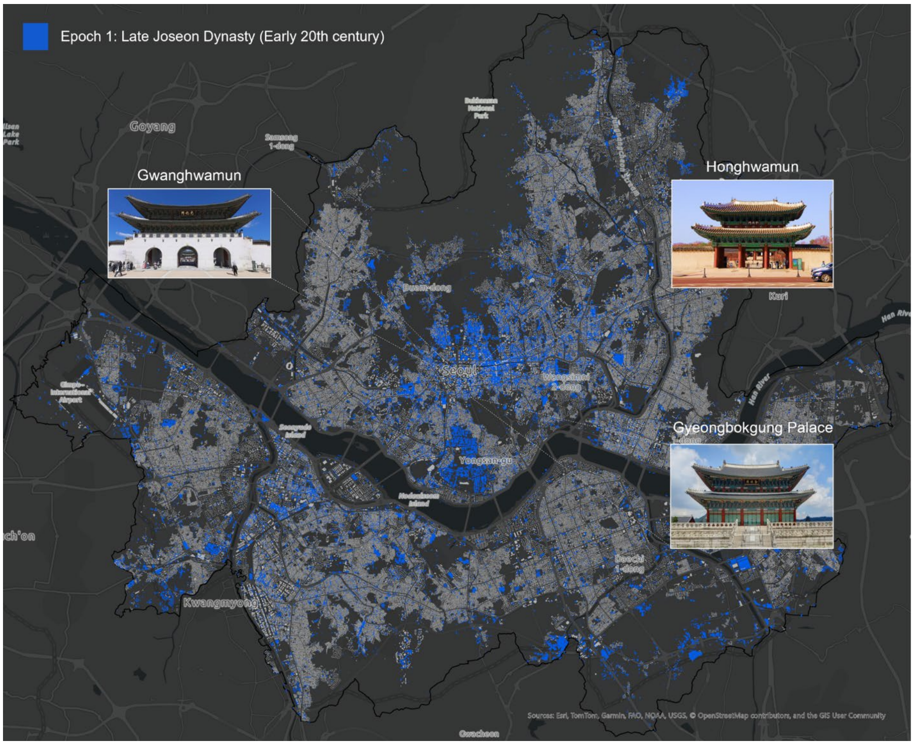


Fig. 2 Spatial distribution of late Joseon period architecture in Seoul with representative heritage landmarks

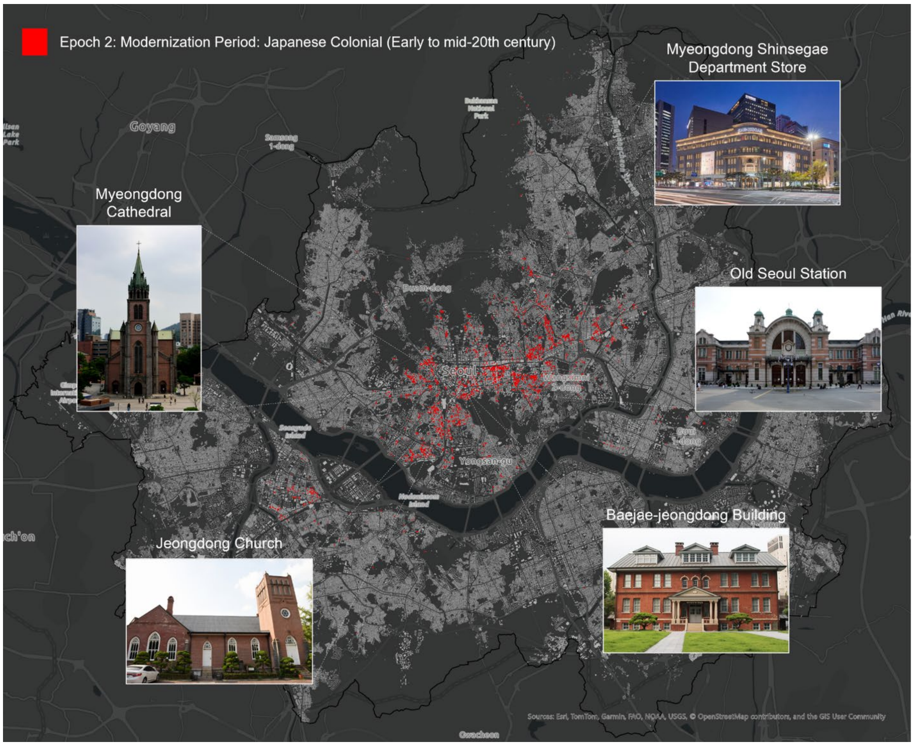


Fig. 3 Distribution of modernization period (Japanese colonial) architecture in Seoul with representative colonial-era and early modern landmarks

conditions. Representative structures include early apartment complexes, industrial facilities, and commercial buildings characterized by utilitarian designs with standardized elements, minimal ornamentation, and repetitive structural organizations. The architectural production of this era prioritized functional efficiency over aesthetic considerations, often resulting in highly regular façade patterns (Fig. 4) [20].

3.4.4 High-density urban expansion period (late twentieth century to early twenty-first century)

Coinciding with South Korea's economic development and international recognition, this period saw increased architectural complexity and material prosperity. Notable examples include apartment complexes in Gangnam, commercial developments, and institutional buildings that display more varied material palettes, complex geometrical arrangements, and increased attention to surface articulation. Despite greater design ambition, buildings from this period often maintained systematic repetition and modular organization principles derived from earlier standardization approaches (Fig. 5) [5].

3.4.5 Digital-transitional era (twenty-first century onward)

Characterized by architectural globalization and technological advancement, this period has produced structures that employ advanced materials and complex façade systems. Significant examples include the Yeouido International Finance Center, Dongdaemun Design Plaza, and high-rise residential developments featuring sophisticated glazing systems, innovative material applications, and computationally-derived patterns. Contemporary façades frequently exhibit high degrees of regular repetition enabled by

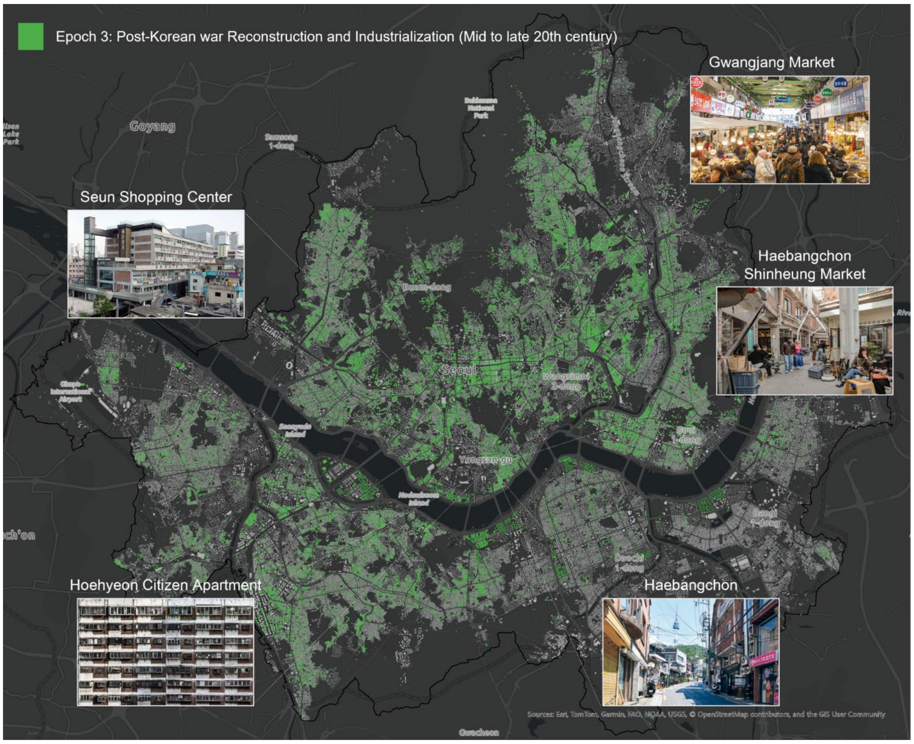
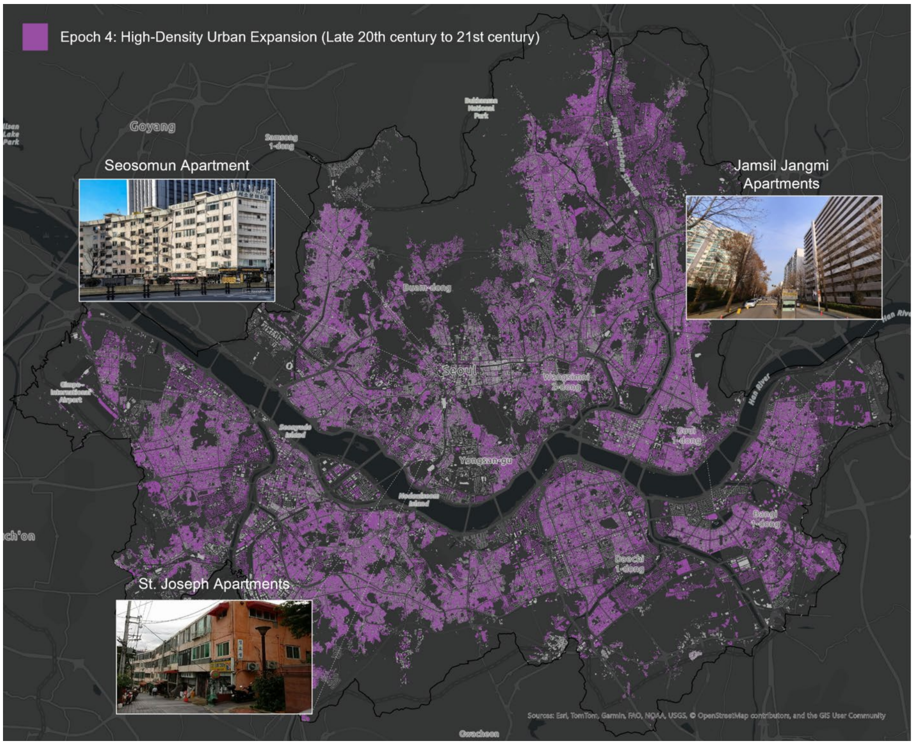


Fig. 4 Spatial distribution of post-Korean war reconstruction and industrialization period architecture in Seoul with representative post-war reconstruction typologies



Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Fig. 5 Distribution of high-density urban expansion period architecture in Seoul highlighting emerging complexity and economic growth

digital design and manufacturing technologies, though they also demonstrate potential for more nuanced pattern control (Fig. 6) [22].

4 Methodology

4.1 Building selection and epochal classification

To systematically classify architectural samples across Seoul's diverse urban fabric, this study employed Geographic Information Systems (GIS) in conjunction with the Seoul Metropolitan Government's comprehensive building registry. The dataset, originally sourced from the Korea Ministry of Land, Infrastructure and Transport, comprised 695,925 registered structures as of 2025. To enhance analytical clarity and remove potential non-primary structures, a data filtering step was implemented: all buildings with a total floor area under 50 m^2—typically auxiliary or non-habitable—were excluded, resulting in the removal of 133,794 entries. The final dataset used for spatial and temporal analysis consisted of 562,131 buildings (Fig. 7). After classifying the citywide dataset by construction year into epochs, we selected a proof-of-concept subset ($n = 120$) for controlled image-based analysis of feature–response relationships.

This registry contains detailed spatial and temporal metadata, enabling accurate chronological classification of the building stock. Based on each building's documented year of construction, the structures were categorized into five historically defined architectural epochs. This temporal classification follows established periodization schemes in Korean architectural history (see Sect. 3.2). The Late Joseon Period (Epoch 1), encompassing buildings constructed in the Early twentieth century, included approximately 60,948 structures, representing Korea's pre-modern architectural heritage. The Modernization Period: Japanese Colonial Period (Epoch 2, Early to mid-twentieth century),

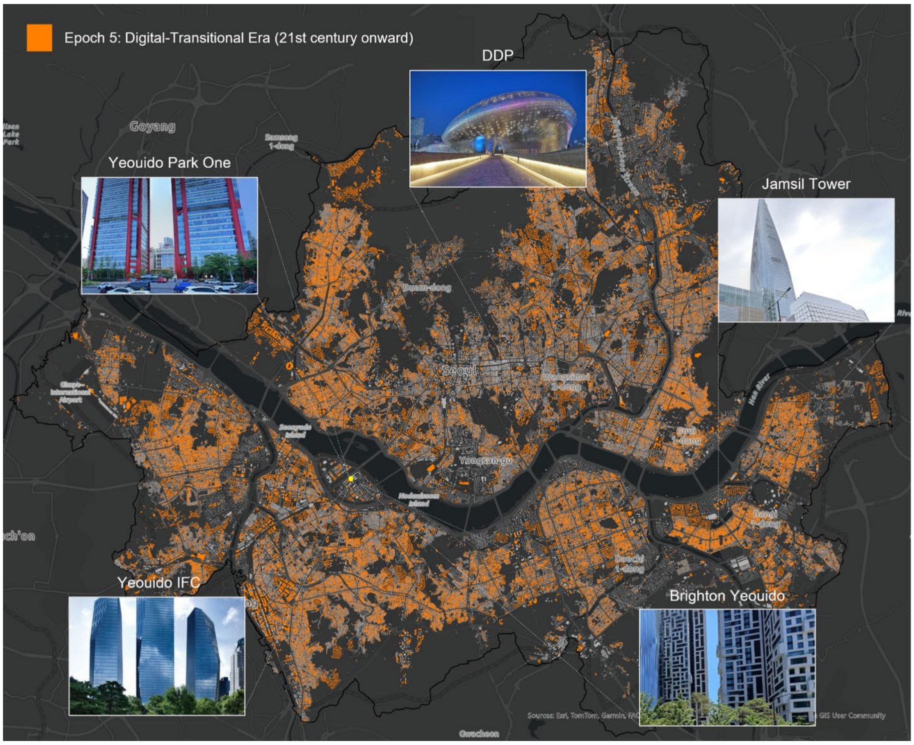


Fig. 6 Spatial distribution of digital-transitional era architecture in Seoul featuring technological innovation and global design trends

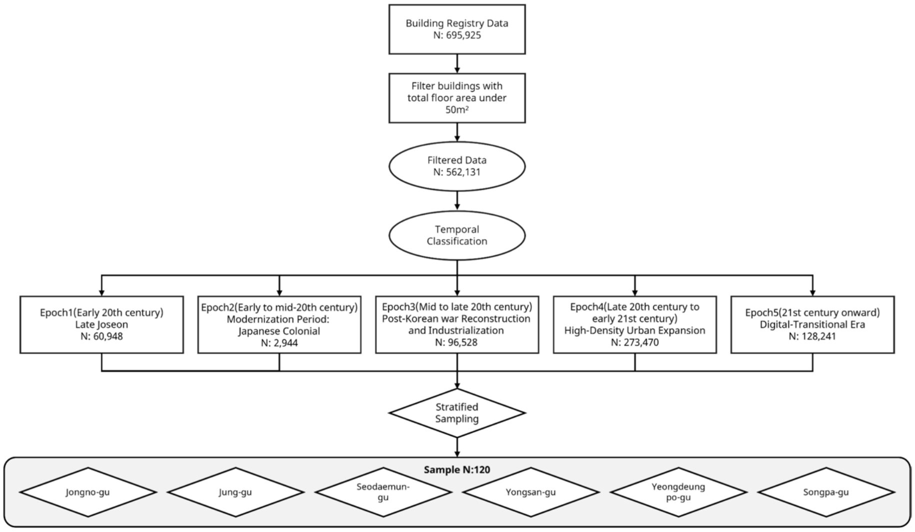


Fig. 7 Sampling workflow and temporal classification of Seoul building dataset

marked by early modernization and Colonial influences, accounted for 2944 buildings. The Post-Korean war Reconstruction and Industrialization Period (Epoch 3, Mid to late twentieth century), comprised 96,528 structures. The High-Density Urban Expansion Period (Epoch 4, Late twentieth century to early twenty-first century), corresponding to rapid economic growth and urban expansion, included 273,470 buildings, forming the largest epochal category. Finally, the Digital-Transitional Era (Epoch 5, twenty-first century onward) reflected ongoing globalization and technological advancements, and comprised 128,241 buildings within the dataset. However, while construction year provided the initial basis for epochal grouping, we acknowledge these categories are heuristic rather than hard boundaries; stylistic transitions in Korean architecture often unfold gradually and overlap across periods, so the classification serves primarily to organize and compare the dataset for analysis rather than to assert discrete historical partitions.

To ensure both temporal and spatial representation, the study employed a stratified sampling strategy for geo-spatial data [6]. This approach enabled the selection of buildings that captured both the architectural heterogeneity within each historical epoch and the geographic diversity across the Seoul metropolitan area, thereby reducing potential sampling bias. Importantly, for each epoch, the district (gu) with the highest relative density of representative buildings was selected using a GIS-based normalization process. Instead of relying solely on the absolute number of structures, we calculated the number of epoch-classified buildings per unit area of each district, thereby ensuring a more accurate identification of spatial concentrations of architectural types. This allowed stratified sampling to be grounded in both temporal and spatial logic.

For field-based photographic documentation, additional pragmatic considerations were incorporated into the sampling design. Recognizing the logistical constraints of completing on-site surveys under consistent environmental conditions (e.g., lighting, weather), the research team conducted preliminary screenings via Google Street View, followed by targeted field visits. Out of the 120 initially identified sites, a total of 111 individual building façades were able to be documented, excluding those that were inaccessible due to demolition, construction, or obstructed street views. Within this framework, six districts were strategically selected: *Jongno-gu, Jung-gu, Seodaemun-gu, Yongsan-gu, Yeongdeungpo-gu,* and *Songpa-gu*. These areas were identified through a GIS-based stratified approach, which prioritized districts with a high concentration of buildings from multiple architectural epochs, alongside practical accessibility and architectural diversity considerations.

Each selected district demonstrated distinctive architectural characteristics reflective of specific historical transitions. *Jongno-gu, Jung-gu,* and *Seodaemun-gu,* located in Seoul's historic core, contained numerous buildings from the Late Joseon and Modernization Period, Japanese Colonial periods. *Yongsan-gu,* particularly neighborhoods like *Itaewon*, was representative of the Post-Korean war Reconstruction and Industrialization period, exhibiting many low-rise brick buildings constructed during the city's mid-20th-century reconstruction. In contrast, *Songpa-gu* and *Yeongdeungpo-gu* offered an abundance of structures from the High-Density Urban Expansion Period and Digital-Transitional Era, including mid- to high-rise residential and commercial typologies.

Priority during site selection was given to buildings with well-preserved and visually distinct façade characteristics, particularly those with unobstructed street-level visibility suitable for image-based analysis. Each selected building was validated through cross-referencing with official municipal records, architectural databases, and satellite imagery to ensure historical accuracy and sufficient visual quality.

This dual-layered sampling framework—structured by both temporal epochs and spatial zones, and filtered by both data quality and practical access conditions—ensured that the resulting photographic dataset was robust and accurately reflected the historical development of architectural façades and the morphological diversity of Seoul's built environment.

4.2 Data collection protocol

A standardized photography protocol was implemented by the research team at Yonsei University to ensure consistency in image capture across all samples. The protocol employed a Fujifilm X-T30 camera with a 23 mm f/2 lens, and high-specification mobile devices (iPhone 15 Pro) to document building façades under controlled conditions. Each selected building was photographed at three standardized viewing distances:

- Close distance: 10–15 m from façade
- Mid distance: 20–30 m from façade
- Far distance: 40–60 m from façade

All photographs were captured from a fixed camera height of 1.5 m (approximating average adult eye level) and under consistent lighting conditions (mid-day diffuse illumination). Images were framed to minimize visual obstructions and maintain consistent perspective and scale across samples to facilitate comparative analysis. Whilst 111 building façades were documented, due to ‘noise’ in the image field from non-target façade related objects (such as people, power lines, cars, or other obfuscating objects in the field of view), the final dataset was further refined down (see limitations for a discussion on the difficulties in examining visual stress within urban contexts). The final dataset comprised 77 images from 26 separate building façades distributed across five epochs and three viewing distances (see breakdown of images per epoch in Table 2).

4.3 Computational visual stress analysis

This study employs the Visual Stress Analysis tool (ViStA) to quantitatively assess the potential visual discomfort associated with architectural façades. ViStA is a computational instrument, developed at the University of Cambridge, that measures visual stress through the evaluation of multiple parameters: visual angle (measured as the angle subtended at the eye), spatial frequency (defined as the reciprocal of the grating period expressed in angular terms), duty cycle (the proportion of the cycle during which elements are bright), and contrast (calculated as the luminance difference between bright and dark elements expressed as a proportion of their luminance sum) [43].

The theoretical foundation of ViStA is grounded in Fourier analysis principles, which demonstrate that any image can be decomposed into spatially defined waves with varying wavelengths, amplitudes, orientations, and phases. This methodological framework operates on the premise that visual discomfort in built environments can be predicted through analysis of these spectral components, as discomfort arises from the human visual system’s enhanced sensitivity to specific spatial frequencies and unnatural contrast energy distributions across these frequencies [43].

Table 2 Visual stress metrics by architectural epoch

Epoch	Average ($\times 10^8$)	Peak ($\times 10^9$)	Images	Buildings
Epoch 1 (late Joseon period)	6.93	4.48	15	5
Epoch 2 (modernization period: Japanese colonial period)	8.59	5.45	15	5
Epoch 3 (post-Korean war reconstruction and industrialization period)	8.24	6.35	14	5 (one image deleted)
Epoch 4 (high-density urban expansion)	8.46	6.42	15	5
Epoch 5 (digital-transitional era)	9.47	5.74	18	6
			n = 77	n = 26

The ViStA methodology employs an advanced algorithm that segments each façade image into overlapping squares rather than analyzing a single central region. Each square represents a two-degree visual field approximating the high-acuity foveal region of the retina [51]. The squares overlap by 50% to ensure that spatial features spanning multiple regions are appropriately captured and analyzed. This segmentation approach enables determination of peak stress scores and generation of relative heat maps based on highest to lowest stress values, providing significant diagnostic capability for identifying the most problematic visual stress elements within architectural compositions.

Each segmented square undergoes analysis using an algorithm established by Penacchio and Wilkins [43], which evaluates the deviation of the image's spatial luminance content from natural scene statistics. These deviations have been empirically linked to subjective expression of visual discomfort and objective measures of neurophysiological responses [28]. The analysis generates several key metrics:

- Peak Visual Stress: Maximum deviation from natural image statistics at any location within the façade, indicating concentrated luminance contrast energy at specific spatial frequencies that may trigger visual discomfort.
- Average Visual Stress: Overall strength of luminance contrast energy across frequencies throughout the entire façade, with elevated values implying higher predicted cortical response and potential visual stress.
- Coefficient of Variation (CoV): Variability in contrast energy distribution across the façade, with values approaching 1.00 indicating consistently high energy across frequencies.

The tool's reliance on Fourier analysis enables comprehensive assessment of visual stress factors, accounting for the complex interplay of scale, spatial frequency, duty cycle, and contrast in contributing to overall visual experience. By applying ViStA to the Seoul façade dataset, this research quantitatively evaluates and maps the visual stress potential of each architectural façade at the three viewing distances examined, enabling the identification of specific design features and elements that may contribute to visual discomfort and serve as environmental stress triggers in urban contexts.

5 Results

5.1 Visual stress analysis by architectural epoch

The comprehensive analysis of 77 façade images sampled across five architectural epochs revealed variation in predicted visual stress metrics. This broad range of values demonstrates significant diversity in visual stress potential across Seoul's architectural landscape. The "Average" ViStA metric was selected as the primary outcome measure based on its established validation in the literature as a predictor of visual discomfort. The "Peak" metric is also reported to examine whether highly localized scene elements contribute to discomfort, though this metric lacks empirical validation as a discomfort predictor and should be considered as exploratory.

5.1.1 Statistical analysis of temporal progression

The statistical analysis of the ViStA results reveals a significant relationship between architectural epochs over time and the visual stress manifestation across Seoul's built environment. To examine the temporal progression of visual stress across Seoul's

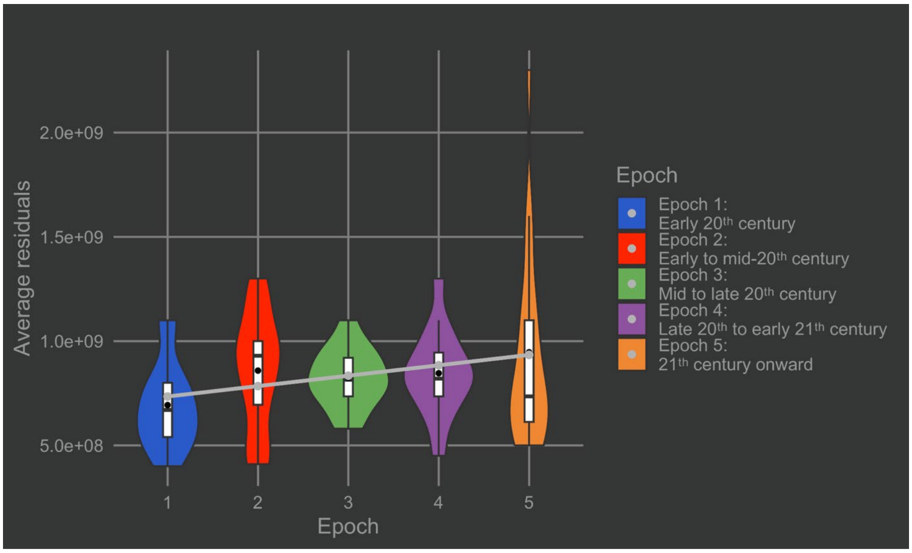


Fig. 8 Violin plots showing the distribution of average residuals across the five historical epochs considered, with superimposed boxplots (*white*) and mean points (*black*). Each plot illustrates the density estimation of the data for a given epoch. The *boxplots* indicate the interquartile range (IQR), with the *horizontal line* marking the median. Whiskers extend to the most extreme data points within 1.5 × IQR, and outliers are not displayed. The *grey line* shows the fitted linear regression (with predicted values, *grey dots*) across epochs, highlighting the temporal trend. *Colours* indicate epoch identity as per Figs. 1–6

Table 3 Visual stress metrics by viewing distance (all buildings, n = 77)

Distance	Average ($\times 10^8$)	Peak ($\times 10^9$)	n
Close	8.14	5.80	26
Mid	9.06	5.29	26
Far	7.93	5.97	25

architectural development, a geometric mean analysis was conducted on the average visual stress values, with data undergoing logarithmic transformation ($\log_{10}$) to normalize the distribution, followed by calculation of the mean log values for each epoch (see Table 2). The antilog transformation (10^mean log values) provided geometric means that were plotted against epochal temporal progression, revealing a clear temporal trend with $R^2 = 0.73$, indicating that 73% of the variance in visual stress can be explained by epochal progression. This demonstrates a statistically significant increase in average visual stress levels over time among the buildings examined (Fig. 8).

The linear models were further analysed to examine the average measured visual stress by epoch and by viewing distance. Model 1 (average ~ epoch) had the lowest AIC (218.83) and significantly outperformed the null model in a likelihood ratio test ($p = 0.030$). Including 'distance' and the interaction term in models 2 and 3 did not improve the fit (AICs = 221.70 and 219.72; LRT ps = 0.57 and 0.050).

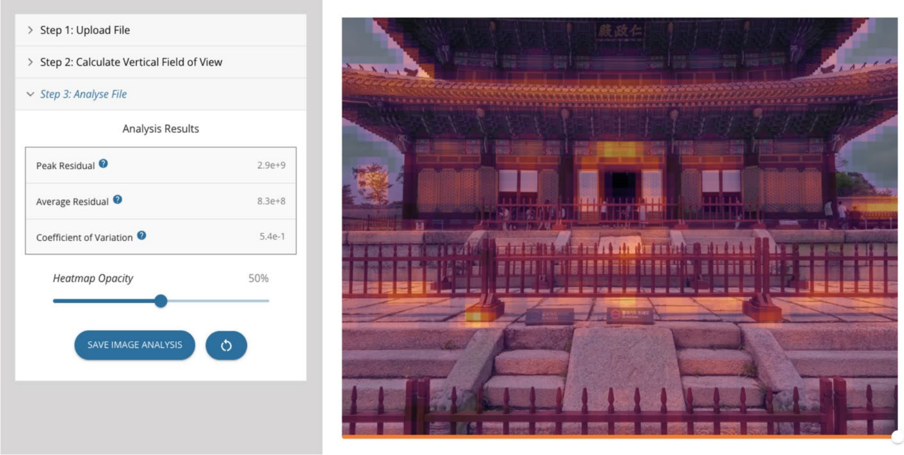
These results indicate that average residuals vary systematically with epoch, suggesting a possible temporal trend in the data, however the relatively small sample size warrants caution in interpretation (Table 3).

5.2 Visual stress analysis by viewing distance

Viewing distance analysis reveals a complex relationship between observer proximity and the visual stress potential of the façades examined. Far viewing distances produce

Table 4 Epoch 1 (late Joseon)

Distance	Average (×10^8)	Peak (×10^9)	n
Close	8.40	4.22	5
Mid	7.16	4.62	5
Far	5.24	4.60	5



Analysis Results

Peak Residual	2.9e+9
Average Residual	8.3e+8
Coefficient of Variation	5.4e-1

Heatmap Opacity 50%

Fig. 9 Epoch 1_Mid distance

Table 5 Epoch 2 (modernization period: Japanese colonial period)

Distance	Average (×10^8)	Peak (×10^9)	n
Close	8.22	3.62	5
Mid	9.54	5.32	5
Far	8.00	7.40	5

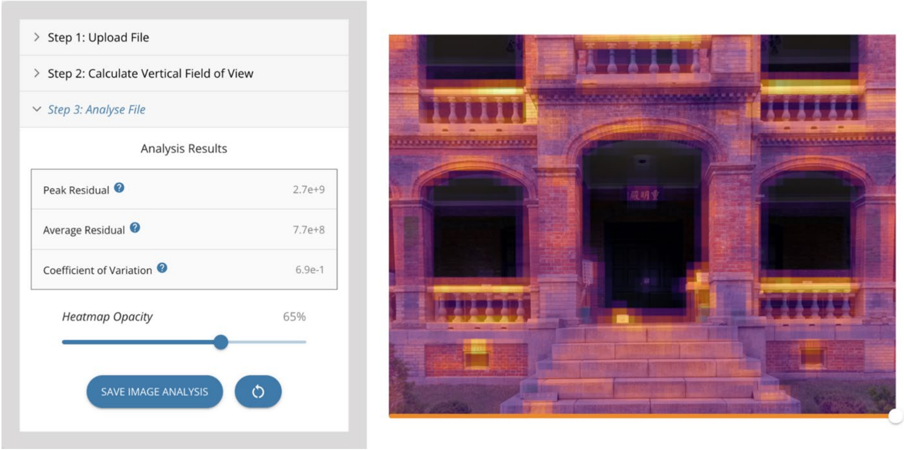
the highest peak visual stress (5.97×10^9) and greatest variability (CoV = 0.996), suggesting that accumulated visual complexity from multiple façade elements may amplify stress indicators when buildings are viewed in their broader urban context. Mid-distance viewing demonstrates the highest average visual stress (9.06×10^8) with relatively low variability (CoV = 0.829), indicating consistently elevated overall visual complexity at intermediate viewing ranges. This finding suggests a critical viewing distance where façade details are clearly perceivable but potentially more visually overwhelming. Close viewing distances show intermediate peak stress levels (5.80×10^9) with low variability (0.840), potentially reflecting the dominance of individual architectural elements over systematic patterns at near viewing ranges (Table 4).

5.3 Detailed epoch-distance interaction analysis

5.3.1 Visual stress metrics by epoch and viewing distance

Traditional architecture demonstrates relatively consistent peak stress across viewing distances, with far viewing showing the greatest variability (CoV = 1.152), potentially reflecting areas of concentrated ornamentation and detail characteristic of traditional Korean building practices (Fig. 9; Table 5).

The Colonial period exhibits dramatic distance-dependent effects, with far viewing producing the highest peak stress levels (7.40×10^9) observed across any epoch-distance combination. This pattern suggests that systematic fenestration patterns and regularized



Analysis Results

Peak Residual 2.7e+9

Average Residual 7.7e+8

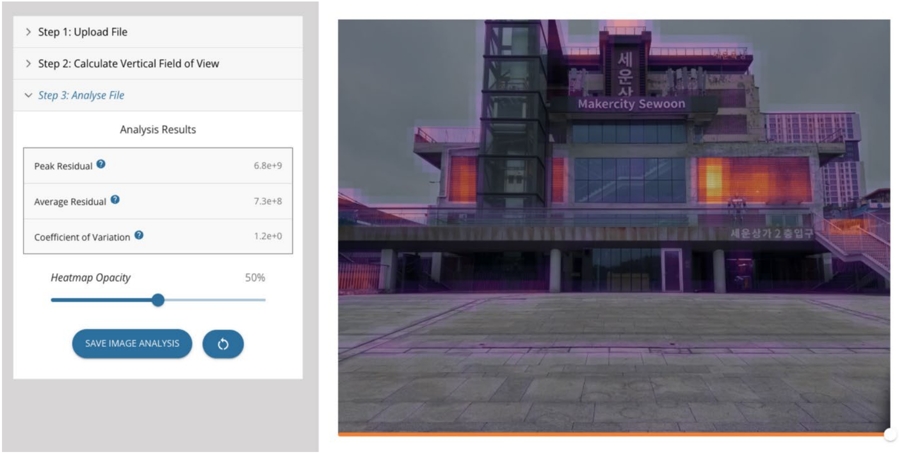
Coefficient of Variation 6.9e-1

Heatmap Opacity 65%

Fig. 10 Epoch 2_Close distance

Table 6 Epoch 3 (post-Korean war reconstruction and industrialization period)

Distance	Average (×10^8)	Peak (×10^9)	n
Close	8.18	8.34	5
Mid	8.64	4.70	5
Far	7.80	5.92	4



Analysis Results

Peak Residual 6.8e+9

Average Residual 7.3e+8

Coefficient of Variation 1.2e+0

Heatmap Opacity 50%

Fig. 11 Epoch 3_Mid distance

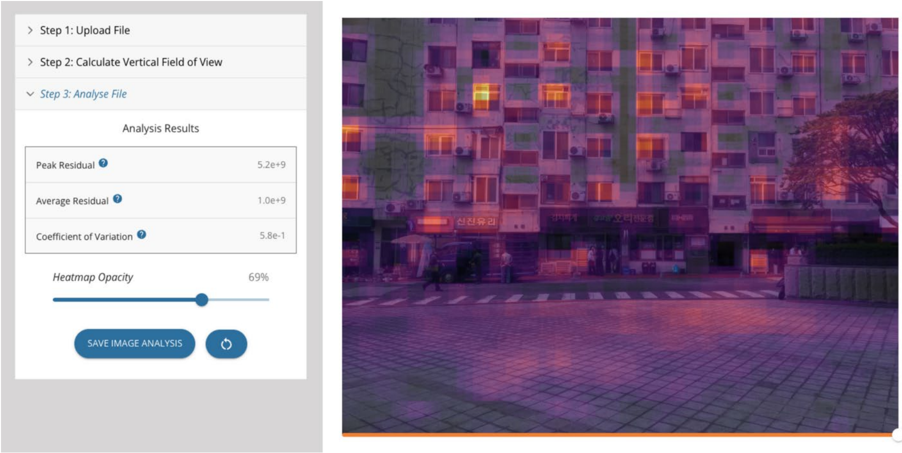
compositions characteristic of this period create cumulative visual stress effects at urban viewing scales (Fig. 10; Table 6).

Post-war reconstruction architecture demonstrates the highest close-viewing peak stress (8.34×10^9) when compared with other epochs examined, potentially reflecting the utilitarian design approaches and repetitive building elements characteristic of the rapid reconstruction efforts and economic constraints at the time (Fig. 11; Table 7).

The High-Density Urban Expansion period exhibits the highest close-viewing peak stress (8.64×10^9) of any epoch, suggesting that changes in architectural design during this period may have inadvertently maximized visual stress through complex geometric arrangements and high-contrast material applications enabled by industrialised construction technologies and prefabrication processes at the time (Fig. 12; Table 8).

Table 7 Epoch 4 (high-density urban expansion)

Distance	Average ($\times 10^8$)	Peak ($\times 10^9$)	n
Close	8.84	8.64	5
Mid	8.18	5.00	5
Far	8.36	5.62	5



Analysis Results

Peak Residual 5.2e+9

Average Residual 1.0e+9

Coefficient of Variation 5.8e-1

Fig. 12 Epoch 4_Mid distance

Table 8 Epoch 5 (digital-transitional era)

Distance	Peak ($\times 10^9$)	Average ($\times 10^8$)	CoV	n
Close	4.43	7.25	0.872	6
Mid	6.55	11.32	0.895	6
Far	6.23	9.83	0.958	6

Contemporary architecture demonstrates substantially reduced close-viewing stress compared to Epochs 3–4, but elevated mid and far-distance metrics. The highest average visual stress at mid-distance (11.32×10^8) across all measurements suggests that contemporary façade systems create highly complex visual environments that are particularly challenging at intermediate viewing ranges (Fig. 13).

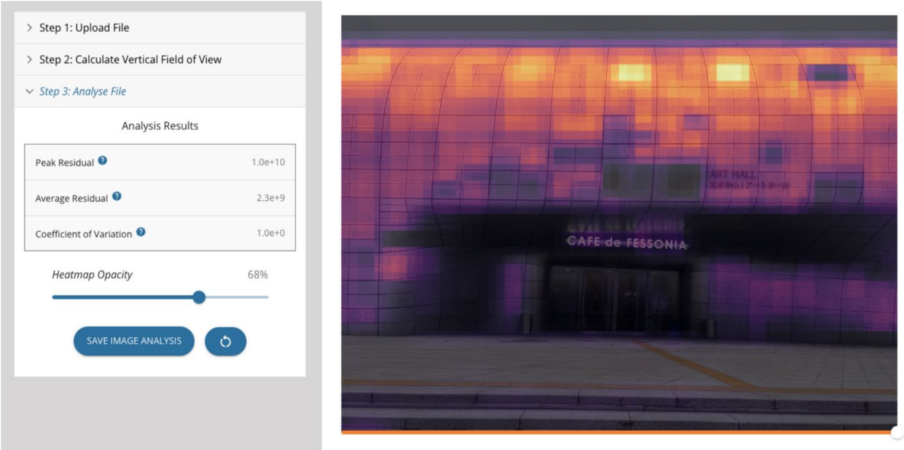
6 Discussion

6.1 Epochal analysis of visual stress morphologies in Seoul's architectural taxonomy

6.1.1 Epoch 1 (late Joseon)

Traditional Korean architectural typologies exhibit distinctive neurophysiological stress signatures, notably characterized by irregular ("stochastic") material distributions and compositional heterogeneity. Here, "stochastic material distributions" refers to the organic, non-repetitive arrangement of building materials—such as timber, clay, and tile—resulting from hand-crafted construction methods and the use of natural materials. Rather than following strict geometric order or modular repetition, these materials are placed in ways that appear irregular and varied, producing subtle asymmetries and a rich diversity of textures across the façade.

It is important to note that most existing examples of traditional Korean architecture, including prominent sites like the Gyeongbokgung Palace, are in fact reconstructions of late Joseon typologies. These reconstructions often combine traditional materials and



Analysis Results

Peak Residual 1.0e+10

Average Residual 2.3e+9

Coefficient of Variation 1.0e+0

Heatmap Opacity 68%

Fig. 13 Epoch 5_Mid distance

craftsmanship with modern techniques and materials introduced during restoration processes, resulting in façades that blend historical construction logic with contemporary restoration practices.

The epochal data for the Late Joseon period demonstrates the highest overall coefficient of variation (CoV = 0.947), with pronounced amplification of variability at extended viewing distances (CoV = 1.152). This empirical finding supports established architectural discourse on the prevalence of subtle asymmetries and organic variations and the dominance of non-uniform patterns that contribute to significant textural richness in traditional Korean architecture [11, 14, 22, 41]. These qualities distinguish traditional Korean façades from those characterized by systematic repetition or geometric regularity, and are thought to underlie their unique visual effects.

The consistency of peak visual stress metrics across scalar viewing conditions (Close: 4.22×10^9, Mid: 4.62×10^9, Far: 4.60×10^9) indicates consistent distribution of visual stimuli rather than concentrated luminance energy accumulation at discrete focal points. Such a distribution pattern implies that the viewer's visual attention is not drawn to any single dominant element, but instead is more evenly engaged across the architectural field. This phenomenon reflects compositional strategies characterized by harmonic equilibrium, consistent with traditional Korean architectural principles emphasizing "harmony with natural surroundings" [40]. At proximate viewing ranges, discrete structural elements—including pronounced eave details and exposed timber columnar systems—dominate the visual field, while at extended distances, roofline configurations and regular striations (as observed in roofing tiles) were visually pronounced. This scale-dependent activation of architectural elements encourages a sequential, exploratory way of seeing and experiencing the façade [53]. In effect, traditional vernacular construction methods—by employing balanced asymmetry and proportions at scales that respond to different viewing distances—appear to elicit less visual discomfort.

The stability of visual stress distribution across viewing distances substantiates how non-uniform surface textures and irregular materiality promote perceptual richness, while maintaining neurophysiological coherence. These findings suggest that traditional Korean façade systems support neuroaesthetic efficacy through their statistical alignment with natural scene spectral characteristics.

6.1.2 Epoch 2 (modernization period: Japanese colonial period)

The Modernization Period: Japanese Colonial Period (early to mid-twentieth century) exhibits pronounced distance-dependent visual stress, which appears to be linked to the adoption of Westernised façade styles and the introduction of standardized, uniformly structured building designs. The systematic building rationalization that occurred during this period through the use of regular, repetitive layouts and standardized components—such as uniform window arrangements and modular structural systems—creates façades that are highly orderly, efficient, and demonstrate a high degree of visual uniformity. Both peak visual stress metrics (5.45×10^9) and average stress indicators (8.59×10^8) for the buildings examined from this period demonstrate significant elevation in visual stress relative to Epoch 1, indicating that regularized and repetitive façade compositions contribute to heightened neurophysiological stimulation through increased deviation from natural scene statistics (as described in Sect. 3.1).

The most significant finding for this epoch emerges in the far-distance peak stress measurement of 7.40×10^9—representing the maximum singular value across all epochal-scalar combinations. This dramatic elevation indicates that, at far viewing distances, a larger portion of each building's façade—and more of its repetitive architectural features—enters the observer's visual field. As the visible volume of the building increases, the cumulative effect of systematic repetition across the façade becomes more pronounced, resulting in amplified visual stress. At mid-range viewing distances, the façades show a high average level of visual stress (9.54×10^8), and this stress is distributed quite evenly across the entire surface (as indicated by the lower coefficient of variation, 0.806). Due to the repetitive patterns used in the façade design, the visual intensity is relatively consistent across the visual field, rather than being concentrated in specific areas.

Rather than exhibiting visual elements characterized by intense fluctuations across discrete surface areas, these façades maintain uniform repetitive patterns—systematically spaced fenestration, horizontal coursing elements, and structural articulations—that attenuate localized stress concentrations while augmenting potential for cumulative cognitive fatigue through the elimination of visual variation and perceptual relief mechanisms. Proximate viewing conditions prioritize material surface textures and ornamental detailing. Mid-distance observations emphasize repetitive fenestration systems, belt coursing, and cornice elements. While at extended viewing distances, systematic patternation of architectural elements becomes apparent.

Principal architectural characteristics include the integration of Western façade syntax (such as pediments, entablatures, and cornices) and the Japanese Jōbō (条坊制) urban grid systematization. While the Jōbō system originally referred to the rigid orthogonal urban planning framework derived from Tang-dynasty Chang'an, its influence extended to architectural design through the standardization of building plots and façade alignments. This spatial rationalization reinforced visual regularity and rhythmic repetition, which, under macro-scale urban viewing conditions, may have amplified perceptual uniformity and potential visual stress.

6.1.3 Epoch 3 (post-Korean war reconstruction and industrialization period)

Amongst the Post-war reconstruction architectural typologies, the highest close-viewing peak stress (8.34×10^9) of all epochal categories was observed. The building façades examined reflect utilitarian design methodologies and repetitive building element configurations characteristic of the accelerated post-war reconstruction efforts and severe economic constraints and material shortages that occurred during this period. Buildings from this period represent low-cost, rapidly constructed structures designed to address acute post-war housing deficits. They are characterized by simplified masonry construction, repetitive rectangular fenestration patterns, and utilitarian compositions with minimal ornamentation. Due to widespread material shortages at the time—particularly of cement and steel—builders frequently relied on materials such as brick, timber, and corrugated metal. This was especially evident in mixed-use buildings, which often featured ad-hoc signage and irregular extensions, further contributing to the visual heterogeneity of the urban landscape.

As a result of post-war material scarcity and rapid construction processes, many of the buildings of this period are characterised by inconsistencies in fenestration placement, dimensional standardization, and surface finish applications that generated irregular repetitive patterns and localized clusters of visual intensity. A distinctive feature of this period is the high level of visual disorder, referred to as environmental visual entropy, especially noticeable at street level in commercial areas. This is seen in the abundance of signage, crowded merchandise displays, and unplanned architectural changes, all of which contribute to a visually chaotic and complex environment. This phenomenon contributes significantly to proximate-distance visual stress through stratified visual complexity that compounds the stress effects generated by the systematic architectural repetition.

During the sampling process, façades from this period demonstrated ready identification through distinctive features including deteriorated signage systems, and weathered material surface treatments that contributed additional visual complexity that was particularly evident at close-range viewing conditions.

6.1.4 Epoch 4 (high-density urban expansion)

The Post-Industrial developmental period exhibits the highest close-viewing peak stress (8.64×10^9) across all epochs examined. Buildings from this period were characterized by complex geometric configurations and high-contrast material applications enabled by industrialized construction and systematized prefabrication. Mirroring global high-rise housing trends of the 1960s–1970s, Seoul adopted residential elevators as a standard feature, supported by evolving building codes and rapid technological advancement. This shift enabled the proliferation of high-rise mass housing and accelerated vertical densification, which became a defining feature of the city's skyline during this epoch.

Buildings from this period reflect industrialized, state-coordinated approaches to mass housing provision, characterized by prefabricated component assemblages, modular fenestration systems, and highly repetitive façade rhythmic patterns. Although the architectural styles of Epoch 3 and Epoch 4 differ, both periods show similar patterns of visual stress. This suggests that the use of standardized, repetitive modular components—typical of prefabricated construction—can generate visually stressful conditions at close range, no matter the building typology.

The technological sophistication of available materials and construction methodologies during this epoch enabled increasingly complex geometric compositions. However, these advances appear to concentrate rather than attenuate visual stress through the implementation of systematic repetition across multiple architectural scales. The policy-driven shift toward high-rise, elevator-served apartment blocks thus not only transformed the city's morphology but also contributed to the emergence of new façade typologies—marked by verticality, modularity, and repetition—that are closely linked to the observed patterns of visual stress in Seoul's high-density urban expansion.

6.1.5 Epoch 5 (digital-transitional era)

Contemporary architectural production demonstrates complex relationships between technological sophistication and potential visual stress. While peak visual stress metrics in Epoch 5 decreased relative to Epochs 3–4 (5.74×10^9), the observed average visual stress for the buildings examined from this epoch was that highest across all epochal categories (9.47×10^8), indicating distributed rather than concentrated configurations of visual stimuli across entire façade surfaces.

The attenuated peak stress under proximate viewing conditions (4.43×10^9) and relatively reduced coefficient of variation (0.895) indicate restrained surface compositional strategies, yet maximum average stress at mid-distance ranges (11.32×10^8) implies densely concentrated visual fields at intermediate observational distances. This pattern indicates that the contemporary façade designs examined tend to spread visual information evenly across the entire surface, rather than concentrating it in specific areas. As a result, the façade maintains a consistent level of visual complexity throughout. While this approach reduces intense visual focus on any single point, it can still create a sustained sense of visual stress due to the overall density and scale of the visual elements.

Principal architectural characteristics include corporate-architectural aesthetics that include glazing assemblages with extensive reflective and transparent material implementation, high-polish surface treatments selected for premium aesthetic expression and ease of cleaning, digitally derived façade compositions exhibiting high-resolution repetitive patterns, and composite material systems emphasizing visual continuity rather than material contrast articulation.

6.2 Construction technology transitions and material system evolution

6.2.1 Material unit standardization and scalar-dependent perceptual effects

The temporal progression of visual stress characteristics across epochal classifications reveals fundamental relationships between construction technological advancements, material standardization, in architectural environments. Standard material unit dimensions have undergone substantial evolutionary transformation across epochal boundaries, generating distinctive visual stress profiles at differential viewing distances and fundamentally altering the scalar conditions under which visual stress achieves maximum concentration.

Traditional Korean architectural construction employed craft-based fabrication methodologies with variable material dimensional characteristics—timber structural elements, clay wall assembly sections, and individual ceramic roof tile components—that generated organic irregularities perceptible across multiple observational scales. The technological transition toward standardized industrial unit production fundamentally transformed these relationships, with systematic repetition inherent in prefabricated construction methodologies creating regular patterns that demonstrate significant deviation from natural scene statistical distributions.

High-contrast linear architectural elements demonstrate scalar-dependent problematic manifestations, with impact magnitude directly correlated to dimensional characteristics and observational distance parameters. Traditional roof tile striations, for instance, typically achieve visual prominence exclusively at mid-range to extended viewing distances, while systematic fenestration pattern configurations generate cumulative effects that are most pronounced when observed at urban-scale viewing conditions.

6.2.2 Structural system transitions and visual pattern generation

Transformations in structural construction systems—progressing from traditional post-and-beam assemblages through to the use of reinforced concrete and contemporary steel and glazing system integration—have profoundly influenced visual stress characteristics and the ways in which visual stress is manifest in the built environment.

Traditional Korean construction systems, emphasizing natural material variation and craft-based assembly protocols, generated visual environments that demonstrated enhanced alignment with natural scene statistical distributions. Conversely, in the facades examined, industrial construction systems prioritized efficiency optimization and standardization implementation through methods that concentrated visual energy at specific spatial frequency bands, resulting in elevated stress responses particularly at intermediate viewing scales in which systematic patterns achieve maximum perceptual prominence.

The technological shift from craft-based to industrialized construction methodologies fundamentally altered visual stress characteristics, with both post-war reconstruction and post-industrial developmental periods exhibiting markedly elevated peak stress under proximate viewing conditions despite differential architectural intentions. This suggests that the repetition evident in the standardized prefabrication employed in the case study facades examined, appears to consistently generate challenging visual environmental conditions. Based on these findings, there is a need to examine the potential for contemporary architectural production to utilize technology-enabled optimization of the design of the built environment to reduce visual stress characteristics through control mechanisms available via digital design tools and advanced material systems.

6.3 Feature-specific visual stress relationship analysis

The computational analysis reveals that systematic repetition, independent of historical contextual factors, generates cumulative visual stress effects. Colonial period fenestration systematization, post-war modular construction methodologies, and contemporary curtain wall assemblages all demonstrate elevated stress levels when multiple architectural elements undergo simultaneous observation, indicating fundamental relationships between repetitive building element configurations and neurophysiological stress response activation.

Traditional Korean construction systems and organic surface variation configurations demonstrate significant potential for visual stress attenuation through statistical alignment with natural scene spectral characteristics. The balanced asymmetrical compositions and scale-sensitive proportional systems characteristic of traditional construction methodologies generate visual environments that do not appear to challenge human perceptual comfort mechanisms to the same degree as the contemporary façades examined, suggesting a valuable application potential for contemporary design practice integration.

Additionally, the relationship between material contrast and visual stress demonstrates significant variation across construction historical periods.

6.4 Implications for contemporary architectural design practice

The findings of this research present significant implications for contemporary architectural design practice, necessitating a fundamental reconsideration of how material selection and spatial composition contribute to urban visual stress. It is also pertinent to note the marked increase in visual stressors over the past century, as highlighted by Wilkins et al. [57], which may have significant implications for understanding the prevalence and impact of visual discomfort in contemporary populations. Architects must critically evaluate the visual stress implications inherent in standard material dimensions when selecting building components, recognizing that modular repetition patterns may inadvertently concentrate visual energy at problematic spatial frequencies. This evaluation requires the implementation of scale-responsive design strategies that employ hierarchical approaches, acknowledging the distance-dependent activation of visual elements and the need for strategic tailoring of material placement, pattern density, and surface articulation based on anticipated viewing conditions across close, intermediate, and distant observation points.

The selection of construction systems extends beyond conventional architectural and economic considerations to encompass fundamental implications for visual stress, particularly in high-visibility urban contexts where the inherent visual patterning of structural and assembly systems requires careful assessment. Contemporary digital design tools offer unprecedented opportunities for optimizing visual patterns to enhance human comfort while still maintaining the architectural design intent, enabling precise control over visual stress characteristics through technology-enabled pattern optimization. These results indicate that to reduce the visual stress potential of the built environment, design practitioners should actively avoid the systematic design repetition characteristic of industrial construction approaches, particularly within urban contexts where cumulative effects amplify visual stress under macro-scale viewing conditions.

The integration of traditional architectural features, as exemplified by the traditional Korean construction systems and organic surface variations in the case study facades examined, demonstrates significant stress mitigation potential. The potential for material contrast optimization requires the use of advanced gradation techniques—such as functionally graded materials or computationally controlled transitions—that enable smooth, controlled changes between materials or design features, independent of stylistic design considerations. The concept of distance-dependent feature design also emerges as a critical consideration, with different architectural features demonstrating optimal performance at specific viewing distances, suggesting strategic potential for feature selection and arrangement based on anticipated urban context requirements and pedestrian movement patterns. Further research into the targeted application of these approaches to maintain visual interest and effectively manage stress concentrations while deliberately avoiding the abrupt contrasts typical of industrial materials could potentially open up novel approaches to design for wellbeing.

The phenomenon of "corporate aesthetic amplification" associated with high-polish surfaces and large-scale glazing systems was found to contribute to elevated overall visual stimulation. This finding indicates a need for careful balance between aesthetic appearance and neurophysiological comfort, and the development and integration of visual stress assessment protocols into design review processes, particularly for buildings situated in high-density urban environments where cumulative effects are most pronounced and potentially problematic for occupant and pedestrian wellbeing.

6.5 Limitations

This study acknowledges several methodological and contextual limitations that constrain the generalizability and comprehensive applicability of the findings. The reliance on static image analysis is unable to capture the inherently dynamic nature of visual stress experience, which is significantly influenced by movement through space and temporal changes in environmental conditions. The analysis does not account for exposure duration to visual stimuli, a critical factor that can substantially influence physiological and psychological responses to environmental stressors over extended temporal periods.

The controlled lighting conditions under which all photographs were captured, specifically mid-day diffuse illumination, do not account for the substantial variations in lighting conditions throughout diurnal cycles, seasonal changes, or artificial lighting effects that significantly alter visual perception and visual stress characteristics. Additionally, environmental visual noise, including vehicles, signage, street furniture, pedestrians, and other contextual urban elements, was not systematically controlled or analyzed, potentially introducing confounding variables that may obscure façade-specific visual stress measurements.

The study's unisensory assessment approach, focusing exclusively on visual stimuli, does not account for the multisensory environmental experiences that influence overall perceptual comfort, including acoustic, thermal, and tactile factors that contribute to comprehensive environmental stress responses. It should also be noted that the computational methodology employed would be strengthened by validation through subjective assessment studies with human participants to establish direct correlation between predicted stress levels and actual physiological responses. This currently represents a critical gap in empirical validation.

Cultural context specificity presents another significant limitation to transferability, as perceptual preferences and visual stress responses may demonstrate substantial variation across different cultural populations. The study's Seoul-specific urban context potentially limits the generalizability of findings to other urban environments and cultural contexts with different architectural traditions. Additionally, the standardization of viewing angles through fixed camera height (1.5 m) and standardized distances does not account for varying observer heights, mobility conditions, or the dynamic viewing angles experienced in authentic real-world observation conditions.

The temporal epoch classification of facades in this study inherently involves a degree of subjective assessment. Architectural transitions rarely occur along strict chronological boundaries; instead, they manifest gradually as overlapping shifts in styles, technologies, and material systems. Some buildings are classified within Epoch 2 despite being completed before 1900, based on their architectural language and historical association with Korea's early modernization. Similarly, distinguishing Epoch 3 from Epoch 4 is complicated by extensive renovations and modifications that blur the line between the original construction period and its current architectural expression. Sample size constraints, with 77 façade images distributed across five epochs and three viewing distances, may limit statistical power for certain epoch-distance combinations, particularly in relation to detecting subtle but potentially significant effects.

Furthermore, the data collection under consistent weather conditions does not account for how seasonal changes, precipitation, atmospheric conditions, and varying sky conditions affect visual perception and stress characteristics. The analysis does not capture interior-to-exterior viewing conditions or consider how visual stress manifests for building occupants looking outward through façade systems, representing a significant gap in comprehensive environmental assessment. Additionally, contemporary digital display technologies, LED lighting systems, and dynamic façade elements were not systematically analyzed despite their increasing prevalence in urban visual environments.

Individual susceptibility variations present a critical limitation, as the study does not account for individual differences in visual stress susceptibility. Research indicates that approximately 10% of the population demonstrates heightened sensitivity to visual stress, with increased prevalence observed in neurodiverse populations. Finally, while the ViStA computational tool provides objective metrics, further validation is required that incorporates neurophysiological measurements, including haemodynamic responses and pattern glare assessments, conducted under real-world environmental conditions to establish more robust clinical and practical validity.

7 Conclusion

This computational analysis of architectural façade design features across Seoul's built environment establishes that specific design characteristics, rather than historical periodization, constitute the primary determinants of visual stress in urban contexts. Through systematic application of the Visual Stress Analysis tool (ViStA) to 77 images of 26 building façades distributed across five architectural epochs and three viewing distances, this research demonstrates that particular material configurations, compositional strategies, and construction methodologies generate distinct neurophysiological response patterns independent of their temporal origins or stylistic classifications.

The empirical findings reveal fundamental relationships between architectural design elements and human visual comfort that transcend conventional historical categorizations. Traditional Korean architectural features—characterized by stochastic material distributions, craft-based dimensional variability, and balanced asymmetrical compositions—demonstrate greater alignment with natural scene statistical properties, consistently producing the lowest visual stress measurements (4.48×10^9) of all the facades across the epochal classifications examined. Conversely, systematic fenestration and regularized architectural compositions, regardless of their historical implementation context, were found to generate cumulative visual stress amplification effects particularly pronounced at urban observational scales, with peak measurements reaching 7.40×10^9 when multiple regularized elements underwent simultaneous observation.

The identification of high-contrast material juxtapositions combined with complex geometric configurations as the most neurophysiologically challenging architectural feature category—generating maximum peak visual stress measurements of 8.64×10^9—provides critical evidence that technological complexity in construction and design can inadvertently maximize rather than mitigate visual stress through concentration of visual energy at problematic spatial frequencies. This finding challenges conventional assumptions regarding architectural advancement and human comfort, suggesting that parametric manipulation, geometric form, and material standardisation require careful neurophysiological consideration to avoid creating regular patterns that challenge efficient neural processing mechanisms.

Contemporary digital design methodologies offer the potential for evidence-based optimization of visual stress characteristics while simultaneously presenting risks for stress amplification through systematic implementation of problematic visual stress pattern configurations. The highest average visual stress measurements (9.47×10^8) that were observed among the contemporary architectural facades examined, concurrent with reduced peak stress events, indicate that advanced computational design tools enable more nuanced control over visual stress distribution but require informed application to achieve neurophysiological optimization rather than creating sustained cognitive tension through refined architectural complexity.

The scalar-dependent activation of different architectural features across viewing distances provides crucial insights for urban design practice, revealing that visual stress manifestations vary significantly based on observational proximity and urban contextual conditions. The dramatic distance-dependent effects observed in systematic fenestration patterns, particularly the cumulative stress amplification at extended viewing distances, demonstrate that architectural design decisions have implications beyond individual building performance, potentially contributing to broader urban visual environmental quality and public health outcomes.

These findings establish a robust methodological framework for integrating neurophysiological considerations into architectural design practice, foregrounding feature-based identification of potential visual stressors rather than relying solely on aesthetic or functional evaluation criteria. While our Fourier-based ViStA analysis demonstrates utility for quantifying façade-related visual stress at the city scale across historical epochs, the present study does not evaluate its application for design decision-making during the design process. Rather, we introduce this possibility here for future work; our primary contribution is an urban-scale assessment of façades over time, establishing an objective basis from which subsequent design-stage tools might be developed.

The research contributes significantly to emerging discourse on architecture and public health by providing quantitative evidence that specific architectural design elements function as active agents in shaping neurophysiological responses rather than passive environmental backdrops. The identification of features that demonstrate comparatively reduced visual stress metrics, including organic surface variations and balanced asymmetrical compositions, alongside higher visual stress systematic patterns, offers practical guidance for contemporary practice so that designers can selectively integrate human-centric design characteristics while avoiding potentially harmful features, regardless of their historical or technological origins.

Future research trajectories should extend this methodological approach to diverse urban contexts beyond Seoul's specific developmental trajectory, validate computational predictions through human subject studies incorporating physiological measurements, and investigate the temporal dynamics of architectural visual stress through longitudinal assessments of urban contextual transformations. The development of real-time computational assessment tools integrated into architectural design software represents a promising direction for embedding neurophysiological considerations into standard practice workflows.

As urban populations continue to expand and architectural environments become increasingly complex, evidence-based approaches to visual comfort in the built environment will become essential for supporting human health and wellbeing in cities. The potential demonstrated by contemporary architecture to optimize rather than compromise human perceptual comfort through technology-enabled pattern control represents a significant opportunity for future practice that integrates computational advancement with neurophysiologically-informed design principles. This research establishes foundational evidence that changes in architectural design, material use, and construction technologies and practices over time have impacted on the visual stress potential of facades within Seoul, resulting in a heightened overall visual stress potential of the built environment. These finding raise considerable questions about the impact of current design practices on wellbeing. Developing a better understanding of the neurophysiological ramifications of design decisions is an important first step in developing design practices that better support human health and cognitive wellbeing.

Acknowledgements
The authors gratefully acknowledge Tom Bashford, Bruce Beckles and Yi Chen Hock for their contributions to the development and conceptualization of the ViStA tool, (Version 2023, Cambridge, UK) which supported key aspects of this study's analysis. Their insights and technical expertise were instrumental in shaping the framework for visual stress assessment. Thank you to the Addenbrooke's Charitable Trust for supporting the development of the ViStA tool. Thank you to the Humanise Campaign for supporting this research. The authors also thank Professor Koen Steemers and Professor Dongwook Sohnfor their ongoing support and guidance throughout the course of this research.

Author contributions
Conceptualization, C.V.; methodology, C.V., L.S., A.J.W., H.M., O.P. and I.H.; validation, C.V., H.M. and I.H.; formal analysis, C.V., H.M., O.P., I.H. and A.J.W.; field data collection, U.J., K.C., D.L., K.O. and S.K.; GIS analysis, U.J., K.C., D.L., K.O. and S.K.; GIS figures, U.J., K.C., D.L., K.O. and S.K.; statistical analysis and figures, O.P.; writing—original draft preparation, C.V. and L.S.; writing—review and editing, C.V., L.S., H.M., A.J.W., O.P., I.H., U.J., K.C., D.L., K.O. and S.K.; project administration, C.V.; funding acquisition, C.V. All authors have read and agreed to the published version of the manuscript.

Funding
This research was funded by the ***Humanise Campaign***. The funder had no role in the study design, data collection, analysis, interpretation, or the writing of the manuscript. The views expressed are solely those of the authors and do not necessarily reflect those of the funding organisation.

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

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing Interests
The authors declare no competing interests.

Received: 1 July 2025 / Accepted: 25 November 2025

References

1. Bilgic N, Ebbini GW. Balancing complexity and restoration in virtual interior environments: user perceptions of organized complexity in biophilic design. Archnet-IJAR Int J Archit Res. 2024;18(4):895–913.
2. Campagna M, Chamberlain R. How material sensory properties and individual differences influence the haptic aesthetic appeal of visually presented stimuli. Sci Rep. 2024;14(1):13690.
3. Chatrian GE, Lettich E, Miller LH, Green JR. Pattern-sensitive epilepsy. I. An electrographic study of its mechanisms. Epilepsia. 1970;11(2):125–49. https://doi.org/10.1111/j.1528-1157.1970.tb03876.x.
4. Cho J. A study on the building shape composition and efficiency of super high-rise office architecture. Journal of the Architectural Institute of Korea–Planning. 2007;23(6):33–40.
5. Cho J-H, Ha B-K, Lee J-J, Nam I-Y. A study on historical and architectural value for the preservation of modern architecture: focused on the Walker House in Busan. J Basic Des Art. 2022;23(1):511–22.

6. Choi J-K, Kim J-Y, Seo G-S. Characteristics of architectural façade color series in cultural urban regeneration areas. J Korean Soc Living Environ Syst. 2018;25(5):541–54.
7. Connellan K, Gaardboe M, Riggs D, Due C, Reinschmidt A, Mustillo L. Stressed spaces: mental health and architecture. HERD Health Environ Res Des J. 2013;6(4):127–68.
8. Cucuzzella C, Rahimi N, Soulikias A. The evolution of the architectural façade since 1950: a contemporary categorization. Architecture. 2023;3(1):1–32. https://doi.org/10.3390/architecture3010001.
9. Diener AC, Hagen J. Geographies of place attachment: a place-based model of materiality, performance, and narration. Geogr Rev. 2022;112(1):171–86. https://doi.org/10.1080/00167428.2020.1839899.
10. Ezz MS, Odah E, Baharetha S, Al Sayed AAKA, Salem DA. Analytical examination of dynamic elements in modern architectural facades for advanced structural aesthetics. Front Built Environ. 2024;10:1302380.
11. Gelézeau, V. (2007). Korean modernism, modern Korean cityscapes, and mass housing development: charting the rise of Ap'at'u tanji since the 1960's. Korea: politics, economy and society yearbook, 165-192.
12. Gibson JJ. The ecological approach to visual perception: classic edition. Psychology Press; 2014.
13. Hamilton GA, Lown J, Littman DM. Embodying place: embodied geographic methods as a method-in-development. Qual Soc Work. 2025. https://doi.org/10.1177/14733250251352909.
14. Hong J, Yoon J. A study on intrinsic nature of architectural materials displayed in traditional Korean-style house. J Basic Des Art. 2009;10(6):469–77.
15. Ingold T. Culture on the ground: the world perceived through the feet. J Mater Cult. 2004;9(3):315–40.
16. Ingold T. The perception of the environment: essays on livelihood, dwelling and skill. Routledge; 2021.
17. Jang Y-M. A study on the compositional elements of contemporary high-rise architecture (Doctoral dissertation, Hanyang University). 2023.
18. Jeon H, Cho H. A study on the design priority analysis of apartment façade elements using AHP. J Archit Inst Korea Plan Design. 2005;21(7):49–56.
19. Jeon H-J. A study on the design priority of façade design elements in apartment buildings. Kor Architects. 2006;9:82–7.
20. Jeong C, Yang C, Lee S, Ko J, Baek H. A study on the characteristics of elevation color and image of apartments in Seoul. In: Proceedings of the Korean Society of Color Studies Conference, 2019. p. 108–111.
21. Jelić A, Tieri G, De Matteis F, Babiloni F, Vecchiato G. The enactive approach to architectural experience: a neurophysiological perspective on embodiment, motivation, and affordances. Front Psychol. 2016;7:481.
22. Jo J, Lim H, Jeon J. A case study on elevation design applied to façades of high-rise residential buildings. J Archit Inst Korea Plann Des. 2011;27(3):99–108.
23. Jung I. Architecture and urbanism in modern Korea. University of Hawaii Press; 2013.
24. Kaplan R, Kaplan S. The experience of nature: a psychological perspective. Cambridge University Press; 1989.
25. Kim, S. J. (2013). Utilization of modern architectural cultural heritage in Korea as museums and exploration of alternatives (Master's thesis). Interdisciplinary Program in Cultural Heritage Studies, Graduate School, Korea University, Seoul, Republic of Korea.
26. Kim D, Yang S. An empirical study on façades of non-residential urban Hanok using user affective evaluation and rough set theory: focused on non-residential Hanok in Ikseon-dong preservation area. J Urban Des Inst Korea. 2022;23(6):37–52.
27. Kim HS. Architectural context and significance of Swoo-Geun Kim's New Ward at the Former Soo-Do Medical College Hospital, 1963–1965. J Archit Inst Korea. 2025;41(3):171–80.
28. Kim J-Y, Kim S-W, Jeon Y-C. A study on the constructional characteristics of porous exterior skins in contemporary architecture. Proc Annual Conf Architect Inst Korea. 2015;35(1):181–2.
29. Kim M-J. A socio-historical perspective on the formation background and housing culture of the urban poor in Korea: from collective migration villages after the Korean War to the new urban poor after the financial crisis. J Korean Housing Assoc. 2007;18(4):79–88.
30. Kim MS. A study on the characteristics of architectural facade expression designed by Kim Han-sup in the 1950's to 1960's. J Reg Assoc Archit Inst Korea. 2019;21(6):119–28.
31. Kirsch W, Kunde W. On the role of interoception in body and object perception: a multisensory-integration account. Perspect Psychol Sci. 2023;18(2):321–39.
32. Le ATD, Payne J, Clarke C, Kelly MA, Prudenziati F, Armsby E, et al. Discomfort from urban scenes: metabolic consequences. Landsc Urban Plann. 2017;160:61–8. https://doi.org/10.1016/j.landurbplan.2016.12.003.
33. Lee G, Kim S. Case study of mass customization of double-curved metal façade panels using a new hybrid sheet metal processing technique. J Constr Eng Manag. 2012;138(11):1322–30.
34. Lee J-Y. Hyangyang-cheolchoong characteristics and meanings found in the interior facades of palaces during the Japanese Colonial period: focused on Daejojeon and Huijeongdang in Changdeokgung Palace. J Kor Inst Interior Des. 2024;33(6):31–44.
35. Lee MJ. Design history: constructing a Korean identity in New Gwanghwamun Square. Habitat Int. 2023;138:102873.
36. Lee S. A study on the trends for expression in Korean contemporary architectural facade design: focusing on large buildings in the City Center. Buildings. 2021;11(7):274.
37. Lee S. A study on the trends for expression in Korean contemporary architectural facade design: focusing on large buildings in the City Center. Buildings. 2021;11(7):274.
38. Lee SH. A study on the rolling stock workshop to analyze the contribution to the modern Korean architecture. J Korean Soc Railway. 2009;12(6):1049–58.
39. Lynch K. The image of the city (1960). In: *Anthologie zum Städtebau. Band III: Vom Wiederaufbau nach dem Zweiten Weltkrieg bis zur zeitgenössischen Stadt*. 2023. p. 481–488. Gebr. Mann Verlag.
40. Maria C, Hollander JB. Urban façades and human stress: evaluating façades' texture and layout. Build Res Inf. 2025. https://doi.org/10.1080/09613218.2025.2506065.
41. Massey DB. For space. 2005.
42. Mitcheltree H, Valentine C, Hosking I, Wilkins A, Sunikka-Blank M, Steemers K. Investigating visual stress within family and domestic violence refuges in Australia. Front Archit Res. 2025. https://doi.org/10.1016/j.foar.2025.05.004.
43. Moon K-J. A study on apartment imagery in Korean films from the 1930s to 1960s. J Archit Inst Kor Plann Des. 2013;29(4):147–58.
44. O'Hare L, Clarke AD, Hibbard PB. Visual search and visual discomfort. Perception. 2013;42(1):1–15.

45. Park H-C. A comparative study on the color landscape of modern rural areas and traditional hanok villages. J Korean Soc Color Stud. 2014;28(2):59–69.
46. Park H-S, Han H-R. A study on healing suggestions for contemporary residential spaces through the analysis of environmental psychological elements of hanok spaces. Proc Korean Inst Interior Des Conf. 2013;15(1):49–54.
47. Park S-J. A study on the classification and trends of integrative architectural forms in supertall buildings. J Korean Soc Sci Art. 2019;37(5):119–33.
48. Park, S., & Choi, S. (2010). A study on the design types and characteristics of domestic apartment façades: Focused on brand apartments completed after 2005 in Seoul's Gangnam area. Proceedings of the Korean Institute of Interior Design Conference, 12(3), 49–54.
49. Park J, Hong J. Convergent Flux: Contemporary architecture and urbanism in Korea. Walter de Gruyter; 2012.
50. Penacchio O, Wilkins AJ. Visual discomfort and the spatial distribution of Fourier energy. Vis Res. 2015;108:1–7.
51. Peri Bader A. A model for everyday experience of the built environment: the embodied perception of architecture. J Archit. 2015;20(2):244–67.
52. Radhakrishnan K, Klass DW. Half a century of visual pattern-sensitive epilepsy. Mayo Clin Proc. 2004;79(2):269–70. https://doi.org/10.4065/79.2.269.
53. Scannell L, Gifford R. Defining place attachment: a tripartite organizing framework. J Environ Psychol. 2010;30(1):1–10.
54. Seo M. The appearance of new architectural representation in Korean modern architecture in the late 19th and early 20th centuries. J Asian Archit Build Eng. 2025. https://doi.org/10.1080/13467581.2025.2553033.
55. Seo, N., Lee, Y., Jeong, Y., & Jung, Y. (2018). Evaluation framework for Korean traditional wooden building (Hanok) through analyzing historical data. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 35, pp. 1-8). IAARC Publications.
56. Shon D, Byun G, Choi S. Identification of facade elements of traditional areas in Seoul, South Korea. Land. 2023;12(2):277.
57. Shon D. A study on the analysis of traditional urban landscape components using data mining techniques: Focused on façades and street elements of Bukchon hanok area (Doctoral dissertation). Seoul: Graduate School of Seoul National University; 2018.
58. Sohn S-W, Koo S-O, Ta N-Y. A study on the visual design image of apartment façade planning. J Korean Hous Assoc. 1999;10(2):247–57.
59. Strasburger H, Rentschler I, Jüttner M. Peripheral vision and pattern recognition: a review. J Vis. 2011;11(5):13. https://doi.org/10.1167/11.5.13.
60. Valentine C. Architectural allostatic overloading: exploring a connection between architectural form and allostatic overloading. Int J Environ Res Public Health. 2023;20(9):9. https://doi.org/10.3390/ijerph20095637.
61. Valentine C, Wilkins AJ, Mitcheltree H, Penacchio O, Beckles B, Hosking I. Visual discomfort in the built environment: leveraging generative AI and computational analysis to evaluate predicted visual stress in architectural façades. Buildings. 2025;15(13):13. https://doi.org/10.3390/buildings15132208.
62. Valentine C, Mitcheltree H. Design for well-being. In: Lavdas AA, Sussman A, Woodworth AV, editors. Routledge Handbook of Neuroscience and the Built Environment (1st edn, p. 313–329). Milton Park: Routledge; 2025. https://doi.org/10.4324/9781003469162-26.
63. Varela FJ, Thompson E, Rosch E. The embodied mind, revised edition: cognitive science and human experience. MIT Press; 2017.
64. Wang JF, Zhang TL, Fu BJ. A measure of spatial stratified heterogeneity. Ecol Indic. 2016;67:250–6.
65. Wilkins, A. J. (1995). Visual Stress. Oxford University Press.
66. Wilkins AJ. A physiological basis for visual discomfort: application in lighting design. Light Res Technol. 2016;48(1):44–54.
67. Wilkins A, Nimmo-Smith I, Tait A, McManus C, Della Sala S, Tilley A, et al. A neurological basis for visual discomfort. Brain. 1984;107(4):989–1017. https://doi.org/10.1093/brain/107.4.989.
68. Wilkins AJ, Penacchio O, Leonards U. The built environment and its patterns: a view from the vision sciences. SDAR J Sustain Des Appl Res. 2018;6(1):5.
69. Wilson HF. On geography and encounter: bodies, borders, and difference. Prog Hum Geogr. 2016;41(4):451–71. https://doi.org/10.1177/0309132516645958.
70. Zukin S. Naked city: the death and life of authentic urban places. Oxford University Press; 2009.

Publisher's Note